HANDBOOK OF ELECTRONIC WASTE MANAGEMENT

INTERNATIONAL BEST PRACTICES AND CASE STUDIES

EDITED BY
MAJETI NARASIMHA VARA PRASAD
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International Best Practices and Case Studies

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Butterworth-Heinemann
An imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-817030-4

For Information on all Butterworth-Heinemann publications
visit our website at https://www.elsevier.com/books-and-journals

Publisher: Matthew Deans
Acquisition Editor: Matthew Deans
Editorial Project Manager: Thomas Van Der Ploeg
Production Project Manager: Nirmala Arumugam
Cover Designer: Mark Rogers

Typeset by MPS Limited, Chennai, India

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Preface

In a technologically progressed world, electronic waste (E-waste)/waste electrical and electronic equipment (WEEE) has become an emerging concern and is in need of urgent attention. To quantify the exact volume of E-waste produced worldwide is challenging primarily due to the absence of suitable systems for tracking this category of waste (Işıldar et al., 2018). For instance, India is one of the largest E-waste producing countries in the world, and there is a lack of updated and clear information on the generation of E-waste in India in terms of the volume that is discarded, collected, and treated annually (Awasthi and Li, 2017). According to the United Nations University, 44.7 million tons of E-waste were generated in 2016 (Baldé et al., 2017). This volume is rising rapidly and developed countries produce major portion of E-waste. However, many Asian and African countries are forced to deal with illegally imported E-waste in addition to their domestic volume. For instance, by 2020, E-waste generated in India is anticipated to be increase drastically which is influenced considerably by the illegally imported obsolete electronics from the Western countries (Kannan et al., 2016). Thus, even though the exact estimation of the E-waste generated annually around the globe is hard to calculate, it is not difficult to judge its growth from the existing studies pointing out huge repercussions of the same.

With the increase in the E-waste volume, its management practices would become complex. Several countries around the globe have come up with plans and procedures to address this emerging category of waste. Most of these countries are from the developed world where it is relatively easier to introduce a formal E-waste management mechanism. Developing countries still struggle to handle their increasing quantity of E-waste in an ecofriendly manner. Unfortunately, the middle- and low-income countries have to deal with considerable amount of E-waste, not only generated from their domestic facilities but also imported from the developed countries. For instance, in 2012, China treated approximately 70% of the global E-waste while the remaining portions mostly find their ways to India and other East Asian and African countries such as Nigeria.[1] Thus, these countries are burdened with both locally generated and exported E-waste from the affluent countries causing serious threats to their environment and human population (Borthakur, 2015). Most of the E-waste in the developing countries are dealt with in the informal waste recycling sector. E-waste contains heavy metals (such as lead, mercury, and cadmium) and persistent organic pollutants (POPs) along with other hazardous substances. However, at the same time, it has valuable and precious metals as components

[1] See https://www.nature.com/news/take-responsibility-for-electronic-waste-disposal-1.20345

(such as gold, silver, palladium, and copper), and this encourages a large number of people to engage in the informal recycling units to extract the substances having potential value. These informal recycling units are unorganized, unregulated, and unsafe, and are often ignored (Ohajinwa et al., 2018). These recycling sites are plagued by huge pollution problems where a significant number of women and children live.

While the volume of E-waste increases, it becomes essential to devise local specific management strategies considering consumers' E-waste disposal behavior and awareness (Borthakur and Govind, 2017). The issue of E-waste should be addressed comprehensively taking into consideration all the relevant factors. For instance, if we consider the generation of E-waste, it differs considerably across nations. While developed countries generate more per capita E-waste than the developing countries, a significant number of low- and middle-income countries are often characterized by a large population size. Thus, even though the per capita waste generation is less in these countries, the total volume generated exceeds considerably the developed countries. Factors like this should be given due attention while addressing the E-waste problem. Further, unlike many developed countries, policy initiatives in the developing countries regarding E-waste are very recent. In majority of them, there were no laws or rules in place to manage the quantity of E-waste generated until very recently. Moreover, the dominance of the informal sector and many other such features come up with major challenges toward implementing the already existed law effectively and positively. Thus, E-waste is an issue which should be dealt with considering the specific socio-cultural, economic, environmental, and geographical circumstances for efficient management.

The uniqueness of this book is its focus on case studies from various countries of six continents such as Africa, Asia, Australia, America (North and South), and Europe. The content of the book is divided into two parts: (1) core subject matter and (2) and case studies.

Chapter 1, An overview of treatment technologies of E-wastes, provides a critical overview of E-waste treatment technologies, including sanitary landfill and recycling of precious metals, nonmetal elements, plastics, and glasses. Authors pointed out that it is essential for developing new technologies to treat E-waste/WEEE.

Chapter 2, Urban mining of E-waste: treasure hunting for precious nanometals, deals with the urban mining of E-waste, which may support cities to reduce the pressure on natural resources by resource recovery, focusing more toward nanometals.

Chapter 3, Biochemical hazards associated with unsafe disposal of electrical and electronic items, details the biochemical hazards associated with the disposal of WEEE metals as well as plastics.

Chapter 4, Policy issues for efficient management of E-waste in developing countries, explains the policy constraints of developing countries and analyzes it comparing current practices and policy comparison between the developed and developing countries, and provides recommendations for a circular economy to the sustainable WEEE management.

Chapter 5, E-waste as a challenge for public and ecosystem health, elaborates the human and ecosystem health impacts of improper handling and management of E-waste through different pathways: soil, water, air, dust, and food.

Chapter 6, Electrochemical enhanced metal extraction from E-waste, deals with electrochemical enhanced metal extraction from WEEE and focuses on the electrochemical processes to enhance the recovery of these different elements that are being accumulated from the E-waste and further details the solvent, electrode conditions required for optimizing the migration of the target metals that either present in the electrolytes as leachate or as anode scrap.

Chapter 7, Phytoremediation for E-waste contaminated sites, describes low-cost and environment-friendly removal of contaminants from E-waste contaminated sites using phytoremediation.

Chapter 8, Organic pollutants from E-waste and their electrokinetic remediation, focuses on the application of electrokinetic remediation for organic contaminants in the soil through electro-migration and electro-osmosis. This chapter demonstrates the need for combining electrokinetics with other techniques such as bioremediation, Fenton techniques, and ultrasonic remediation.

Chapter 9, Mapping the emergence of research activities on “E-waste”: a scientometric analysis and an in-depth review, attempts to map the trends and gaps of research activities on WEEE through a scientometric analysis using the ‘Scopus’ database—a major journal indexing platform.

Chapter 10, Waste electrical and electronic equipment in India: diversity, flows, and resource recovery approaches, onwards are case studies from various countries in different continents. Chapter 10 deals with India with a special focus on its diversity, flows, and resource recovery approaches.

Chapter 11, Socio-technological challenges in formalization of E-waste recycling in India, explores the technologies used in the recycling of E-waste and identifies the major challenges faced by the formal recyclers in India in secondary data regarding the techniques used for recycling and challenges faced by the other formal recyclers in India have listed with major issues related to WEEE recycling in India.

Chapter 12, Electrical and electronic waste in Pakistan: the management practices and perspectives, is focuses on WEEE management practices in Pakistan, existing regulation policy, and major constraints on its implementation together with examples of local practices.

Chapter 13, Challenges in E-waste management in Sri Lanka, highlights the major challenges in E-waste management in Sri Lanka. Introduction of economic instruments that influence consumer behavior such as extended producer responsibility, subsidies for environmentally friendly products, taxes for importation of secondhand products is timely. Authors have pointed the need for formal and informal sectors integration with a strong awareness of the public.

Chapter 14, Electronic waste management practices in Nigeria, provides a detailed discussion on WEEE management practices in Brazil with regards to generation, flow, current practices, legislations, and regulations.

Chapter 15, E-waste recycling slum in the heart of Accra, Ghana: the dirty secrets, reports the impact of WEEE on public policy in Latin-America based on integral management model with data on different WEEE characteristics, collection, dismantling, recycling, and recovery materials.

Chapter 16, E-waste situation and current practices in Brazil, focuses on Ecuador's' solutions shaped in a participatory process through a systemic design methodology which was successfully applied for the development of the national policy for WEEE management in Colombia (2014–16).

Chapter 17, The impact of waste of electrical and electronic equipment public police in Latin America: analysis of the physical, economical, and information flow, presents the current situation and perspectives of WEEE management in Ecuador. It explores common issues of WEEE management such as an inefficient collection, improper disposal, limited financial resources, lack of a legal framework, and insufficient data on generation and composition.

Chapter 18, Environmental pollution of E-waste: generation, collection, legislation, and recycling practices in Mexico and focuses on the implications and challenges produced along with the encounters and affectations of WEEE management system. The implication of inclusion of the informal sector, their possibilities of real participation, the limits, and challenges of this incorporation are detailed in the chapter.

Chapter 19, Improving sustainability of E-waste management through the systemic design of solutions: the cases of Colombia and Ecuador, describes Nigeria, a country which lacks the necessary recycling infrastructure to manage E-waste; hence, relying on informal sectors with the crude dismantling and uncontrolled open burning. Actions which have taken in Mexico to deal with WEEE by several sectors are well detailed in this chapter.

Chapter 20, E-waste management in Ecuador, current situation and perspectives, deal with Ghana's WEEE.

Chapter 21, The Chilean regulation of waste electrical and electronic equipment (WEEE): some of the challenges and opportunities to incorporate informal E-waste recyclers, focuses electronic waste management in Romania: pathways for sustainable practices.

Chapter 22, Electronic waste management in Romania: pathways for sustainable practices, provides a general overview of the E-waste management system in Australia.

Chapter 23, E-waste management practices in Australia, covers an overview of the consequences for health and the environment, the estimating quantities for E-waste, current legislation, recycling benefits/reasons, and current management practices in Mexico.

Chapter 24, E-waste policies in the United States: minimalistic federal action and fragmented subnational activities, explains different subnational initiatives, traces their evolution over time and policies on WEEE management in the United States.

Thus the book will help the readers to locate solutions of the E-waste problem in their own country taken into consideration the experiences of the other geographically, ecologically, and socio-culturally similar countries. Sincere attempts have been made to include a diverse range of topics: from chemical and microbiological analysis to policy concerns. Thus, this book is a vital resource for all the researchers, scientists, policymakers, and the general population toward having a broader understanding of the E-waste crisis in the present global scenario.

Editors

References

Awasthi, A.K., Li, J., 2017. Management of electrical and electronic waste: a comparative evaluation of China and India. Renew. Sustain. Energy Rev. 76, 434−447.

Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann, P., The Global E-Waste Monitor, 2017. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna.

Borthakur, A., 2015. Generation and management of electronic waste in India: an assessment from stakeholders' perspective. J. Devel. Soc. 31 (2), 220−248.

Borthakur, A., Govind, M., 2017. Emerging trends in consumers' e-waste disposal behaviour and awareness: a worldwide overview with special focus on India. Resour. Conserv. Recycl. 117, 102−113.

Işıldar, A., Rene, E.R., van Hullebusch, E.D., Lens, P.N.L., 2018. Electronic waste as a secondary source of critical metals: management and recovery technologies. Resour. Conserv. Recycl. 135, 296−312.

Kannan, D., Govindan, K., Shankar, M., 2016. Formalize recycling of electronic waste. Nature 530, 281.

Ohajinwa, C.M., van Bodegom, P.M., Vijver, M.G., Peijnenburg, W.J.G.M., 2018. Impact of informal electronic waste recycling on metal concentrations in soils and dusts. Environ. Res. 164, 385−394.

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Acknowledgments

The editors would like to thank all the authors of this volume for their cogent and comprehensive contributions. The editors would also like to place on record their appreciation and thanks to Mathew Deans for his inspiration and vital thoughts regarding key inputs for the work. We thank Editorial Project Manager: Thomas Van Der Ploeg, for the excellent coordination of this fascinating project, suggestions, and help in many ways that resulted in timely publication. Thanks are also due to the Production Project Manager, Nirmala Arumugam and Cover Designer Mark Rogers.

Last, but not least, we wish to thank our numerous colleagues for sharing their knowledge and ideas, and lending assistance, which helped to shape this book.

Editors

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An overview of treatment technologies of E-waste

1

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1.1 Introduction

During the last two decades, technological advancement has rapidly happened causing obsolete and end-of-life electronic devices to become electronic wastes (E-waste) (Kiddee et al., 2013a). For instance, lifespan of a computer has reduced from 4−6 years in 1992 to 2−3 years in 2015 (Widmer and Lombard, 2005; Yazici and Deveci, 2013; Shamim et al., 2015). In 2016, the quantity of E-waste generated globally grew up to approximately 44.7 million tons equivalent to 6.1 kg per inhabitant (Ilankoon et al., 2018). The increase rate of E-waste generation is 3%−5% per annum globally (Kumar et al., 2017; Ilankoon et al., 2018). Despite problem in terms of quantity, E-waste itself is also toxic. E-waste contains up to 1000 toxic substances (Puckett and Smith, 2002). Common toxicants found in E-waste include toxic metals and metalloids such as arsenic, barium, beryllium, cadmium, cobalt, chromium, copper, iron, lead, mercury, nickel, and zinc, and persistent organic pollutants such as dioxin, brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated dibenzo-p-dioxins, dibenzofurans (PBDD/Fs), polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs), polyvinyl chloride (PVC), and alternative halogenated flame retardants (AHFRs). Such a variety of toxicants could cause environmental problems and harm human health unless appropriate management procedure applied.

E-waste disposal to landfills and incineration can produce significant quantities of toxicants. Hazardous substances found in landfill leachates are worsened specifically with the old landfills that were not initially designed to receive E-waste, and do not have proper liners or barriers to prevent leakage of leachates (Kiddee et al., 2014). Landfill leachates can be a source of contamination to the soil, surface water, and groundwater (Baccini et al., 1987). A number of studies (e.g., Osako et al., 2004; Danon-Schaffer et al., 2006; Spalvins et al., 2008; Odusanya et al., 2009;

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00022-X

Hearn et al., 2011; Kiddee et al., 2014) reported high level of heavy metals and polyhalogenated organics including polybrominated diphenyl ether (PBDE) found in landfill leachates. During incineration of E-waste, greenhouse gases, mercury, and dioxins are also released into the environment (Balde et al., 2015).

Although E-waste is simply categorized as hazardous waste, it has significant potential for value recovery. E-waste in fact consists of several valuable materials (such as iron, copper, aluminum, and plastics) as well as precious metals (such as gold, silver, platinum, and palladium). Hence, it could be said that E-waste is a feasible urban mine. It provides materials for remanufacture, refurbishment as well as recycling. For example, 11% of the global gold production (2,770 tons) came from mines in 2013 while approximately 300 tons of gold was recovered from E-waste in 2014 (USGS, 2014). The resource in E-waste is normally recycled by both formal and informal procedures. Manual E-waste recycling inescapably leads to the release of toxins and persistent organic pollutants into the environment in addition to harming the health of the recycling person due to the primitive techniques used (Wong et al., 2007). The hazards of E-waste contamination to the surrounding environment including soil, sediment, water, and air has become a serious issue in many countries such as in China (Tang et al., 2010; Wang et al., 2011; Bi et al., 2018; Wu et al., 2019), India (Ha et al., 2009), and Thailand (Muenhor et al., 2010; Kiddee and Decharat, 2018). In case of humans, exposure to toxic substances through inhalation, ingestion and dermal contact can harm the human health in both chronic and acute conditions (Julander et al., 2014). Several studies demonstrated high level of health risks in E-waste recycling sites (Ha et al., 2009; Bi et al., 2018: Kiddee and Decharat, 2018; Oguri et al., 2018; Singh et al., 2018; Wu et al., 2019). Therefore, E-waste recycling industries become increasingly aware of such danger, and start to mitigate impacts from unsafe procedures along with applying appropriate E-waste treatment technologies. Innovative technologies including pyrometallurgy, hydrometallurgy, biometallurgy, high-pressure compaction, thermal treatment, organic dissolution, thermal plasma coupled with acid leaching, substrate oxidation and bioleaching can be applied to recover the potential resources in E-waste. This chapter provides an overview of the toxicity of hazardous substances in E-waste and various E-waste treatment strategies.

1.2 Types of contaminants in E-waste

E-waste is a complex mixture of many materials that contain up to 1,000 toxic substances (Puckett and Smith, 2002). E-waste is classified as a hazardous waste because it is composed of toxic substances such as antimony, arsenic, barium, cadmium, chromium, lead, manganese, mercury, indium, selenium, brominated flame retardants, polyaromatic hydrocarbons, polybrominated diphenyl ethers, and polychlorinated biphenyls. Distinct from other categorization, E-waste also has significant potential for value recovery. E-waste can be composed of several valuable materials (such as aluminum, copper, iron, and plastics) and precious metals (such as gold, silver, platinum, and palladium) (Table 1.1).

Table 1.1 Toxic substances and precious metals associated with E-waste and their health impacts.

Substances	Precious metals	Component of electrical and electronic equipment	Effects
Aluminum (Al)	✓	Printed wiring board, cathode ray tubes, computer chips, hard drives, central processing unit, mobile phones, and connectors	Skeletal development and metabolism, neurotoxicity, and fetal toxicity
Antimony (Sb)		Housing, printed wiring board, mobile phones, and cathode ray tubes	Respiratory problem, associated with lead intoxication, with symptoms including headache, abdominal pain, constipation, colitis, distaste for food, loss of appetite, small mouth ulcers with salivation, dizziness, loss of weight, albuminuria, and glycosuria
Arsenic (As)		Printed wiring board and mobile phones	Skin alterations, decreased nerve conduction, increased risk of diabetes and of cancer (skin and other tissues)
Barium (Ba)		Cathode ray tubes, mobile phones, and fluorescent lamps	Low blood potassium, cardiac arrhythmias, respiratory failure, gastrointestinal dysfunction, paralysis, muscle twitching, and elevated blood pressure
Beryllium (Be)		Power supply boxes, computers, x-ray machines, mobile phones, and ceramic components of electronics	Affect organs such as the liver, kidneys, heart, nervous system, and the lymphatic system, may develop beryllium sensitization or chronic beryllium disease
Bismuth (Bi)		Printed wiring board	Nephropathy, encephalopathy, osteoarthropathy, gingivitis, stomatitis, and colitis
Cadmium (Cd)		Switches, springs, connectors, printed circuit boards, batteries, infrared detectors, semiconductor chips, ink or toner photocopying machines, cathode ray tubes, housing, and mobile phones	Long-term cumulative poison, bone disease, affecting the kidneys, reproductive damage, and lung emphysema

(*Continued*)

Table 1.1 (Continued)

Substances	**Precious metals**	**Component of electrical and electronic equipment**	**Effects**
Cerium (Ce)		Catalyst, fuel additive, and optical polish	Toxicological effects on aquatic-terrestrial organisms, itching, sensitivity to heat, and skin lesions
Chromium (Cr)		Anticorrosion coatings, decorative hardener, data tapes, floppy disks, mobile phones, and housing	DNA damage, lung cancer, human carcinogens, impacts on neonates, reproductive, and endocrine functions
Cobalt (Co)		Printed wiring board, cathode ray tubes, housing, hard drive, and mobile phones	Human osteoblast and osteoclast proliferation and function
Copper (Cu)	✓	Printed wiring board, cathode ray tubes, computer chips, central processing unit, heat sinks, cables, and mobile phones	Liver damage
Dysprosium (Dy)		Lasers and magnets	Nausea, headache, and paresthesia
Gold (Au)	✓	Printed wiring board, computer chips, central processing unit, mobile phones, and connectors/fingers	
Holmium (Ho)		Lasers, magnets and optics	Stimulate metabolism
Indium (In)		Printed wiring board	Lung damage
Iron (Fe)	✓	Printed wiring board, cathode ray tubes, mobile phones, and housing	Liver damage
Lanthanum (La)		Batteries, catalyst, lenses, and cathode ray tubes	Pneumoconiosis
Lead (Pb)		Printed circuit boards, glass in cathode ray tubes, light bulbs, televisions, mobile phones, solder, and batteries	Kidney failure, central and peripheral nervous systems, damage to blood and reproductive systems, anemia, and chronic neurotoxicity
Lithium (Li)		Batteries	Cause nausea, diarrhea, dizziness, muscle weakness, fatigue, and a dazed feeling

(*Continued*)

Table 1.1 (Continued)

Substances	Precious metals	Component of electrical and electronic equipment	Effects
Manganese (Mn)		Printed wiring board, housing, mobile phones, and cathode ray tubes	Respiratory symptomatology and a neuropsychology
Mercury(Hg)		Thermostats, sensors, monitors, cells, printed circuit boards, housing, batteries, and cold cathode fluorescent lamps	Chronic damage to brain, liver damage, cause damage to the central and peripheral nervous systems as well as the fetus, neurobehavioral development of children (methyl mercury), anemia, kidney damage, and chronic neurotoxicity
Nickel (Ni)	✓	Batteries, printed wiring board, housing, mobile phones, and cathode ray tubes	Lung cancer, cardiovascular disease, neurological deficits, developmental deficits in childhood, and high blood pressure
Palladium (Pd)	✓	Hard drives, circuit board components (capacitors), mobile phones, and printed wiring board	Skin and eye irritations
Platinum (Pt)	✓	Hard drives and circuit board components	Respiratory effect
Scandium (Sc)		Lasers, lighting, and aerospace	Respiratory effect
Selenium (Se)		Rectifiers, mobile phones, and printed wiring board	Hair loss, nail brittleness, cardiovascular, renal, and neurological abnormalities
Silver (Ag)	✓	Printed wiring board, computer chips, keyboard membranes, mobile phones, and capacitors	Induction of genes associated with cell cycle progression and DNA damage
Tantalum (Ta)	✓	Printed wiring board, capacitors, and power supply	Low toxicity; irritation to eye, skin, mucous membranes, and upper respiratory tract; coughing
Thulium (Tm)		Lasers and X-rays	Stimulates metabolism
Tin (Sn)	✓	Printed wiring board, cathode ray tubes, solder, liquid-crystal display screens, and computer chips	Adverse gastrointestinal effects

(*Continued*)

Table 1.1 (Continued)

Substances	Precious metals	Component of electrical and electronic equipment	Effects
Vanadium (V)		Cathode ray tubes and mobile phones	Neurological disorders and cardiovascular diseases
Yttrium (Y)		Lasers and superconductors	Causes shortness of breath, coughing, chest pain, and cyanosis
Zinc (Zn)	✓	Cathode ray tubes, printed wiring board, mobile phones, batteries, and metal coatings	Increased risk of copper deficiency (anemia and neurological abnormalities)
Brominated flame retardants (BFRs)		Fire retardants for electronic equipment, plastic casings of computers, cables, as dielectric fluids in capacitors and transformers, lubricants and coolants in generators, fluorescent lighting, ceiling fans, dishwashers, electric motors, components such as connectors and mobile phones	Bioaccumulation in the environment, neurotoxicity, long-term exposure can lead to impaired learning and memory functions, interfere with thyroid and estrogen hormone systems, exposure in the womb has been linked to behavioral problems
Dioxin-like polychlorinated biphenyls (DL-PCB)		Released as a combustion by product but also found in dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Tumor promoters in tissues, such as liver; different congeners may alter different pathways, such as the induction of oxidative stress and/or inhibition of apoptosis
Polyaromatic hydrocarbons (PAH)		Released as combustion by product	Carcinogenicity, mutagenicity, and teratogenicity
Polybrominated diphenyl ethers (PBDEs)		Fire retardants for electronic equipment	Reproductive development, neurobehavioral development, thyroid function, and hormonal effect levels in animals
Polychlorinated biphenyls (PCBs)		Dielectric fluids, lubricants, and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors	Carcinogenicity, liver, thyroid, immune function, reproduction, and neurobehavioral development

(*Continued*)

Table 1.1 (Continued)

Substances	Precious metals	Component of electrical and electronic equipment	Effects
Polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs)		Released as combustion by product, significant bioaccumulation related to lipid solubility, interaction with the aryl hydrocarbon receptor (AhR)	Reproductive and neurobehavioral development Immune development and carcinogenicity
Polyvinyl chloride (PVC)		Insulation on wires and cables	Incineration of PVC produces chlorinated dioxins and furans, which are highly persistent in the environment and toxic even in very low concentrations

Source: Slikkerveer, A., deWolf, F.A., 1989. Pharmacokinetics and toxicity of bismuth compounds. Med. Toxicol. Adverse Drug. Exp. 4 (5), 303−323; Cooper, R.G., Harrison, A.P., 2009. The exposure to and health effects of antimony. Indian J. Occup. Environ. Med. 13 (1), 3−10; Frazzoli, C., Orisakwe, O.E., Dragone, R., Mantovani, A., 2010. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environ. Impact Assess. Rev. 30, 388−399; Andrew, R.E., Shah, K.M., Wilkinson, J.M., Gartland, A., 2011. Effects of cobalt and chromium ions at clinically equivalent concentrations after metal-on-metal hip replacement on human osteoblasts and osteoclasts: implications for skeletal health. Bone 49 (4), 717−723; Kiddee, P., Naidu, R., Wong, M.H., 2013a. Electronic waste management approaches: an overview. Waste Manag. 33, 1237−1250; Grant, K., Goldizen, F.C., Sly, P.D., Brune, M., Neira, M., van den Beg, M., et al., 2013. Health consequences of exposure to e-waste: a systematic review. Lancet Global Health, 1 (6), e350−e361; Rim, K.T., Koo, K.H., Park, J.S., 2013. Toxicological evaluations of rare earths and their health impacts to workers: a literature review. Saf. Health Work. 4 (1), 12−26; Needhidasan, S., Samuel, M., Chidambaram, R., 2014. Electronic waste − and emerging threat to the environment of urban India. J. Environ. Health Sci. Eng. 12, 36, Song, Q., Li, J., 2014. A systematic review of the human body burden of e-waste exposure in China. Environ. Int. 68, 82−93; Dahle, J.T., Arai, Y., 2015. Environmental geochemistry of cerium: applications and toxicology of cerium oxide nanoparticles. Int. J. Environ. Res. Public Health 12, 1253−1278; Tansel, B., 2017. From electronic consumer products to e-wastes; Global outlook, waste quantities, recycling challenges. Environ. Int., 98, 35−45; Chen, Y., Chen, M., Li, Y., Wang, B., Chen, S., Xu, Z., 2018. Impact of technological innovation and regulation development on e-waste toxicity: a case study of waste mobile phones. Sci. Rep., 8, 7100; Ilankoon, I.M.S.K., Ghorbani, Y., Chong, M.N., Herath, G., Moyo, T., Petersen, J., 2018. E-waste in the international context: a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manage. 82, 258−275.

The materials and their concentrations in E-waste depend mainly on the type of manufacturer, type of devices, model, technology, and age of the equipment (Stenvall et al., 2013). Broadly, the materials in E-waste are categorized into four groups, namely (1) ferrous metals (38.1%), (2) nonferrous metals (16.5%), (3) plastics (26.5%), and (4) others (18.9%) (Bigum et al., 2012). The metals in E-waste are found mostly in their native metallic form, and some are in alloys of multiple elements embedded in nonmetallic components (Tuncuk et al., 2012; Sun et al., 2015). Further, E-waste components are grouped based on heavy metal contents as rare earth metals, precious metals, hazardous heavy metals, and halogenated compounds (Fig. 1.1).

E-waste contains 70% of the hazardous waste in heavy metals (Li et al, 2008). These hazardous pollutants comprise only about 2.7% of the total but causes a variety of health hazards due to environmental contamination. The hazardous heavy metals enter into the biological system through soil, water, and air. The health effects of E-waste derived heavy metals and other compounds are listed in Table 1.1.

1.3 Treatment strategies of E-waste

1.3.1 Recycling

Growing quantities of E-waste pose a major challenge for its recycling efforts. E-waste recycling can be intended as part of the "formal" or "informal" economic sector. Commonly, E-waste is exported from developed to developing countries.

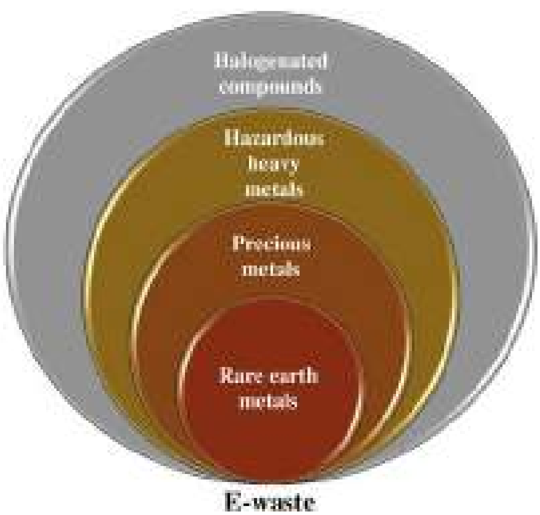

Figure 1.1 Constituents of E-waste grouped based on heavy metals and other elements/compounds.

It is evaluated that 23% of E-waste produced in developed countries is transferred to developing countries (Balde et al., 2015). Particularly, because of the limited policies, precaution, legislation and enforcement, imported E-wastes and second-hand electronic equipment have led to human hazard and ecological system problems in many countries. The primitive techniques including, stripping of metals in open-pit acid baths, chipping, and melting plastics without suitable ventilation, burning cables in open air, disposing unsalvageable matters in the sites and dismantling devices are used at informal E-waste recycling sites (Wong et al., 2007). Numerous studies have shown that the contamination of toxic substances from E-waste recycling sites release directly into the surrounding environment, and impact human health (Ha et al., 2009; Tang et al., 2010; Muenhor et al., 2010; Wang et al., 2011; Bi et al., 2018; Kiddee and Decharat, 2018; Wu et al., 2019). Ha et al. (2009) studied the contamination of trace elements at E-waste recycling sites. They found that the concentrations of Cu, Zn, Ag, Cd, In, Sn, Sb, Hg, Pb, and Bi were higher in soil from E-waste recycling sites compared to reference sites. Tang et al. (2010) investigated the contamination of heavy metal(loid)s (Cu, Cr, Cd, Pb, Zn, Hg, and As) and persistent organic compounds (PAH and PCBs) in soil at E-waste recycling sites. The results found that most heavy metals exceeded the Dutch optimum values. Total PAHs in soil reached 1,231.2 g/kg, and comparatively higher PAHs concentrations were found in soils taken from simple household. Total PCBs were measureable in all samples with concentrations ranging from 52.0 to 5789.5 g/kg. Kiddee and Decharat (2018) investigated the concentrations of lead and cadmium in soil and in the blood of workers at E-waste recycling facilities and assessed the health risks. The results found that the concentration of Pb in soil reached up to 2,866.97 mg/kg. The greatest hazard quotient (HQ) of lead exceeded 1.74, signifying that high exposure of Pb posed a health risk to workers in E-waste recycling sites. Wu et al. (2019) studied the contamination of metals, PBDEs, and AHFRs in the vicinity of an abandoned E-waste recycling site and translocation of the pollutants in rice plants cultivated at the nearby paddy field. They found that the rice plants could effectively absorb some metals such as Mo, Cr, and Mn (bioconcentration factor > 1) from soil and translocate them to the leaves. The health risk from rice consumption was high principally because of Sb and Sn ($HQ > 20$). Thus, many results support that E-waste recycling sites still act as the pollution source to the ecological systems and adversely affect the human health.

1.3.2 Landfill disposal

E-waste disposal in landfills leads to resource loss and can facilitate the contamination of the groundwater and soil via leaching that has the potential to pose negative impact on the surrounding environment. For instance, many developed countries [such as Belgium (17 kilo ton), Denmark (3 kilo ton), France (62 kilo ton), Germany (114 kilo ton), Great Britain (394 kilo ton), Italy (61 kilo ton), Spain (45 kilo ton), Sweden (12 kilo ton), and Switzerland (10 kilo ton)] threw away E-waste in mixed residual waste to landfills (Balde et al., 2015). Toxic substances and putrescible materials in landfills are decomposed and transferred by water to percolate through the soil as landfill leachate. Leachate can contain high levels of dissolved and suspended organic substances, inorganic compounds, and heavy metals. Nevertheless, the concentration of hazardous substances from leachate depends on the waste characteristics and stages of waste decomposition in a particular landfill (Qasim and Chiang, 1994). Hazardous substances found in landfill leachates are worsened specially with the old landfills that were not primarily designed to receive E-waste and had no appropriate liners or no barriers to prevent leakage of leachates (Kiddee et al., 2014). Several researches studied the leaching of components that evolve from E-waste. Toxicity characteristic leaching procedure (TCLP) test, simulated landfill, and realistic landfill monitoring are the techniques to investigate the leachate quality. Jang and Townsend (2003) compared leachates from eleven Florida landfills with TCLP test to define Pb leachability of printed circuit boards from computers and cathode ray tubes from computers and televisions. They found that the concentration of Pb in landfill leachates ranged from <0.04 to 0.07 mg/L while Pb in TCLP extracts were detected from 0.53 to 5.0 mg/L in printed circuit boards and 1.7 to 6.0 mg/L in cathode ray tubes. Leachability by TCLP technique demonstrated higher chemical concentration than monitoring in realistic landfill. Spalvins et al. (2008) used the simulated landfills to assess the impact of E-waste disposal on Pb leachability from electronic devices including computers, keyboards, mouse devices, smoke detectors, monitors, cell phones, and cell phone batteries. They found that Pb concentrations (7−66 μg/L) in the simulated landfill column containing E-waste was higher than the concentration of Pb in the simulated landfill column without E-waste (<2−54 μg/L). Kiddee et al. (2013b) investigated bioavailable metal(oid)s including Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Ni, Pb, Sb, V, Zn, and polybrominated diphenyl ethers (PBDEs) in leachates from three different landfill columns that contained intact or broken E-waste under conditions that simulate landfills in terms of waste components and methods of disposal of E-wastes, and with realistic rainfall. They found that the average concentrations of Al, Ba, Be, Cd, Co, Cr, Cu, Ni, Pb, Sb, and V in leachates from the column that contained broken E-waste elements were significantly higher than the column without E-waste. Both Spalvins et al. (2008) and Kiddee et al. (2013b) confirmed that the Pb concentrations in the columns containing E-waste were higher than those in the simulated landfill columns without E-waste. Danon-Schaffer et al. (2006) studied PBDEs in landfill leachate and potential for transfer from E-waste. They found significant difference in PBDE levels in the leachate over 5 years period. Kiddee et al. (2014) investigated 14 metals and metalloids, including Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, Ni, Pb, Sb, V, Zn, and PBDEs in leachates from four selected Australian landfills receiving E-waste. They found a range of total PBDEs values from 2.13 to 59.75 ng/L in the leachates. Thus, several researches confirmed the high concentration of heavy metals and PBDEs in landfills receiving E-waste.

1.3.3 Biological treatment

Metal recovery by biological processes has emerged as an alternative technology today especially in metals like Au and Cu. Biometallurgical processes utilize microorganisms that convert metals into soluble salts in aqueous media from ores/concentrates/wastes. Biometallugy is a complete blending of biotechnology and metallurgy. Scientifically, the physicochemical process is a branch of hydrometallurgy that involves the use of microorganisms to generate chemical oxidants. It has been an established process for the extraction of metal(loid)s including Cu, Au, Co, Ni, Zn, As, Mo, Cd and U (Watling, 2014). More than 15% of the total annual Cu and 5% of Au along with a small fraction of Ni and Zn are produced using biometallurgical processes (Johnson, 2014; Schlesinger et al., 2011). Both prokaryotic and eukaryotic microbes interact with metal species for structural and/or catalytic functions. The basis of biometallurgy is the interaction between metals and microbes, which aids in the recovery of metals. It was reported that mesophilic, moderately thermophilic and extremely thermophilic bacteria and archaea were involved in biometallurgy (Norris, 2007; Schippers, 2007; Vera et al., 2013). Acidophilic bacteria, cyanogenic heterotrophs, and/or acid-producing heterotrophs were used in biometallurgy to selectively recover metals from waste streams. Biometallurgy is broadly divided into two types, namely bioleaching and biosorption, on the ground of mobilization and immobilization of metals due to biological activities.

Bioleaching is a method tested for the recovery of many base and precious metals. There are two leaching mechanisms for increasing the release rate of metals. Firstly, microorganisms can directly oxidize minerals and solubilize metals in a direct action mechanism, as the below for sulphidic minerals (MS) [Eqs. (1.1) and (1.2)] (Suzuki, 2001):

$$MS + H_2SO_4 + 0.5O_2 \rightarrow MSO_4 + S_0 + H_2O \tag{1.1}$$

$$S_0 + 1.5O_2 + H_2O \rightarrow H_2SO_4 \tag{1.2}$$

The other mode of leaching mechanism is an indirect action mechanism where the microorganisms generate the oxidizing agent (Fe^{3+} from Fe^{2+}). The reactions for indirect action mechanisms are as follows [Eqs. (1.3) and (1.4)]:

$$MS + 2Fe^{3+} \rightarrow M^{2+} + 2Fe^{2+} + S_0 \tag{1.3}$$

$$2Fe^{2+} + 0.5O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \tag{1.4}$$

Biosorption is a process where both living and nonliving organisms can be used for releasing metals from substrates. It is a passive physicochemical interaction between the organism's surface and the metallic ion in the solution. The microorganisms used for biosorption include algae (Greene et al., 1986; Romera et al., 2006; Vilar et al., 2007), bacteria (De Vargas et al., 2004; Yong et al., 2002), yeasts (Bakkaloglu et al., 1998; Wang and Chen, 2006), and fungi (Nui and Volesky, 1999) which are known to accumulate heavy metals and precious metals actively. Bioaccumulation is a particular type of active biosorption in which microorganisms accumulate heavy metals within the living biomass (Fomina and Gadd, 2014). Immobilization of metals can be done by complexation with intracellular proteins (metallothionein and phytochelatins) (Harms et al., 2011). The advantages of biosorption are low operating cost, minimization of the volume of chemicals and/or biological sludge, and high efficiency in detoxifying the effluents (Figueira et al., 2000; Mack et al., 2007; Pethkar and Paknikar, 1998). Biometallurgy has both advantages and disadvantages from other conventional processes. The advantages are low operating costs, reduction in chemical usage, easier manageability of waste effluents, and environmental friendliness. However, the major issues related to biometallurgy are it is a slow process and not fully developed for waste/ore of high metal complexity.

A limited number of studies have explained the extraction of metals from E-waste with mesophilic chemolithotrophic, acidophilic moderately thermophilic, and cyanogenic bacteria. Chen et al. (2015) investigated a one-step bioleaching process using a column for the extraction of Cu with a pulp density of 24.8% of the printed circuit board (PCB) using *Acidithiobacillus ferrooxidans* for 28 days. After 28 days, Cu extraction was 94.8% of the initial Cu concentration. The results (Chen et al., 2015) indicated that the efficiency of bioleaching decreased by precipitation of jarosite at the surface of the material, and the precipitation could be prevented by adding diluted sulfuric acid. Wang et al. (2018) carried out a two-step leaching process by using steel pickling waste liquor as the leaching agent and used a domesticated microbe *A. ferrooxidans*. This study (Wang et al., 2018) found that an optimum pulp density of 60 g/L and pH 0.5−1.0 were effective in recovering almost 100% of Cu and 51.94% of Fe. The rate of Cu leaching was controlled by external diffusion rather than internal diffusion (Wang et al., 2018). Similarly, Ilyas et al. (2007) applied moderately thermophilic acidophilic bacterial strains of chemolithotrophic and heterotrophic consortia for column bioleaching of metals from scrap electrical and electronic equipment. It was found that the leaching efficiency of Zn, Al, Cu, and Ni was 80%, 64%, 86% and 74%, respectively, after a preleaching period of 27 days followed by a bioleaching period of 280 days (Ilyas et al., 2007). In subsequent experiments, the authors observed 91%, 95%, 96%, and 94% efficiency for Al, Cu, Zn, and Ni recovery, respectively, at a pulp density of 10% (w/v) using a moderately thermophilic adapted culture of *Sulfobacillus thermosulfidooxidans* (Ilyas and Lee, 2014). The bioleaching trials were enriched with air (25% O_2 and 0.03% CO_2) and 2.5% (w/v) biogenic S_0 at 45°C (Ilyas and Lee, 2014). Because of the higher bioavailability of the biogenic S_0, the acidophiles oxidized the substrate at a faster rate by which increased the efficiency of bioleaching (Ilyas and Lee, 2014). Recently, Rizki et al. (2019) reported an alternative approach for Au recycling from E-waste where they investigated the potential utility of microbiologically mediated thiourea leaching (TU-bioleaching) for Au recovery. The degree of thiourea tolerance for different Fe-oxidizing bacteria/archaea was in the range of 5−100 mM, and *Acidiplasma* sp. displayed a vigorous Fe-oxidation when thiourea and PCB coexisted as substrates (Rizki et al., 2019). The biogenic Fe^{3+} regeneration due to microbial action enhanced the steady and continuous dissolution of Au (98% Au released at 1 mM Fe^{3+} and 10 mM thiourea) (Rizki et al., 2019). Pradhan and Kumar (2012) investigated a two-step bioleaching of metals from E-waste using cyanogenic bacterial strains (*Chromobacterium violaceum*, *Pseudomonas* *aeruginosa*, and *Pseudomonas fluorescens*). The authors used both single and consortial cyanogenic bacteria to mobilize metals from E-waste with different efficiencies. At an E-waste concentration of 1% (w/v), *C. violaceum* alone, and a consortium of *C. violaceum* and *P. aeruginosa* exhibited the maximum metal mobilization (Pradhan and Kumar, 2012). While *C. violaceum* leached around 79%, 69%, 46%, 9%, and 7% of Cu, Au, Zn, Fe, and Ag, respectively, the mixture of *C. violaceum* and *P. aeruginosa* leached 83%, 73%, 49%, 13%, and 8% of the above elements (Pradhan and Kumar, 2012). Likewise, Faraji et al. (2018) performed fungal bioleaching of PCBs using *Aspergillus niger*. After 21 days of bioleaching, around 97%, 44%, and 64% of Zn, Ni, and Cu, respectively, were recovered based on acidolysis and complexolysis dissolution mechanisms of organic acids, and a two-step bioleaching process was more promising than one-step or spent-medium bioleaching processes (Faraji et al., 2018).

Several reports are available on the scaling up of bioleaching of E-waste for recovery of base, precious and rare earth metals, and methods are improving day by day. A variety of microbes can participate in the E-waste bioleaching process, and a huge potential exists for discovering new microorganisms for industrial applications. However, still there are many challenges to transfer laboratory-scale experiments to pilot plant testing and commercial plant design. This is mainly due to the heterogeneity of E-waste, toxic effects to microbes, environmental factors, and optimum conditions for the production of microbial biomass.

1.3.4 Advanced methods

Among the advanced E-waste treatment methods, high-pressure compaction, cement solidification, thermal treatment, organic dissolution, simple acid leaching, plasma-coupled acid leaching and substrate oxidation are the most prominent ones. In an attempt to compare between the high-pressure compaction and cement solidification methods, Niu and Li (2007) found that the former method although being able to reduce the volume of printed wire boards (PWBs) significantly, the impact resistance of the compacts was not long-lasting under environmental conditions. The latter method on the other hand was able to lock heavy metal Pb strongly in the solidified materials (using Portland cement and slag cement) that lasted long even under harsh environmental conditions (Niu and Li, 2007). Vehlow et al. (2000) suggested that pretreated electrical and electronic waste (free of metallic components) could be added with municipal solid waste (MSW) followed by their thermal treatment at high temperature in order to reduce the volume of the final bottom ash. The authors (Vehlow et al., 2000) found that the cocombustion of the mixed E-waste and MSW substrate did not significantly alter the emission levels of polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF) during the heat treatment. However, this method of E-waste treatment can be highly energy-intensive, and requires adequate facilities to contain the emitted gaseous substances that are highly toxic to the human health. On the other hand, methods such as organic dissolution can be more energy saving than the thermal incineration method. For example, Verma et al. (2017) reported that dimethylacetamide

(DMAc) dissoluted PCBs more effectively than dimethylformamide (DMF), and the optimum conditions for PCB dissolution was under DMAc at 140°C with a PCB:DMAc ratio (w/v) of 3:10. Rath et al. (2012) suggested that thermal plasma treatment followed by mineral acid leaching could be an environmentally benign method for recovering metals from E-waste. This combined method achieved Cu, Ni, and Co leaching from E-waste with >90% efficiency with HCl at room temperature, and thus was highly energy efficient (Rath et al., 2012). Similarly, the grinding and shredding of E-waste could be avoided, and thus energy could be saved by employing a substrate oxidation method to the waste. For example, ammonium persulfate oxidation was found effective to recover Au from the superficial coating of E-waste with an estimated 98% recovery (Alzate et al., 2016). Additionally, recent years have seen significant advancement in the implementation of biological treatment strategies of E-waste (as described in Section 1.3.3). The biological treatment methods are considered as the most environmentally friendly processes but might lack in achieving high resource recovery performance.

1.4 Conclusions

The currently available E-waste treatment strategies have several limitations. Many of these processes demonstrated successful performance under laboratory conditions but failed to perform under real environmental conditions at large commercial scale. The selection of a particular E-waste treatment method involves several considerations including the energy consumption, availability of facilities, risk of secondary pollution, and scalability of the method. Therefore, continuous research effort is a need of the hour in order to develop region specific new E-waste treatment methods.

References

Alzate, A., López, M.E., Serna, C., 2016. Recovery of gold from waste electrical and electronic equipment (WEEE) using ammonium persulfate. Waste Manag. 57, 113−120.

Andrew, R.E., Shah, K.M., Wilkinson, J.M., Gartland, A., 2011. Effects of cobalt and chromium ions at clinically equivalent concentrations after metal-on-metal hip replacement on human osteoblasts and osteoclasts: implications for skeletal health. Bone 49 (4), 717−723.

Baccini, P., Henseler, G., Figi, R., Belevi, H., 1987. Water and element balances of municipal solid waste landfills. Waste Manage. Res. 5, 483−499.

Bakkaloglu, I., Butter, T.J., Evison, L.M., Holland, F.S., Hancock, I.C., 1998. Screening of various types biomass for removal and recovery of heavy metals (Zn, Cu, Ni) by biosorption, sedimentation and desorption. Water Sci. Technol. 38, 269−277.

Balde, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global e-waste Monitor-2014. United Nations University, IAS − SCYCLE, Bonn, Germany.

Bi, C., Zhou, Y., Chen, Z., Jia, J., Bao, X., 2018. Heavy metals and lead isotopes in soils, road dust and leafy vegetables and health risks via vegetable consumption in the industrial areas of Shanghai, China. Sci. Total Environ. 619–620, 1349–1357.

Bigum, M., Brogaard, L., Christensen, T.H., 2012. Metal recovery from high-grade WEEE: a life cycle assessment. J. Hazard. Mater. 207–208, 8–14.

Chen, S., Yang, Y., Liu, C., Dong, F., Liu, B., 2015. Column bioleaching copper and its kinetics of waste printed circuit boards (WPCBs) by *Acidithiobacillus ferrooxidans*. Chemosphere 141, 162–168.

Chen, Y., Chen, M., Li, Y., Wang, B., Chen, S., Xu, Z., 2018. Impact of technological innovation and regulation development on e-waste toxicity: a case study of waste mobile phones. Sci. Rep. 8, 7100.

Cooper, R.G., Harrison, A.P., 2009. The exposure to and health effects of antimony. Indian J. Occup. Environ. Med. 13 (1), 3–10.

Dahle, J.T., Arai, Y., 2015. Environmental geochemistry of cerium: applications and toxicology of cerium oxide nanoparticles. Int. J. Environ. Res. Public Health 12, 1253–1278.

Danon-Schaffer, M., Grace, J., Wenning, R., Ikonomou, M., Lukemburg, W., 2006. PBDEs in landfill leachate and potential for transfer from electronic waste. Organohalogen Compd. 68, 1759–1762.

De Vargas, I., Macaskie, L.E., Guibal, E., 2004. Biosorption of palladium and platinum by sulfate-reducing bacteria. J. Chem. Technol. Biotechnol. 79, 49–56.

Faraji, F., Golmohammadzadeh, R., Rashchi, F., Alimardani, N., 2018. Fungal bioleaching of WPCBs using *Aspergillus niger*: observation, optimization and kinetics. J. Environ. Manag. 217, 775–787.

Figueira, M.M., Volesky, B., Ciminelli, V.S.T., Roddick, F.A., 2000. Biosorption of metals in brown seaweed biomass. Water Res. 34, 196–204.

Fomina, M., Gadd, G.M., 2014. Biosorption: current perspectives on concept, definition and application. Bioresour. Technol. 160, 3–14.

Frazzoli, C., Orisakwe, O.E., Dragone, R., Mantovani, A., 2010. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environ. Impact Assess. Rev. 30, 388–399.

Grant, K., Goldizen, F.C., Sly, P.D., Brune, M., Neira, M., van den Beg, M., et al., 2013. Health consequences of exposure to e-waste: a systematic review. Lancet Global Health 1 (6), e350–e361.

Greene, B., Hosea, M., McPherson, R., Henzl, M., Alexander, M.D., Darnall, D.W., 1986. Interaction of gold(I) and gold(III) complexes with algal biomass. Environ. Sci. Technol. 20, 627–632.

Ha, N.N., Agusa, T., Ramu, K., Tu, N.P.C., Murata, S., Bulbule, K.A., et al., 2009. Contamination by trace elements at e-waste recycling sites in Bangalore, India. Chemosphere 76, 9–15.

Harms, H., Schlosser, D., Wick, L.Y., 2011. Untapped potential: exploiting fungi in bioremediation of hazardous chemicals. Nat. Rev. Microbiol. 9, 177–192.

Hearn, L.K., Thompson, J., Kennedy, K., Mueller, J., 2011. Perfluorinated compounds and polybrominated diphenyl ethers in leachate from Australian landfill sites. In: 31st International Symposium on Halogenated Persistent Organic Pollutants, Brussels, Belgium.

Ilankoon, I.M.S.K., Ghorbani, Y., Chong, M.N., Herath, G., Moyo, T., Petersen, J., 2018. E-waste in the international context: a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manage. 82, 258–275.

Ilyas, S., Anwar, M.A., Niazi, S.B., Afzal Ghauri, M., 2007. Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria. Hydrometallurgy. 88, 180–188.

Ilyas, S., Lee, J., 2014. Bioleaching of metals from electronic scrap in a stirred tank reactor. Hydrometallurgy 149, 50–62.

Jang, Y.-C., Townsend, T.G., 2003. Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates. Environ. Sci. Technol. 37, 4778–4784.

Johnson, D.B., 2014. Biomining-biotechnologies for extracting and recovering metals from ores and waste materials. Curr. Opin. Biotechnol. 30, 24–31.

Julander, A., Lundgren, L., Skare, L., Grander, M., Palm, B., Vahter, M., et al., 2014. Formal recycling of e-waste leads to increased exposure to toxic metals: an occupational exposure study from Sweden. Environ. Int. 73, 243–251.

Kiddee, P., Decharat, S., 2018. Risk assessment of lead and cadmium exposure from electronic waste recycling facilities in Southern Thailand. Environ. Earth Sci. 77, 456.

Kiddee, P., Naidu, R., Wong, M.H., 2013a. Electronic waste management approaches: an overview. Waste Manag. 33, 1237–1250.

Kiddee, P., Naidu, R., Wong, M.H., 2013b. Metals and polybrominated diphenyl ethers leaching from electronic waste in simulated landfills. J. Hazard. Mater. 252–253, 243–249.

Kiddee, P., Naidu, R., Wong, M.H., Hearn, L., Muller, J.F., 2014. Field investigation of the quality of fresh and aged leachates from selected landfills receiving e-waste in an arid climate. Waste Manag. 34, 2292–2304.

Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32–42.

Li, Y., Jiang, G., Wang, Y., Wang, P., Zhang, Q., 2008. Concentrations, profiles and gas-particle partitioning of PCDD/Fs, PCBs and PBDEs in the ambient air of an E-waste dismantling area, southeast China. Chin. Sci. Bull. 53, 521–528.

Mack, C., Wilhelmi, B., Duncan, J.R., Burgess, J.E., 2007. Biosorption of precious metals. Biotechnol. Adv. 25, 264–271.

Muenhor, D., Harrad, S., Ali, N., Covaci, A., 2010. Brominated flame retardants (BFRs) in air and dust from electronic waste storage facilities in Thailand. Environ. Int. 36, 690–698.

Needhidasan, S., Samuel, M., Chidambaram, R., 2014. Electronic waste – and emerging threat to the environment of urban India. J. Environ. Health Sci. Eng. 12, 36.

Niu, X., Li, Y., 2007. Treatment of waste printed wire boards in electronic waste for safe disposal. J. Hazard. Mater. 145 (3), 410–416.

Norris, P.R., 2007. Acidophile diversity in mineral sulfide oxidation. In: Rawlings, D.E., Johnson, D.B. (Eds.), Biomining. Springer, Berlin, Heidelberg, pp. 199–216.

Nui, H., Volesky, B., 1999. Characteristics of gold biosorption from cyanide solution. J. Chem. Technol. Biotechnol. 74, 778–784.

Odusanya, D.O., Okonkwo, J.O., Botha, B., 2009. Polybrominated diphenyl ethers (PBDEs) in leachates from selected landfill sites in South Africa. Waste Manag. 29, 96–102.

Oguri, T., Suzuki, G., Matsukami, H., Uchida, N., Tue, M.N., Tuyen, L.H., et al., 2018. Exposure assessment of heavy metals in an e-waste processing area in northern Vietnam. Sci. Total Environ. 621, 1115–1123.

Osako, M., Kim, Y.-J., Sakai, S.-I., 2004. Leaching of brominated flame retardants in leachate from landfills in Japan. Chemosphere 57, 1571–1579.

Pethkar, A.V., Paknikar, K.M., 1998. Recovery of gold from solutions using *Cladosporium cladosporioides* biomass beads. J. Biotechnol. 63, 121−136.

Pradhan, J.K., Kumar, S., 2012. Metals bioleaching from electronic waste by *Chromobacterium violaceum* and *Pseudomonads sp*. Waste Manag. Res. 27, 1151−1159.

Puckett, J., Smith, T., 2002. Exporting harm the high-tech trashing of Asia, In: Silicon Valley Toxics Coalition (Ed).

Qasim, S.R., Chiang, W., 1994. Sanitary Landfill Leachate: Generation, Control and Treatment. CRC Press, Boca Raton, FL.

Rath, S.S., Nayak, P., Mukherjee, P.S., Roy Chaudhury, G., Mishra, B.K., 2012. Treatment of electronic waste to recover metal values using thermal plasma coupled with acid leaching: a response surface modeling approach. Waste Manag. 32 (3), 575−583.

Rim, K.T., Koo, K.H., Park, J.S., 2013. Toxicological evaluations of rare earths and their health impacts to workers: a literature review. Saf. Health Work 4 (1), 12−26.

Rizki, I.N., Tanaka, Y., Okibe, N., 2019. Thiourea bioleaching for gold recycling from e-waste. Waste Manag. 84, 158−165.

Romera, E., González, F., Ballester, A., Blázquez, M.L., Muñoz, J.A., 2006. Biosorption with algae: a statistical review. Crit. Rev. Biotechnol. 26, 223−235.

Schippers, A., 2007. Microorganisms involved in bioleaching and nucleic acid-based molecular methods for their identification and quantification. In: Donati, E.R., Sand, W. (Eds.), Microbial Processing of Metal Sulfides. Springer, Dordrecht, pp. 3−33.

Schlesinger, M., King, M., Sole, K., Davenport, W., 2011. Extractive metallurgy of copper. Available from: https://doi.org/10.1016/C2010-0-64841-3.

Shamim, A., Ali, Mursheda, K., Rafiq, I., 2015. E-waste trading impact on public health and ecosystem services in developing countries. Int. J. Waste Resour. 5, 1−12.

Singh, M., Thind, P.S., John, S., 2018. Health risk assessment of workers exposed to the heavy metals in e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India. Chemosphere 203, 426−433.

Slikkerveer, A., deWolf, F.A., 1989. Pharmacokinetics and toxicity of bismuth compounds. Med. Toxicol. Adverse Drug. Exp. 4 (5), 303−323.

Song, Q., Li, J., 2014. A systematic review of the human body burden of e-waste exposure in China. Environ. Int. 68, 82−93.

Spalvins, E., Dubey, B., Townsend, T., 2008. Impact of electronic waste disposal on lead concentrations in landfill leachate. Environ. Sci. Technol. 42, 7452−7458.

Stenvall, E., Tostar, S., Boldizar, A., Foreman, M.R.S., Möller, K., 2013. An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste Manag. 33, 915−922.

Sun, Z.H.I., Xiao, Y., Sietsma, J., Agterhuis, H., Visser, G., Yang, Y., 2015. Characterisation of metals in the electronic waste of complex mixtures of end-of-life ICT products for development of cleaner recovery technology. Waste Manag. 35, 227−235.

Suzuki, I., 2001. Microbial leaching of metals from sulfide minerals. Biotechnol. Adv. 19, 119−132.

Tang, X., Shen, C., Shi, D., Cheema, S.A., Khan, M.I., Zhang, C., et al., 2010. Heavy metal and persistent organic compound contamination in soil from Wenling: an emerging e-waste recycling city in Taizhou area, China. J. Hazard. Mater. 173, 653−660.

Tansel, B., 2017. From electronic consumer products to e-wastes; Global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35−45.

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25, 28−37.

USGS, 2014. U.S. Geological Survey, Mineral Commodity Summaries, U.S. Geological Survey (USGS).

Vehlow, J., Bergfeldt, B., Jay, K., Seifert, H., Wanke, T., Mark, F.E., 2000. Thermal treatment of electrical and electronic waste plastics. Waste Manag. Res. 18 (2), 131–140.

Vera, M., Schippers, A., Sand, W., 2013. Progress in bioleaching: fundamentals and mechanisms of bacterial metal sulfide oxidation-part A. Appl. Microbiol. Biotechnol. 97, 7529–7541.

Verma, H.R., Singh, K.K., Mankhand, T.R., 2017. Comparative study of printed circuit board recycling by cracking of internal layers using organic solvents-dimethylformamide and dimethylacetamide. J. Clean. Product. 142, 1721–1727.

Vilar, V.J.P., Botelho, C.M.S., Boaventura, R.A.R., 2007. Methylene blue adsorption by algal biomass based materials: biosorbents characterization and process behaviour. J. Hazard. Mater. 147, 120–132.

Wang, J., Chen, C., 2006. Biosorption of heavy metals by saccharomyces cerevisiae: a review. Biotechnol. Adv. 24, 427–451.

Wang, L., Li, Q., Li, Y., Sun, X., Li, J., Shen, J., et al., 2018. A novel approach for recovery of metals from waste printed circuit boards and simultaneous removal of iron from steel pickling waste liquor by two-step hydrometallurgical method. Waste Manag. 71, 411–419.

Wang, Y., Luo, C., Li, J., Yin, H., Li, X., Zhang, G., 2011. Characterization of PBDEs in soils and vegetations near an e-waste recycling site in South China. Environ. Pollut. 159, 2443–2448.

Watling, H., 2014. Review of biohydrometallurgical metals extraction from polymetallic mineral resources. Minerals 5, 1–60.

Widmer, R., Lombard, R., 2005. E-waste assessment in South Africa: a case study of the Gauteng Province. EMPA 1–62.

Wong, M.H., Wu, S.C., Deng, W.J., Yu, X.Z., Luo, Q., Leung, A.O.W., et al., 2007. Export of toxic chemicals: a review of the case of uncontrolled electronic-waste recycling. Environ. Pollut. 149, 131–140.

Wu, Q., Leung, J.Y.S., Du, Y., Kong, D., Shi, Y., Wang, Y., et al., 2019. Trace metals in e-waste lead to serious health risk through consumption of rice growing near an abandoned e-waste recycling site: comparisons with PBDEs and AHFRs. Environ. Pollut. 247, 46–54.

Yazici, E.Y., Deveci, H., 2013. Extraction of metals from waste printed circuit boards (WPCBs) in H_2SO_4-$CuSO_4$-NaCl solutions. Hydrometallurgy 139, 30–38.

Yong, P., Rowson, N.A., Farr, J.P.G., Harris, I.R., Macaskie, L.E., 2002. Bioreduction and biocrystallization of palladium by *Desulfovibrio desulfuricans* NCIMB 8307. Biotechnol. Bioeng. 80, 369–379.

2 Urban mining of E-waste: treasure hunting for precious nanometals

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2.1 Introduction

With the technological advancement, many types of electrical and electronic equipment (EEE) products are now in the market and due to traditional linear economic system (make-use-dispose) waste EEE has already become a massive issue in the world. Because of the complexity and rapid advancement of technology, it is difficult to group them into sensible and practically useful categories. Electronic waste, or E-waste, is a generic term which refers to the waste generated from all EEE and their parts without the intent of reuse. Moreover, E-waste is also referred to as WEEE—waste electrical and electronic equipment. E-waste includes a wide range of products—almost any household or business item with circuitry or electrical components with power or battery supply (Baldé et al., 2017). Six categories have been listed to be considered as WEEE, and those categories are (1) temperature exchange equipment; (2) screens and monitors; (3) lamps; (4) large equipment; (5) small equipment; and (6) small IT and telecommunication equipment (Perkins et al., 2014). Further descriptions for the categories are as follows.

1. *Temperature exchange equipment*: Those are in general referred to as cooling and freezing equipment such as refrigerators, freezers, air conditioners, and heat pumps.
2. *Screens and monitors*: Those include televisions, monitors, laptops, notebooks, and tablets.
3. *Lamps*: Fluorescent lamps, tungsten bulbs, compact fluorescent lamps, high-intensity discharge lamps, and LED lamps.
4. *Large equipment*: Commonly referred to washing machines, clothes dryers, dish-washing machines, electric stoves, large printing machines, copying equipment, and photovoltaic panels.
5. *Small equipment*: Those equipment include vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, and small monitoring and control instruments.
6. *Small IT and telecommunication equipment*: Mobile phones, global positioning systems (GPS), pocket calculators, routers, personal computers, printers, telephones, and e-book reader.

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00023-1

It has been observed that WEEE disposal has been doubled between 2009 and 2014 to 41.8 million tons per year globally, and in 2016, it reached 44.7 million tons per year (Fig. 2.1). Projections have been made and reported that the total amount of WEEE disposal per year could exceed 50 million tons by 2021 (Hsu et al., 2019). The projected data shows that by 2030, the obsolete computer waste will reach 1000 million tons (Tiwary et al., 2017). Fig. 2.1 further illustrates that the global annual E-waste generation per inhabitant had been 6.1 kg, whereas it has been projected to be 6.8 kg in 2021. However, the estimates report that only 8.9 million tons of E-waste is collected and recycled, which resembles 20% of all the annual E-waste generated (Baldé et al., 2017).

2.1.1 Driving factors for E-waste

The global information society is growing at a pronounced speed due to the advancement in technology. Availability of Internet, mobile networks, new applications, and services supplied at increasingly high speeds and techniques for handling big data have provided new opportunities to the public for health, education, government, entertainment, and commerce. At the same time, a throw-away society characterized by the consumerism, high income, urbanization, and industrialization are some of the factors for experiencing leading to growing amounts of EEEs, and consequently E-waste. Simultaneously, technologies that became obsolete because the technology is old and replaced by new technology drive the production of E-waste. As an example, the most significant declines in sales were found for

Figure 2.1 Schematic diagram representing global E-waste production.

portable audio, portable video, the bulky cathode ray tube (CRT) monitors and televisions with the advancement of technology. Furthermore, devices with single functionality are being replaced by items with multiple functionalities is another driving force for E-waste generation. Multiple device ownership, the tendency to electrify nonelectrical equipment such as wristwatches with shorter replacement cycles, growth in cloud computing services, a rising number of data centers, and unavailability of universal power adapters promote E-waste generation.

Most recent assessments reported that the amount of E-waste generated from Asia was 18.2 million tons and reached as the largest, followed by Europe (12.3 million tons), the Americas (11.3 million tons), Africa (2.2 million tons), and Oceania (0.7 million tons). Although Oceania generated the smallest amount, the E-waste generation density is 17.3 kg/inh. Based on the E-waste generation per inhabitant, Europe is the second largest with an average of 16.6 kg/inh whereas Americas generate 11.6 kg/inh. The E-waste collection in Europe has been the highest of 35% where the Americas collect only 17% and 15% in Asia. An alarming situation is noted from India where the generation of E-waste was around 470,000 million tons as on 2011, out of which the annual generation from each big cities, Mumbai generates around 11,000 million tons, Delhi 9000 million tons, Bengaluru 8000 million tons, and Chennai 5000−6000 million tons (Vidyadhar, 2016).

Nanotechnology has become an exciting route to chemical innovation basically in every field as diverse as medicine, water treatment, and energy storage to improve technologies related to human health, communications, and transportation. It is well known that WEEE is a complex mixture of metals, plastics, glass components, and more. Among the mixture, precious metals such as gold, silver, and palladium, in E-waste continues to drive recycling although they are not trivial to recover in an economic sense. Therefore recovery of high added-value products from the metals, for example, nanoparticles from WEEE has recently become a trending research direction. Few attempts have been made to convert WEEE to nanodust, nanoparticles, and extract nanometal elements for other benefits using different resource recovery techniques. Nanoscale materials in electronics are able to transform, release heavy metals, and potentially toxic elements (PTEs).

Consequently, E-waste could be an unintended exposure source to PTEs which may pose a significant risk to human health and the environment. Hence, extracting nanomaterials from E-waste can be considered as a dual benefit in terms of the economy and ecological and human health risk. This chapter summarizes the resource recovery techniques and pathways of nanoparticles extraction from E-waste.

2.1.2 Raw materials in electrical and electronic equipment and their waste

E-waste is a combination of heterogeneous materials, where the mass fraction is bulk metals (aluminum, copper, and ferrous), plastics, and glass. Each EEE contains as many as 60 elements, for example, the thin, conductive layer of indium tin oxide on a screen to the lithium in the batteries of a smartphone; many precious metals are used. Furthermore, trace amounts of economically important critical materials such as rare earth metals, indium, and platinum group metals are present in high concentrations in WEEE than their respective ores indicate the potential of WEEE as a secondary resource (Li et al., 2007). Microelectrical components of EEE's wiring mainly comprise copper, gold, and silver, while tantalum is used in microcapacitors. In microphones, speakers, and vibration units, neodymium–iron–boron magnets are commonly used. Some of the precious metals used in EEEs are hard to replace with substitution, and the best example is Tantalum metal used in phones (Davies, 2017). Manufacturing of EEE consumes considerable fractions of the gold (Au), silver (Ag), and palladium (Pd) mined annually worldwide for phones and computers (Hadi et al., 2015). The third largest consumer of Au is the electronic industry. It has been estimated that more than one million people in 26 countries across Africa, Asia, and South America work in Au mining mostly in illegal conditions due to its demand for EEEs (Işıldar et al., 2018).

It has been estimated that the total value of all raw materials present in E-waste is approximately 55 Billion Euros in 2016 (Baldé et al., 2017). Linear economic practices will lead the raw materials in E-waste to end up in landfills and contaminate the environment as there is no closing loop of material flow. The rate at which EEE is discarded and replaced will contribute to global resource depletion due to high resource consumption (Li et al., 2015). Table 2.1 reports the precious metals that are being used as raw materials in different EEEs and E-waste streams, which will gain future attention as secondary raw materials.

Among the major metals present in E-waste, the iron amount exist is considered has no real economic value. However, E-waste contains around 20% copper and the main metallic constituent (Ilankoon et al., 2018). It is evident that the chemical composition of WEEE varies with its type, age, origin, and manufacturer, however,

Table 2.1 Precious metals in various EEEs and their waste streams.

Electrical and electronic equipment	Precious metals
Photovoltaic panels	Cadmium, tellurium, indium, and gallium
Liquid crystal displays (LCDs), Cathode ray tubes (CRTs) and light emitting diode (LED)	Indium, gallium, and germanium
Printed circuit boards (PCBs)	Gold, silver and platinum, copper, aluminum, iron, antimony, arsenic, mercury, and lead
Notebooks and tablets	Gold, silver, palladium, and copper
Hard drives	Neodymium (Nd), praseodymium (Pr), dysprosium (Dy), aluminum, iron, copper, tin, nickel, silver, gold, and palladium
Cell phones and smartphones	Copper, silver, gold, palladium, lithium, aluminum, cobalt, lead, nickel, and zinc

estimates denote the gold content in E-waste is in the range 80−250 g/tons in general (Cui and Zhang, 2008). Both gold and copper seem to be present in WEEE at higher concentrations than their respective ores. The quantity of precious metals in WEEE is crucial to the economics of recycling and recovery processes. It is known that as much as 75% of the intrinsic value of E-waste is in the gold, copper, and palladium content (Cucchiella et al., 2015); for example, recycling and recovery of one million mobile phones would generate 24 kg of gold, 250 kg of silver, 9 kg of palladium, and 9000 kg of copper as per the Electronics Take Back Coalition, 2014. Moreover, it has been estimated that the entire global gold quantity of WEEE inventory as 300 tons in 2014, which is valued at 10.4 billion euros (Bigum et al., 2017).

2.1.3 E-waste resource recovery

Different driving forces act upon the resource recovery through recycling of WEEE; major is the value of the precious metals, whereas environmental pollution has also been a reason. Up until recent times, the E-waste recycling was done primarily to separate and recover individual precious metals, predominantly copper and gold due to their high grade and economic value. Feasibility and cost-effectiveness of the recovery processes were given the priority for the extraction of other metals. Visibly, the nonmetallic is considered as the most significant proportion of E-waste compared to metallic fraction, were in general treated by incineration or landfilling. E-waste contains potentially toxic metals, such as lead, mercury, and cadmium, hazardous chemicals, such as flame retardants, PAHs (polycyclic aromatic hydrocarbons), and plastics (Lecler et al., 2018). As an example, the CRT screen in old television used to contain 2−3 kg of lead (Cui and Forssberg, 2011). Whereas the flat screens contain less lead, which is no more than 1 kg (Bigum et al., 2017). End of the life of CRT screens, large Pb concentrations are observed entering the waste inventory. Therefore resource recovery may play a significant role in recycling the precious metals rather their contribution to environmental pollution.

Different metals in WEEE can be clustered into five major categories: precious metals (Au and Ag); platinum group metals (Pd, Pt, Rh, Ir, and Ru); base metals (Cu, Al, Ni, Sn, Zn, and Fe); metals of concern (Hg, Be, In, Pb, Cd, As, and Sb); and scarce elements (Te, Ga, Se, Ta, and Ge) (Tesfaye et al., 2017). Resource recovery is based on the extraction of precious metals, platinum group metals, and base metals from E-waste. Printed circuit boards (PCBs) have received the attention of the recyclers as the most treasurable part in E-waste streams. PCBs are found in all EEEs such as TVs, computers, and mobile phones. Precious metals can be found in the components such as PCBs, connectors as well as in the solders; for example, PCB from an LCD TV contains 575 mg of Ag, 138 mg of Au, and 44 mg of Pd (Tesfaye et al., 2017). It has been reported that the precious metals in PCB are worth more than 80% of the total intrinsic value, although their composition is <1 wt.% in E-waste (Park and Fray, 2009).

Several different technical and nontechnical tools have been applied to recover resources from WEEE in a sustainable manner (Ravi Naidu, 2013). WEEE is rich in a complex mixture of metals, alloys, and polymetallic compounds and hence is considered as a better source than primary ores (Ongondo et al., 2015). Resource recovery encounters sustainable use of the natural resources by breaking the closed loop of traditional linear use of resources to a cyclical utilization that allows maximum recovery of resources from waste (Cossu, 2013). Advancement of technology relies on a great number of elements, and therefore the complexity of WEEE increased. As modern devices consist of up to 60 elements in various mixtures of metals, the resource recovery becomes difficult since complex alloys pose a challenge for efficient metal recovery technologies (Bloodworth, 2014).

2.2 Urban mining E-waste for metals

Urban mining is a concept linked to resource efficiency which extends landfill mining to the process of resource recovery from anthroposphere that represents a significant source of resources, with concentrations of elements often comparable to or exceeding natural stocks (Cossu and Williams, 2015). About the critical raw materials, WEEE is considered as the backbone stream in urban mining. Urban mining activities involve systematic management of anthropogenic resource stocks and waste in order to protect the environment, conserve resources, and derive economic benefits (Baccini and Brunner, 2012). Although urban mining is a pleasing concept from an environmental perspective, it is still in the kindergarten level from the resource recovery perspective as a lot of valuable materials are ending up in a landfill. Therefore resource recovery in urban mines requires a paradigm shift (Baccini and Brunner, 2012).

Urban mining is a collection of processes. The first phase in the urban mining chain is the collection and consolidation of E-waste (Fig. 2.2). Efficient E-waste collection is lacking in many countries where it requires a high awareness level of

Figure 2.2 Schematic diagram for urban mining in an ideal circular economy model which leads to sustainable production and consumption.

consumers as well as collectors. Usually, the collection happens in different scenarios: stationary and mobile methods. Cost minimization has been the primary concern in the E-waste collection (Nowakowski, 2017). Source separation is a must, which will benefit in many ways in order to reduce labor involvement and time. The fixed collection points can easily be established in places where municipal waste is being collected, service shops, and community centers.

Ensure consumer participation may lead to achieving good collection rates of E-waste. Awareness plays a major role to improve WEEE collections and recycling. Economic incentives such as providing free collection services, including transportation of EEE to collection or recycling centers may improve the WEEE collection. It has been observed that only 9% of respondents claimed to have delivered their used mobile phones to a proper recycling system in 2011 (Nowakowski, 2017). Though, in general, a large proportion of mobile phones in the developing countries specifically are stored by the consumers over more extended periods. Also, since it is easy for the small-sized devices to be thrown away with the municipal solid waste plays a role in the improper disposal and end up in landfills or dump sites.

With the objective of the highest recovery of precious metals, E-waste recycling includes three stages: pretreatment, size reduction, and separation including comminution and separation of materials using mechanical/physical processing, and metallurgical/chemical refining/purification through pyro/hydro/electro/biohydro metallurgical processes (Hsu et al., 2019; Kaya, 2016; Lu and Xu, 2016).

2.2.1 Physical techniques

Physical separation techniques are conducted to separate metallic and nonmetallic fraction without any loss of valuable metals. The physical properties such as size and shape of WEEE influence the efficiency of physical recycling. Three different physical separation techniques are being practiced: density separation or particle shape-based separation, electrostatic separation mostly eddy current separation, and magnetic separation (Hsu et al., 2019). Process of physical recycling is well demonstrated by Kaya (Kaya, 2016). When the collected WEEE reaches the recycling facility, it may undergo various processes before actual recycling to take place. During the pretreatment operation, size reduction and separation are conducted. The WEEE is ended up with physical separation techniques for further processing through recycling techniques (Hsu et al., 2019).

2.2.1.1 Dismantling

Dismantling or disassembly is mainly conducted to remove hazardous components in order to minimize the toxic materials into the recycling stream and to separate reusable parts (Lu and Xu, 2016). Dismantling can also be performed manually or mechanically where mechanical disassembly further classified semiautomatic or automatic dismantling. Desoldering is done via heating the solder above the melting point and separate reusable items for reselling. Removal of components, parts and/ or a group of parts attached through fastening by screws, clinks, and rivets, inserting, welding, binding, wrapping, coating, and plating in a systematic manner from E-waste is called as dismantling. Disassembly is a manual or mechanical process based on the economy of the country and not energy intensive. Two basic forms of dismantling are selective and simultaneous disassembly. In selective dismantling, look and pick specific components and removed. Simultaneous dismantling is an efficient process; however, there is a risk for the components to be damaged and, also requires an additional sorting that increases the time and cost. In simultaneous disassembly, desoldering is done by heating the whole unit in a tin furnace. Geometrical and physical criterions are used in identifying and sorting which is called as "evacuate and sort."

2.2.1.2 Crushing, shredding, and milling

After physical dismantling, the remaining WEEE undergoes crushing, shredding, and grinding to pulverize the waste to powder. Shredding/crushing is conducted to strip metals from WEEE (Tesfaye et al., 2017). Further reduction of the dimensions of WEEE is made through shredding. Double shaft shredder is widely used E-waste recycling (Tesfaye et al., 2017). After shredding, crushing/pulverizing is done with dust collection systems. Subsequently, density separation isolates the nonmetals and metals. Crushing consumes energy and useful in selective efficiency. Comminution of WEEE and effective detachment of metals from nonmetals is the prerequisite. Low-speed high torque shear shredders are considered as the best for the primary crushing (Lu and Xu, 2016). Crushing in two steps has proved efficient shearing actions which generated by the rotor, stator cutters, and crude crusher and afterward further crushing in a hammer grinder are explicitly used for printed circuit boards. It has been described that shredding or grinding may lead to a 40% loss of precious metals (Jiang et al., 2012). Crushing can generate hazardous dust due to the strength and tenacity of the WEEE; hence, an efficient dust collection system is a must. Grinding process makes metals to be turned into a spherical shape due to their malleability and ductility, whereas nonmetals (plastics and glass fibers) remain nonspherical in shape, usually as rods or strands, due to stress (Hsu et al., 2019). After crushing process, pulverizing of WEEE is done using ball and disc milling (Ghosh et al., 2015). Various types of mills have been described for the finer comminution where swing hammer types appearing to be the standard.

2.2.1.3 Sieving and separation

Sieving is carried out in the physical recycling process to classify the different sized particles based on the various sizes of sieve apertures to the desired particulate size for separation. Sieving is not only been utilized to prepare a uniformly sized feed but also to upgrade metal contents (Kaya, 2016). The screening is essential as the particle size and shape of metals are different from that of plastics and ceramics. Rotating screen is used mainly for metal recovery in WEEE recycling process.

Based on the variation in shape, density, and electric conductivity of metallic and nonmetallic materials in WEEE electrostatic separation are considered as a promising way to recover metals from pulverized WPCBs. Recycling industry basically used shape separation by tilted plate and sieves. Copper recovery is promising by an inclined conveyor with a vibrating plate from electric cable waste, printed circuit board scrap, and waste television and personal computers in Japan (Cui and Forssberg, 2003).

Magnetic, electrostatic, and density separation are mechanical separation techniques that have been widely used in urban mining of WEEE. Low-intensity drum separators are the standard method of magnetic separation for the recovery of ferromagnetic metals from nonferrous metals and other nonmagnetic wastes (Hsu et al., 2019). Magnetic separation is in general performed first, followed by shredding or grinding to fine particle size, and after that electrostatic separation is applied. High-intensity separators are used for possible separation of copper alloys from the waste matrix (Veit et al., 2005). Through an intense magnetic field, copper alloys with relatively high mass susceptibility (Al multicompound bronze), copper alloys with medium mass susceptibility (Mn multicompound bronze, special brass) and copper alloys with low mass susceptibility and/or diamagnetic material behavior (Sn and Sn multicompound bronze, Pb and Pb multicompound bronze, and brass with low Fe content) can be separated (Cui and Forssberg, 2003).

Electrostatic separation is considered as advantageous compared to the other physical techniques as it is smooth operation, less hazardous, and requires less energy (Lu and Xu, 2016). Electrostatic separation is based upon electrical conductivity and separates the nonconductive materials from the conductive ones. Although the electrostatic separators were initially recovered nonferrous metals from automobile scrap or municipal solid waste, now widely used for WEEE utilized explicitly for the recovery of copper or aluminum from chopped electric wires and cables and recovery of copper and precious metals from printed circuit board scrap (Lu and Xu, 2016). It has been observed that the multistage process is needed to separate conductors from nonconductors (Hsu et al., 2019). Both corona discharging and eddy current-based electrostatic separation have received significant attention in the separation of ferrous and nonferrous metals and the separation of plastics from the plastic and metal mixture. Particle size has become a limiting factor, along with the sticking effect of larger particles in terms of corona separation, whereas eddy current-based electrostatic separation depends on the flow of the particles (Cui and Forssberg, 2003).

Gravity separation is considered as the best physical separation option for nonmetals from the metals by different specific gravities. Density separation is dependent on the density and the size of the components. Viscous liquids such as tetrabromoethane can serve as the separation medium where the metals can be separated from the plastics or ceramics. Conventional gravity separators that are used in E-waste recycling are water or airflow tables, dense media separation, and sifting. Density separation techniques that have extensively been used in the mineral processing industry are now applied into E-waste recycling as WEEE consists of many plastics, with a density less than 2.0 g/cm^3; light metal, primarily Al and glass, with a density of 2.7 g/cm^3; and heavy metals, predominantly Cu and ferromagnetic, with a density more than 7 g/cm^3 (Kaya, 2016). The enriched fractions are treated by chemical techniques: pyrometallurgical and hydrometallurgical processes after mechanical/physical treatments in order to extract precious metals.

2.2.2 Chemical techniques

Chemical processes that are used in resource recovery of WEEE include pyrolysis and pyrometallurgical processes for the nonmetallic fractions, whereas various metallurgical processes are used for the separation of the metallic fraction of E-waste. Most common chemical techniques for precious metal recovery from WEEE are pyrometallurgy and hydrometallurgy. Pyrometallurgy is the most traditional and standard treatment process where hydrometallurgy is a recent advancement (Khaliq et al., 2014). For the resultant, electrometallurgical/electrochemical processes and biometallurgy can be applied for further separation.

2.2.2.1 Pyrometallurgy

Pyrometallurgy involves incineration, smelting in plasma arc or blast furnaces, drossing, sintering, melting, and gas-phase reactions at high temperatures (Hsu et al., 2019). Presently, WEEE recycling is dominated by pyrometallurgical routes (Khaliq et al., 2014). Pyrometallurgical routes are similar to mechanical or hydrometallurgical processes with the steps of liberation, separation/upgrading, and purification. More than 70% of WEEE is treated in smelters instead of mechanical processing (Cui and Zhang, 2008). After the reduction of size via physical techniques, WEEE essentially transferred into smelters for separation and recovery of copper and other precious metals. In the pyrometallurgical process, the liberation of valuable metals is achieved by smelting in furnaces at high temperatures. In these processes, metals are sorted by exploiting their chemical and metallurgical properties. “Bath” or “flash” smelting are known as the copper smelting processes. Bath smelting is a molten liquid bath where the smelting and converting occurs, and the concentrate is in contact with the liquid slag and matte. Injection of air into the bath or on top of the bath converts the matte. In the case of flash smelting, the converting happens in the air stream. Physical techniques result in preprocessed E-waste which is composed of Fe, Al, Cu, and Pb in high amounts and precious metals in low concentrations. Typical E-waste is rich in Fe and Al followed by Cu and Pb. Therefore WEEE may undergo Pb smelting and Cu smelting routes in order to separate Pb, Cu, and precious metals. Recent techno-economic analysis of pyrometallurgy has revealed that the E-waste recycling process embedded in copper smelting has potential value and is economically feasible with a minimum plant capacity of 30,000 tons of E-waste/year (Khaliq et al., 2014).

Incineration: The incineration process can be done at a high temperature where a tremendous amount of mass losses (70%) and E-waste scraps converted into liquid matte and slag. The organic matter presents in WEEE facilitates burning and turns it into solid char, gases, and oil.

Smelting: In the process of smelting, physical and chemical changes occur in the furnace at a temperature between 1000 °C and 1300 °C. There have been several processes employed during the smelting process, including flash and bath smelting. Various metallurgical processes such as oxidation, reduction, vulcanization, melting, matte forming, slag forming, and fumes of nonferrous metal compounds can occur during the smelting process (Ma, 2019).

The metal sulfides impurities such as Pb, Zn, and Fe, oxidized to metal oxides in the presence of oxidizing environment and moved to the slag while recovering metals such as Cu and precious metals (Ag, Pt, Pd, and Au) formed liquid matte (Namias, 2013). The typical reactions took place during the oxidation as given in chemical Eqs. (2.1)–(2.3):

$$2\ M_2S_m + 3m\ O_{2(g)} \rightarrow 2\ M_2O_m + 2m\ SO_{2(g)} \tag{2.1}$$

$$M_2S_m + 2m\ O_{2(g)} \rightarrow M_2O_m + m\ SO_{3(g)} \tag{2.2}$$

$$M_2S_m + 2m\ O_{2(g)} \rightarrow M_2(SO_4)_m \tag{2.3}$$

For an example, In Cu recovery from WEEE, during the smelting process, Cu with precious metals and iron sulfide formed liquid matte whereas some other metal sulfides like Fe and Zn, oxidized to metal oxide and produced slag. This process illustrated by the following chemical Eq. (2.4):

$$\begin{aligned}&\{(4\ CuFeS_2)-\text{precious metals}\}_{(gangue)}\\&\quad + 2\ SiO_2 + 5\ O_2 \rightarrow \{(2\ FeSe \cdot Cu_2S)-\text{precious metals}\}_{(matte)}\\&\quad + 2\ FeO \cdot SiO_{2(slag)} + 4\ SO_2\end{aligned} \tag{2.4}$$

The above-mentioned process continued by the conversion process where the matte is oxidized further in the presence of an oxidizing atmosphere and produced impure copper blister liquid, whereas chemical Eqs. (2.5) and (2.6) illustrates:

$$\begin{aligned}&\{(2\ FeS \cdot Cu_2S)-\text{precious metals}\}_{(matte)}\\&\quad + 2\ SiO_2 + 3\ O_2 \rightarrow 2\ Cu_2S + 2\ FeO \cdot SiO_{2(slag)} + 2\ SO_2\end{aligned} \tag{2.5}$$

$$Cu_2S + O_2 \rightarrow 2\ Cu_{(blister)} + SO_2 \tag{2.6}$$

Finally, the copper blister liquid treated with anode furnace to separate the pure copper from the blister. About 99% of copper from the blister can be separated, and the remaining can be recovered during the electrorefining process (at the cathode terminal). Using the electrorefining cell, 99.99% of copper was recovered from the WEEE and precipitated the precious metals such as Au, Ag, Pt, and Pd. The further recovering process needs to be carried out to recover the precious metals from the final residue (Dennis, 2018; Ding et al., 2019; Ma, 2019).

Although the pyrometallurgy is traditional and commonly used in metal recovery in the past two centuries, it has borne some merits and demerits. The ability to accept any form of WEEE scrap since the organic matters in WEEE has been used as fuel during the incineration process is one of the main merits (Kaya, 2016). However, there are some demerits of pyrometallurgy process have been reported as follows (Namias, 2013; Ma, 2019):

- Pyrometallurgy process cannot recover metals like Al and Fe since these are oxidized to metal oxides and shifted into the slag.
- It produces a large quantity of slag.
- It is impossible to recover some certain products such as plastic, ceramic, and glass since these are provided thermal energy to the burning process.
- The combustion of plastics generated environmentally toxic fumes such as furans, polybrominated diphenyl ethers and dioxins and individual attention needed to be controlled this harmful emission.
- This process emits fumes along with heavy metals which have low melting points such as Pb, Hg, and Cd.
- Uncontrolled combustion of WEEE during the incineration process.
- Lengthy process: at the end of the process the precious metals such as Au, Ag, and Pt residue obtained and it is very challenging tasked to recover the precious metals from the residue.

2.2.2.2 Hydrometallurgy

Compared to pyrometallurgy, hydrometallurgy is considered to be better as the technique can be conducted in controllable, more exact, predictable conditions through an environmental friendly manner. The hydrometallurgical process involves a series of acid or caustic leaches of WEEE followed by separation and purification techniques, such as cementation, solvent extraction, ion exchange, and activated carbon adsorption, to isolate and concentrate the metals from the leached solutions (Hsu et al., 2019). Chemical leaching processes have gained traction, and a plethora of research on leaching has been done in recent years. Similar technology of acid or caustic leaching is employed in traditional hydrometallurgical processes for metal extractions from the particular primary ores are applied for WEEE. The separation of metal of interest is conducted through solvent extraction, adsorption, and ion exchange enrichment processes (Khaliq et al., 2014). Four methods are used commonly for chemical leaching, based upon the extraction chemistry: acid, cyanide, thiourea, and thiosulfate. In the case of acid leaching various different acids in different ratios are involved, nitric acid, aqua regia (a mixture of hydrochloric and nitric acids), and sulfuric acid:H_2O_2. The most popular leaching method for metals in WEEE treatment is acid leaching, which provides high leaching rate and fast kinetics regardless of the corrosiveness. Leaching from cyanide is standard practice in gold mining; however, due to its high toxicity, it is not in practice at today's industry. It has been found that thiourea and thiosulfate leaching as the least hazardous techniques for the recovery of precious metals, however, are not cost-effective. In the case of thiourea, the stability is poor whereas, the leaching kinetics of thiosulfate is slow and hence require large amounts of reagent, makes it unrealistic in large scale use. Finally, metals are recovered from the mixture through electrometallurgy or chemical reduction processes.

2.2.2.2.1 Acid/alkaline leaching

The acid or alkaline leaching is the basic and fundamental process of recovering precious metals such as Au, Ag, Pt, and Pd from E-waste, where the dissolution of selective precious metals taken place. However, the usage of aqua regia (the mixture of HCl and HNO_3 in 3:1 ratio) in the leaching process is a nonselective method for both precious and base metals. Numerous studies have investigated the usage of an inorganic acid such as HCl, HNO_3, and H_2SO_4 in recovering the precious metals from E-waste (Guo et al., 2016; Yang et al., 2017). Table 2.2 explains some inorganic acids leaching in urban mining.

Moreover, the usage of strong inorganic acids in the recovery of precious metals from E-waste may results, secondary contaminants formation: 540 tons of CO_2, 1.4 tons of SO_2, 2 kg of Sb, 98 kg of ethane, 130 kg of phosphate, and thousands of tons of tailings and similar amount of sludge, corrosion of the equipment, and spoilage of nonmetallic components (Innocenzi et al., 2017; Rocchetti et al., 2013). A special attention needs on the formed secondary contaminants before it dispose into the environment (Tesfaye et al., 2017).

Recently, the organic acids also have used to recover the metals from E-waste, especially cellphone batteries. The organic acids are considered as potentially harmless to the environment, efficiently leaching the metals, less corrosive, and biodegradable green chemicals (Fu et al., 2019; Musariri et al., 2019). Moreover, organic acids do not produce any secondary pollutants. Table 2.3 summarizes the recent

Table 2.2 Urban mining of precious and base metals using inorganic acids.

Acid	Used E-waste	Recovered metal	References
2.0 M, HCl	Printed circuit boards (PBCs) of mobile phones	Au (5.0%) Cu (94.91%)	Kim et al. (2011)
0.1 M, HCl	PBCs of mobile phones	Au (93.06%) Cu (0.58%)	Kim et al. (2011)
2–5 M HNO_3	TV board scraps	Cu (88.5%–99.9%)	Bas et al. (2014)
1–5 M HNO_3		Ag (14%–68%)	
HNO_3	PBCs of cell phones	Ag (100%)	Petter et al. (2014)
5.5 M HCl	PBCs	Sn (95.97%)	Jha et al. (2012)
2.0 M HCl	PBCs	Cu (71%) Zn (98%) Sn (96%) Pb (96%)	Kim et al. (2006)
0.5 M H_2SO_4	Lithium–ion batteries	Mn (100%) Co (99%) Ni (85%)	Yang et al. (2017)

Table 2.3 Recovery of metals using organic acids as a leaching agent.

Acid	E-waste	Conditions	Metals recovered (%)				References
			Co	Li	Ni	Ga	
Citric acid	LIBs	Temp: 95 °C [Acid]: 1.5 M Reductant: H_2O_2 2 vol% Leaching time: 30 min	95	97	99	–	Musariri et al. (2019)
DL-malic acid	LIBs	Temp: 95 °C [Acid]: 1.0 M Reductant: H_2O_2 2 vol. % Leaching time: 30 min	98	96	99	–	Musariri et al. (2019)
Oxalic acid	LEDs	Temp: 90 °C [Acid]: 0.7 M Leaching time: 0 min	–	–	–	90.36	Zhou et al., 2019
Benzenesulfonic acid	LIBs	Temp: 90 °C [Acid]: 0.75 M Reductant: H_2O_2 3 vol.% Leaching time: 80 min	96.53	99.58		–	Fu et al., 2019

efforts of recovering precious metals using organic acid as leaching agents. The metal leaching from organic acids can be given by Eqs. (2.7) and (2.8):

$$2\ MO + RCOOH + H_2O_2 \rightarrow 2\ M^{m+} + RCOO^- + O_2 + 2\ H_2O \quad (2.7)$$

$$n\ M^{m+} + m\ RCOOH \rightarrow M_n(RCOO)_m + m\ H^+ \quad (2.8)$$

where RCOOH is organic acid.

2.2.2.2.2 Cyanide leaching

The utilization of cyanide (CN^-) as a leaching agent in the recovery of precious metals is well known for more than 100 years (Cui and Zhang, 2008). The usage of cyanide is preferable due to its significant capacity on the recovery of precious metals. It is imperative to maintain the pH between 10 and 11 during the leaching process, since below pH 8.5, CN^- exist as HCN, which is a highly volatile and toxic substance. The temperature has to be maintained around 160 °C, to overcome the strength of metallic bonds present in metals during the chemical reaction and to oxidize metals in the alkaline medium under an oxygen-rich environment (Akcil et al., 2014; Chen and Huang, 2006; Naghavi et al., 2016). In the leaching process of precious metals under alkaline conditions, metals are oxidized while the oxygen is being reduced. The typical reaction involved in the metal recovery using cyanide is given in Eq. (2.9):

$$M + n\ NaCN + O_2 + 2H_2O \rightarrow n\ Na^+ + [M(CN)_n]^{m-} + 4\ OH^- \quad (2.9)$$

2.2.2.2.3 Thiourea leaching

Thiourea (NH_2CSNH_2) is an organosulfur compound, which is known as a sulfur-containing organic compound. Thiourea has the ability to bind with precious metals such as Ag and Au by coordination bonds since it has a lone pair of electrons on nitrogen and sulfur atoms. The low environmental impact, fast kinetics, and financial profitability considered thiourea as a right leaching agent in Au and Ag recovery process from WEEE (Gurung et al., 2013).

Utilization of thiourea for recovery of precious metals in alkaline medium is not feasible, because of the easy decomposition in alkaline solution, while thiourea exhibits a rapid recovery of leaching in an acidic environment. Furthermore, the reaction kinetic of thiourea leaching process in the acidic environment has been speeded up by introducing the iron (III) (Fe^{3+}) ion into the reaction mixture (Gurung et al., 2013). In acidic medium, thiourea forms cationic coordination complexes with precious metals such as Au and Ag and the dissolution takes place by the anodic reaction indicated by chemical Eq. (2.10) (Jing-ying et al., 2012):

$$M + 2\ NH_2CSNH_2 \rightarrow [M(NH_2CSNH_2)_2]^+ + e^- \quad (2.10)$$

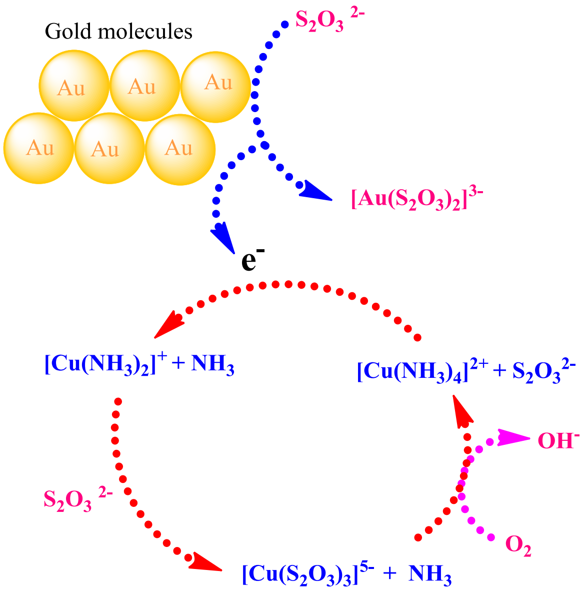

Figure 2.3 The proposed mechanism of gold leaching from WEEE using thiosulfate agent.

With this process, up to 100% of Au and Ag can be leach out from WEEE. The leaching rate of Au and Ag with thiourea influences by the pH of the solution, the strength of thiourea, the concentration of Fe^{3+} ion, leaching time, and particle size (Hilson and Monhemius, 2006).

Although, the recovery process is kinetically fast, less environmental influences compared to cyanide leaching process and insensitive to other metals such as Cu, As, Pb, and Zn, thiourea is still hidden from its commercial applications due to the high cost and the rapid oxidation in the reaction system. Therefore a large amount of thiourea needs in order to complete the recovery process, which is a significant drawback of the method (Hilson and Monhemius, 2006) (Fig. 2.3).

2.2.2.2.4 Thiosulfate leaching

Thiosulfate ($S_2O_3^{2-}$), an anionic chemical compound which is used in redox reactions as a reducing agent (Fig. 2.4). Since 20 years, it has been used to leach out the precious metals, instead of cyanide leaching method (Akcil et al., 2014). The usage of thiosulfate for the recovery of precious metals is peaceful to the environment since it is nontoxic and can be decomposed easily by the thio-bacteria in the environment (Wentzien et al., 1994). Leaching efficiencies of 98% and 93% of Au and Ag were recorded by ammonium thiosulfate leaching for 48 h (Ficeriová et al., 2011). Thiosulfate leaching process has been carried out in the alkaline medium since in low pH, thiosulfate has decomposed and formed elemental sulfur which covers the metal surface and prevents from the leaching (Hilson and Monhemius, 2006). Furthermore, the leaching kinetics of precious metals using thiosulfate solution, enhanced by the addition of copper (II) ions in the reaction mixture.

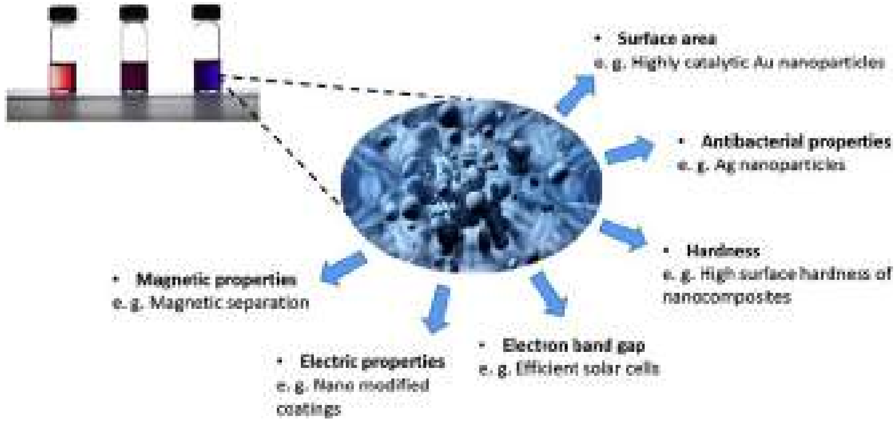

Figure 2.4 The unique characteristics of nanomaterials, which are beneficial for basic electronic components.

2.2.2.3 *Biometallurgy*

Biometallurgy has received recent attention due to low investment cost, low environmental impact, and low energy consumption and therefore has become a well-established pathway for recovering precious metals from WEEE. Biometallurgy is a two-step process: bioleaching and biosorption. Bioleaching employs diverse organisms for the extraction of metals where many factors can influence the extraction: microbial tolerance, microbial consortia, bacterial attachment, and abiotic factors including the metallic composition of the waste, pH, particle size, and the secondary reactions (Cui and Zhang, 2008). Two main types of bacteria: ferooxidans and thiooxidans, can solubilize metals specifically from metallic sulfides (Mahmoud et al., 2017; Morin et al., 2006). Biosorption process is different from bioleaching, a passive physicochemical interaction between the charged surface groups of microorganisms including algae, bacteria, yeasts and fungi, and ions in solution (Bandara et al., 2017). Biosorption-based recovery offers several advantages compared to the conventional methods including low operating costs, minimization of the volume of chemical and biological sludge to be handled, and high efficiency in detoxifying effluents.

2.2.2.3.1 Bioleaching

Bioleaching is a simple process for the recovery of metal particles from E-waste, with the use of microorganisms such as bacteria, fungi, and actenomycetes (Vakilchap et al., 2016). This particular process has considered as low energy consuming, highly efficient, environmental friendly, and a low operational cost process that can be carried out at room temperature and atmospheric pressure (Xiang et al., 2010). Generally, the microorganisms leach the metal particles from the metal sulfide, which presents in ore or E-waste by two types of mechanisms, which are known as direct action and indirect action mechanisms.

Indirect mechanism, microorganisms oxidized the metal sulfide directly, which means, the electron transfer takes place between the metal sulfides and the surface of the particular organism (Vera et al., 2013). Some bacteria such as *Acidithiobacillus ferrooxidans*, which has the ability to transfer the electrons between the cell and the mineral metals, are mediated by the secretion of extracellular polymeric substances (Zhao and Wang, 2019). However, studies on the direct action mechanism have to be further investigated (Zhao and Wang, 2019). Direct action mechanism has illustrated by Eqs. (2.11) and (2.12) (Cui and Zhang, 2008):

$$2\ MS + 2\ H_2SO_4 + O_2 \rightarrow 2\ MSO_4 + 2\ S + 2\ H_2O \tag{2.11}$$

$$2\ S + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4 \tag{2.12}$$

In the indirect mechanism, the microorganisms such as iron (II)-oxidizing bacteria regenerates the Fe^{3+} ions from Fe^{2+} ions by oxidization and then the Fe^{3+} ions oxidize the metal minerals by itself. This reaction represents in the chemical Eqs. (2.13) and (2.14):

$$MS + 2\ Fe^{3+} \rightarrow M^{2+} + 2\ Fe^{2+} + S \tag{2.13}$$

$$2\ Fe^{2+} + 1/2\ O_2 + 2\ H^+ \rightarrow 2Fe^{3+} + H_2O \tag{2.14}$$

The indirect mechanism further classified into two categories: thiosulfate pathway and polysulfide pathway. In the thiosulfate pathway, thiosulfate formed as an intermediate (Cui and Zhang, 2008). Generally, this mechanism plays on the acid insoluble metal sulfides such as molybdenum disulfide and iron disulfide. The thiosulfate pathway can be forwarded by *A. ferrooxidans* and *Leptospirillum ferrooxidans* bacteria (Balci et al., 2007).

In polysulfide pathway, acid soluble metal sulfides such as FeS, PbS, MnS_2, $CuFeS_2$, As_4S_4, Fe_7S_8, As_2S_3, and ZnS undergo oxidative attack by protons and/or Fe^{3+} ions and produced chemically inert elemental sulfur (Vera et al., 2013). However, the elemental sulfur can finally be oxidized biologically by bacteria to sulfuric acid, which produced enough protons for the dissolution of metal sulfide. This mechanism can be catalyzed by sulfur-compound oxidizing bacteria such as *A. ferrooxidans* and *Acidithiobacillus thiooxidans*.

Table 2.4 has summarized some previously studied documents about the bioleaching process in the recovery of precious and base metals using microorganisms. *A. ferrooxidans* and *A. thiooxidans* are the mostly utilized bacteria in the bioleaching process.

Although *A. ferrooxidans* and *A. thiooxidans* are frequently used in the metal recovery processes from E-waste (Table 2.4), some other bacteria such as *Chromobacterium violaceum* also have been used in the bioleaching of metals. *C. violaceum* is a gram-negative bacteria which has the ability to produce cyanide ions, where Au particles can be leach out from the WEEE (Liu et al., 2016). The chemical reaction about cyanide leaching of Au is explained nicely in Eq. (2.14). Over 70% of Au, biologically leached out from the WEEE using *C. violaceum* bacteria (Liu et al.,

Table 2.4 Recovery percentage (%) of metals from different types of E-waste using bioleaching process.

E-waste	Organisms	Recovered metals	Recovered (%)	References
PCBs of computer	*Acidithiobacillus ferrooxidans*	Cu Zn Pb Ni	94 92 64 81	Priya and Hait (2018)
LCDs	*Acidithiobacillus thiooxidans*	In Sr	100 10	Jowkar et al. (2018)
PCBs	*A. ferrooxidans*	Zn Cu Al	83.8 96.8 75.4	Yang et al. (2014)
Dust from WEEE shredding	*A. thiooxidans*	Ce Eu Nd La Y	> 99 > 99 > 99 80 80	Marra et al. (2018)

2016). The *Pseudomonas putida* is another type of gram-negative bacteria with the ability to generate cyanide ions. It is reported that 48% of Au has been recovered from the dust of WEEE, which is preleached with *A. thiooxidans*. It is also reported that no other precious metal such as Ag and Pd have been leached out from the preleached dust by *A. thiooxidans*. The bioleaching is an effective manner to recover the precious metals from the WEEE. Therefore it is necessary to study further in order to improve the leaching abilities and discover new species of microorganisms.

2.2.2.3.2 Biosorption

Biosorption is another technique, which can be used in the recovery process of precious metals from WEEE. The biosorbent used in this process can be either dead or alive or product biomasses of bacteria, fungi, algae and protein, etc. The adsorption of metals take place due to the physiochemical interaction between the metals in solution and surface of biosorbents, while complex formation, microbial oxidation and reduction, chelation between biosorbent and metals, and microprecipitation are taken place as the chemical interactions. The physical interactions include ion exchange and electrostatic forces (De Vargas et al., 2004). The biosorption of metals by a particular biosorbent depends on the properties of the surface of biosorbent. Surface functional groups such as amine, amide, hydroxyl, carboxyl, and carbonyl have driven the adsorption of positively charged metals efficiently (Wang and Chen, 2006, 2009). The biosorption capacity of metals affected by several factors: temperature, solution pH, the dosage of biosorbents, and charge of metals. In order to achieve the highest biosorption capacity, the surface of biosorbent has chemically further modified. Polyethylenimine (PEI) modified bacteria *Corynebacterium glutamicum* has shown biosorption capacity of 110.5 mg/g for Ru whereas raw bacterial biomass shown 16 mg/g of biosorption capacity which is determined by the Langmuir adsorption model (Kwak et al., 2013). The main drawback of the biosorption process is that the experiments cannot be carried out when the WEEE is in solid form. Once it leached out, the biosorption process can be carried out. From thiourea leachate of the discarded microprocessor of computer, 80% of Au has been recovered using chitin as the biosorbent and treating for 4 h with an ambient temperature (Côrtes et al., 2015).

There are some bottlenecks on the biosorption of metals, it needs to be leached out the solid waste prior to carry out the biosorption, and the biosorbents are necessary to undergo a chemical surface modification to achieve maximum biosorption capacity. Due to these limitations, the biosorption process is carried out at the small scale and laboratory levels (Işıldar et al., 2019). Further implementation is needed for the biosorption process to industrial and commercial levels.

2.3 Extraction of nanometals from E-waste

Recycling E-waste has been introduced as an effective solution for the massive accumulation of waste electrical and electronic equipment (WEEE), with a growth rate of 5% per year (Afroz et al., 2013). A wide range of waste types can be seen in electronic waste, such as plastics, precious metals (e.g., gold, silver, palladium, and platinum), base metals (e.g., copper, zinc, nickel, and ferrous), potentially toxic elements (e.g., lead, cadmium, and mercury), carbon-based insulate materials (e.g., quartz, silica and carbon material containing parts), and halogenated derivatives (Majumder, 2014). However, more than 90% of WEEE can be recycled and regenerate to reuse in new electronic devices (Afroz et al., 2013). The amount of E-waste generated due to limited utilization, low generating rate of E-waste compared to municipal solid waste and relatively large starting cost of recycling process are some of the drawbacks which limit the intention of recycling WEEE (Kim et al., 2017). Among different aspects of recycling E-waste, recovering metals in nanoscale results in high purity commercial grade nanometals (Deep et al., 2011).

Nanomaterials (NMs) have unique characteristics, which is very beneficial in electrical and electronic applications (Fig. 2.5). Synthesis of NMs can be carried out in two main pathways: top-down approach and bottom-up approach (Fig. 2.5). In the top-down approach, bulk materials have broken down to nanoscale particles, while nanoscale particles have built up starting from the atomic scale, in the bottom-up approach (Thakkar et al., 2009; Sinha et al., 2011). A variety of bottom-up methods, such as physical, chemical, and biological methods have been used to synthesize nanoscale metals and metal oxides particles from E-waste.

2.3.1 *Pure metals*

2.3.1.1 *Precious metals*

Various chemical and physical techniques have been used in the case of precious metal extraction. However, recent attention is focused on biological extraction.

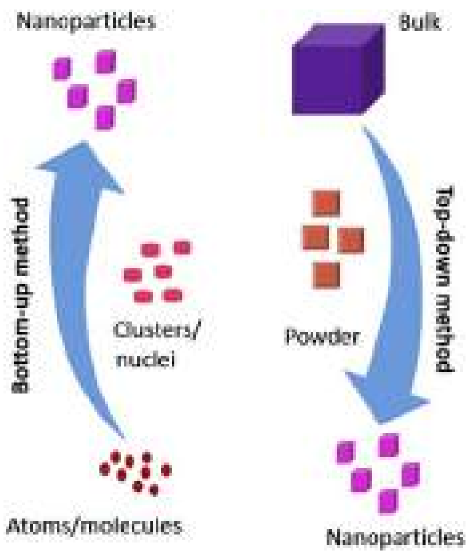

Figure 2.5 Bottom-up and top-down approaches of synthesis of nanoparticles from E-waste using both chemical and biological methods.

Most of the precious metals have recycled to obtain nanoparticles, with the process which is known as bioleaching, by using microorganisms, weed extracts, and enzymes (Jain et al., 2010). Biosynthesis of nanoparticles is beneficial due to the formation of natural protein coat over the nanoparticle during the synthesis. This cover prevents aggregation, provides longer shelf life and stability due to less reactivity (Majumder, 2014). Microorganisms, which are known as mini biofactories of nanometal production, are able to produce metal particles in the range of $5 - 200$ nm (Husseiny et al., 2007). They commonly extract, gold (Au), silver (Ag), and palladium (Pd) with bacteria, fungi, algae, yeast, and actinomycetes.

2.3.1.1.1 Gold (Au) nanoparticles

Extraction of nanogold from E-waste can be carried out in two pathways: chemically and biologically. Hydrometallurgical process of extracting metals results in a high recovery yield of metal with low temperature and cost. This method appropriates in small scale applications and therefore suits for small scale applications such as precious metal recovery (Ghosh et al., 2015). Extractions under hydrometallurgical process have done with different lixiviants and solution pH values. Alkaline pH conditions were used with cyanide and thiosulfate leaching, while thiourea and halide leaching was done in acidic pH conditions (Tuncuk et al., 2012). Halide and cyanide complexes have expressed higher leaching rate of Au, with compared to thiosulfate and thiourea complexes. Overall, 97% of recovery of gold can be seen with $NaClO_3$-HCl, H_2O_2-H_2SO_4, and iodine solutions under appropriate conditions (Ding et al., 2019). The hydrometallurgical process has been modified to leach out gold in nanoscale, to achieve high leaching rate (Behnamfard et al., 2013) and to reduce environmental influence (Ding et al., 2019) with chloride/sodium chlorate to recover 99% of Au and with noncyanide leaching agents (e.g., thiourea, thiosulfate, and thiocyanate), respectively. Polyaniline powders, films, and coated fibers were used hydrometallurgical process, through spontaneous reduction to extract gold nanoparticles from E-waste (Wu et al., 2017). Traditional leaching methods also can be used to extract gold with cyanide as an active ingredient in the leaching process. However, due to high toxicity, noncyanide alternatives such as thiourea and thiosulfate have introduced by authorities to avoid environmental accidents (Ding et al., 2019).

Recovery of gold nanoparticles from WEEE also can be carried out with spent catalysts, which exhibits several advantages such as short production cycle, simple process, and eco-friendliness (Jha et al., 2013; Dong et al., 2015). Crushed spent catalysts mixed with fluxes such as Al_2O_3, CaO, or SiO_2 are used in the pyrometallurgical process, and chemical properties, mutual solubility, and melting point were considered (Ma et al., 2017).

In biological methods, nanometal extraction with microorganisms plays a significant role. *Pseudomonas aeruginosa*, *Stenotrophomonas maltophilia*, *Plectonema boryanum*, and *Rhodopseudomonas capsulate* are some of the bacterial types, which is used in the biosynthesis of Au nanoparticles (He et al., 2008; Nangia et al., 2009). Other than bacteria, fungi types such as *Verticillium luteoalbum* and *trichothecium* species also can be used in bioleaching of nano Au (Ahmad et al., 2006; Maliszewska, 2012). *Yarrowia lipolytica*, a type of yeast and *Rhodococcus* sp., a type of actenomycetes are reported as microorganisms for bioleach gold nanoparticles (Ramani et al., 2004; Pimprikar et al., 2009). Algae also have the ability to synthesized metal nanoparticles, and therefore *Calothrix pulvinata*, *Anabaena flos-aquae*, *Leptolyngbya foveolarum*, and *Laminaria japonica* algae species have been used in Au nanometal extraction (Brayner et al., 2007; Ghodake and Lee, 2011). Gold also can be extracted in nanoscale with weed extract with a range of 8−12 nm in size (Singaravelo et al., 2007).

2.3.1.1.2 Silver (Ag) nanoparticles

Silver is a precious metal which is widely used in basic electrical components manufacturing. Therefore Ag can be commonly found in PCBs and other electrical appliances. Nanoscale silver can be extracted out from EEEW into a cyanide solution by using traditional leaching out methods. Cyanide and aqua regia are used in traditional hydrometallurgy process to leach out silver, and the oxidant dosage, solution pH, temperature, and concentration of cyanide directly affect on the efficiency of leaching (Xie et al., 2014). Precious metals such as Ag, dissolve by complexation with CN^- in an optimal pH of 10.2. Considering the toxic effect of cyanide, to avoid environmental accidents, few noncyanide lixiviants has been introduced by the authorities. Aqua regia exhibits a nonselective dissolution of precious metals and results in 98% of recovery of silver (Park and Fray, 2009). Even though aqua regia gives a high yield of Ag and Au, it expresses drawbacks such as toxicity, corrosiveness, and strong oxidative (Petter et al., 2014).

To extract nanosilver, noncyanide extraction technologies also can be used, and 48% of Ag could be recovered with thiourea leaching method (Jing-ying et al., 2012). The modified hydrometallurgical process to recover precious metals selectively and 71% of Ag can be obtained (Behnamfard et al., 2013). Extraction of Ag with iodine−iodide leaching is another method to take out silver in nanoscale with supercritical water oxidation (Xiu et al., 2015). Electrochemical methods also have been used in the extraction of Ag from E-waste. The chemical utilization in the recovery of metals is considerably low in electro-recycling process and results in nearly 97% of recovery of Ag (Lister et al., 2014).

Other than chemical methods, silver nanoparticles can be extracted by using biological methods suchlike microbial leaching and weed extraction. *Shewanella oneidensis*, *Escherichia coli*, and *Klebsiella pneumoniae* are some of the bacterial types that produce extracellular spherical silver in a range of 50−100 nm (Natarajan et al., 2010; Suresh et al., 2011). Fungal species, *Penicillium purpurogenum NPMF*, *Trichoderma reesei*, and *Aspergillus fumigatus*, are some of the many, which has the ability to synthesize silver nanoparticles less than 25 nm in scale (Pradhan et al., 2011; Vahabi et al., 2011). *C. pulvinata* and *Anabaena* species are algae, which is a type of microbe and contribute to the synthesis of nanosilver (Vahabi et al., 2011).

2.3.1.1.3 Platinum (Pt), palladium (Pd) and rhodium (Rh) nanoparticles

Plasma melting iron capture technology is the most commonly used and an effective way of recycling platinum group metals (PGM) using spent catalysts. Iron has been selected as the promising collector due to low coat and strong chemical affinity. The slag and the Fe-PGM alloy was separated using the significant density difference and the recovery of Pt, Pd, and Rd was above 98%, 98%, and 97%, respectively (He et al., 2016). Iron trapping method has introduced to overcome the high energy consumption of plasma melting technology and Pt, Pd, and Rh result in a recovery of 98.6%, 92%, and 97.6%, respectively (Ding et al., 2019). To leach PGMs from spent automotive catalysts, an eco-friendly electro-generated chlorine leaching method has been developed (Kim et al., 2013). To prepare the most effective chlorinated species such as Cl_3 and $HClO.Cl_3$ for dissolving Pt, Cl_2 has fed into HCl solution. The dissolution of Pt is increased with Cl_3^- in a particular HCl concentration and exhibits leaching rates of 71%, 68%, and 60% Pt, Pd, and Rd (Upadhyay et al., 2013).

Aqua regia in nonselective dissolution method was used in both base and precious metals leaching and 93% of Pd could be possible to recover (Park and Fray, 2009). With a solid/liquid ratio of 1/10 at 25ºC within 24 h, 100% of Pd was able to dissolve (Fontana et al., 2018). Recovery of platinum group metals (PGM) with copper smelting has been studied, and two types of recovery methods have proposed: wetting and settling mechanisms. Microparticles of PGM were used in metal separation process (Kolliopoulos et al., 2014).

Other than chemical methods, Pd can be biologically extracted by using bacteria. *Clostridium pasterianum*, *S.oneidensis*, and *Desulfovibrio desulfuricans* are bacteria, which are used in biological methods. Metal particles of Pd are synthesized in the range of 1–50 nm (De Windt et al., 2006).

Matte acts as an excellent collector in matte trapping methods for extracting metal Rd, due to the high affinity for PGM and recovering Rd from spent organic Rd catalysts, high nickel matte has been used, and a recovery of 94.65% of Rd was observed (Xiaotang et al., 2012). Using nickel and sulfur as collectors in smelt spent catalysts in the presence of Na_2CO_3 and$Na_2B_4O_7$ at 1050 ºC for 30 min with a recovery rate of 90%, 93%, and 88%, respectively (You et al., 2016).

2.3.1.2 Base metals

Other metals Cu, Sn, Zn, Al, and Ni are commonly used in electrical and electronic appliances also can be leached out in the E-waste recycling process. An alkali fusion-leaching-separation process has been developed with fluxing agents (e.g., $NaNO_3$-NaOH) to recover metals from crushed metal enrichment (CME) from printed circuit boards (PCBs). In the fusion process, metals have oxidized and converted into soluble salts obtaining leaching rates of 97%, 91%, 98%, and 98% for Sn, Zn, Al, and Cu, respectively. Aqua regia has achieved 100% recovery of Cu with compared to thiourea, sulfuric acid, and ammonia (Lee et al., 2011). The developed hydrometallurgical process with two repeated leaching systems of H_2SO_4-H_2O_2 leaches Zn, Cu, Fe, Ni, and Sn in 100, 100, 59, and 94%, respectively (Birloaga et al., 2014).

An electrochemical process has developed to recover Cu from waste PCBs. The introduced process has the ability to recover Au simultaneously. Two different types of reactors coupled in series and one reactor for dissolution of base metals with a perforated rotating drum and the other reactor for leaching solution with the parallel electro-winning of copper. In the stage of Cu, Sn, and Ag recovered with Fe^{3+} in sulfate, 97% of Cu was recovered (Fogarasi et al., 2014).

Using biological methods, Cu can be extracted in nanoscale. Microorganisms such as bacteria (e.g., *Pseudomonas stutzeri*, *Morganella* sp. and *Pseudomonas* sp.), fungi (e.g., *Fusarium oxysporum*), and actinomycetes (e.g., *Streptomyces* sp.) have used to extract Cu as nanoparticles less than 150 nm (Usha et al., 2010; Majumder, 2012). Other than microbes, weeds also can be used to synthesize metal nanoparticles successfully. *Lantana camara* is an ornamental weed which considers as a green-approach for the synthesis of Cu nanoparticles (Majumder, 2012).

Besides of Cu, other metals such as Se, Ti, and Mn also can be extracted using biological methods. Using bacteria species and fungal species, metal particles in nanoscale have been extracted. *Pseudomonas alcaliphila*, *Lactobacillus* sp., and *Bacillus* sp. are some of the bacterial species that can be used in the extraction of nanoparticles of Se, Ti, and Mn (Sinha et al., 2011; Zhang et al., 2011).

2.3.1.3 Toxic metals

In printed circuit boards Pb is commonly used as a soldering material to create contact between basic electronic components. Therefore Pb is ubiquitous in E-waste and can cause serious health issues by accumulating in the environment. Alkali fusion-leaching-separation process has been used with a fluxing agent (e.g., $NaNO_3$-NaOH) to recover Pb, by converting to a soluble salt in the fusion process. Under optimal conditions, 91% of Pb can be leach out (Guo et al., 2017). Mercury (Hg) and cadmium (Cd) are found in E-waste from small nonrecyclable fractions, and research has been carried out to extract and disposed of carefully (Ilankoon et al., 2018).

2.3.2 Metal oxides

Nanomaterials can be extracted in pure metal form as well as metal oxides. Zinc is one of the metal types, which can be extracted in metal oxide form. By using spent Zn−Mn dry alkaline batteries, pure zinc oxide (ZnO) nanoparticle in the range of 40−50 nm can be recovered. The extraction of ZnO nanoparticles can be carried out under Hydrometallurgy-precipitation and liquid−liquid extraction pathways resulting in a 99% recovery (Deep et al., 2011).

Nano-Al_2O_3 can be synthesized from the waste aluminum electrolytic solution with the co-precipitation method. Particles less than 200 nm was able to recover with a percentage of 99.9. The used ammonia during the recovery process could be recycled up to 80% and reused in the reaction process (Wu and Chang, 2016).

An effective synthesis of copper oxide (Cu_2O) nanoparticles from E-waste (e.g., PCBs) has been developed. Highly uniform and monodisperse Cu_2O nanoparticles with a range of 5−40 nm in size could be able to synthesize using supercritical water, combined with an electrokinetic technique. Under optimized conditions, over 90% of Cu in E-waste have recovered as Cu_2O nanoparticles (Xiu and Zhang, 2012).

2.3.3 Metal nanocomposites

Recovery as a nanocomposite is one of the methods that can be used in extracting metals from E-waste. Using a facile physical mixing method, MnO_2/graphene nanocomposite can be prepared for the electrode materials for supercapacitors. Spent battery powder was used as a raw material in the precipitation process of synthesizing MnO2/grapheme nanocomposite (Deng et al., 2015).

2.4 Challenges

Urban mining is a process, which recovers the resources such as precious metals and base metals from WEEE. This process will bring the landfills of E-waste to zero, will reduce the natural mining and industrial production processes. However, the collection of domestic WEEE highly costs due to the labor cost and the initial cost in the establishment of E-waste collection points, especially in developing countries.

With the increasing usage of electronic and electrical equipment globally, the accumulation of WEEE gradually grows in the environment. As E-waste is a source rich in metals, it is important to recover those metals rather than disposing into the environment. The base metals and precious metals can be recovered from WEEE with high purity pyrometallurgy routes. Even though these routes achieved recovery of high purity metals, the major problem is identified as the environment pollution. During the smelting process of feed WEEE materials, it ignites at high temperature and releases a massive amount of hazardous gas to the environment. This hazardous gas contain dioxins, furans, polybrominated diphenyl ethers, and many hydrocarbons, which causes serious issues to both environment and living beings. Uncontrollable temperature elevation and high energy consumption are challenges and arise during the smelting of WEEE. Prevention of these environmental issues is a challengeable task, and it needs to be paid more attention to the pretreatment of hazardous waste gas prior to dispose of the environment.

Hydrometallurgy process is a highly efficient and environmentally friendly process compared to pyrometallurgy. Commonly, four methods are employed in hydrometallurgy process: acid leaching, cyanide leaching, thiourea leaching, and thiosulfate leaching. In acid leaching, the usage of acid, especially sulfuric acid in precious metal leaching from WEEE creates many secondary pollutants. Cyanide efficiently leaches the precious metals such as Au and Ag from WEEE in the urban mining process. However, in the presence of Cu, the leaching quantity of precious metals from WEEE become less and further implementation needed to eliminate the Cu from WEEE due to the most of WEEEs are abundant in Cu than other metals. Thiourea is a great leaching agent than cyanide and acid in precious metals leaching. Thiourea shows a complete recovery of Au and Ag from WEEEs. However, thiourea leaching has some disadvantages, which prevents the commercial applications of thiourea. A large amount of thiourea is needed in order to obtain the maximum recovery of precious metals since it undergoes oxidation in the solution. Although thiosulfate causes less environmental impacts and insensitive to other metals, currently, it is known as the best method to recover Au from WEEE. However, the major problem of using thiosulfate as leaching agent is high reagent consumption during the leaching process, and generally, it is slow in leaching of precious metals (Ficeriová et al., 2011).

Moreover, scientists put their footprint on the biohydrometallurgy using microorganisms such as bacteria and fungi, or products derived from microorganisms due to its reduced investment cost, less environmental impact, and low energy consumption. However, the selection of right species of organism and its pure culture is an essential task since the availability of a range of varieties and the low process speed (Priya and Hait, 2018). In case of biosorption, even it shows high sorption capacity with biosorbents, chemical surface modification has to be done and the recovery of metals is not possible with the solid initial mixture, without a pretreatment prior to the biosorption process. Therefore further studies are required in order to overcome these limitations in the urban mining process.

Transboundary WEEE is one of the major issues related to recycling and recovery as once WEEE reaches developing nations, there is no capacity for recycling and recovery due to limited financial assistance and willingness. Challenge is how to encourage the general public to proper discarding of WEEE and increase and improve the collection and transportation to recycling facilities. Even at a large scale recovery process of WEEE, nanometals may not be taken with care due to the process difficulties. At the same time, the gap between laboratory and real scale applications limits innovative techniques and inventions to be used in commercial scale to recover precious metals.

2.5 Future research developments

The urban mining of precious metals from WEEE is needed since WEEEs are highly rich in precious metals, and the accumulation of WEEE in the environment very frequent. All of the processes such as physical and chemical techniques involved in the urban mining and limitations of this processes are discussed in the previous sections (section 2.2.1 and 2.2.2). The major consideration of urban mining is the environmental impacts. The pyrometallurgy process created huge of toxic gases and sludge, and the hydrometallurgy process created fewer pollutants compared to the pyrometallurgy process. However, pretreatment of pollutants prior to open to the environment is a must. Therefore further studies are required in order to reduce the pollutant generated after the urban mining process.

Nevertheless, the bioleaching process is an efficient method as it is eco-friendly and which is mediated by the secretion of extracellular polymeric substances by the bacteria. However, the bioleaching is a very slow process it may take a few days to leach the metals from WEEE. Further studies are needed to be improved in the bioleaching process. According to currently available technologies, it is possible to genetically modified bacteria in order to secret more extracellular polymeric substances which may promote more metal leaching from the WEEEs. However, the presence of many toxic substances in the WEEE may kill the microorganisms during the bioleaching. Hence, all toxic substances would be removed before attending the bioleaching process. Therefore further studies would essential to make it as efficient leaching in the future.

Using the ultra-small particles that were disintegrated, small circuit boards are being produced which will result comparatively a small final product. This particular advantage has done a revolutionary change in the market, which attract people to buy handy and portable instruments with high efficiency: liquid crystal display (LCD), solar cells, and chemically inert additives (e.g., carbon and silica polymer fillers). Nanometals are highly valuable resource embedded in WEEE in which the recovery is essential in terms of sustainable development. Although various techniques for nanometal extraction have been reported with promising results in laboratory scale, gaps present in upscaling into commercial use. Many research focused their efforts on precious nanometal extraction, for example, Au and Ag, while the base nanometal extraction is not paid enough attention other than Cu. Process developments is essential for nanometal extraction using cost effective top-down and bottom-up techniques may be with novel catalysts. Pure nanometal extraction needs more attention over the metalloids or composites as pure metal has many uses and high worthiness. Therefore research must drive toward cost effective pure nanometal extraction. Physical disintegration may change the crystal structure of the metals may lead to the formation of composites and alloys through extraction should be taken care. Even though microorganism mediated nanometal extraction has been widely researched, however, lacking in real application due to the technical capacity. However, process development with biological extraction is highly valuable as it produces protein coated pure nanometals which will result noble precious and base nanometals. At the same time, research efforts should focus on nanometal usage in various applications may induce the willingness for recovery.

E-waste collection, handling, recycling and recovery is not solely a scientific method, it involves social and economic factors as well and therefore research on such should be encouraged. Research with direct benefits toward circular economy should be supported well. Gaps in transboundary WEEE flow needs to be secured for developing nations. Most of the countries do not have a WEEE inventory and it is essential to maintain such an inventory in order to understand the flow and recovery of WEEE.

References

Afroz, R., Masud, M.M., Akhtar, R., Duasa, J.B., 2013. Survey and analysis of public knowledge, awareness and willingness to pay in Kuala Lumpur, Malaysia – a case study on household WEEE management. J. Clean. Prod. 52, 185–193. Available from: https://doi.org/10.1016/j.jclepro.2013.02.004.

Ahmad, A., Senapati, S., Khan, M.I., Kumar, R., Sastry, M., 2006. Extra-/Intracellular biosynthesis of gold nanoparticles by an alkalotolerant fungus, *Trichothecium* sp. J. Biomed. Nanotechnol. 1 (1), 47–53. Available from: https://doi.org/10.1166/jbn.2005.012.

Akcil, A., Erust, C., Gahan, C.S., Ozgun, M., Sahin, M., Tuncuk, A., 2014. Precious metal recovery from waste printed circuit boards using cyanide and non-cyanide lixiviants – a review. Waste Manag. 45, 258–271. Available from: https://doi.org/10.1016/j.wasman.2015.01.017.

Baccini, P., Brunner, P.H., 2012. Metabolism of the Anthroposphere Metabolism of the Anthroposphere. MIT Press.

Balci, N., Shanks, W.C., Mayer, B., Mandernack, K.W., 2007. Oxygen and sulfur isotope systematics of sulfate produced by bacterial and abiotic oxidation of pyrite. Geochim. Cosmochim. Acta 71 (15), 3796–3811. Available from: https://doi.org/10.1016/j.gca.2007.04.017.

Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-waste Monitor.

Bandara, T., Herath, I., Kumarathilaka, P., Seneviratne, M., Seneviratne, G., Rajakaruna, N., et al., 2017. Role of woody biochar and fungal-bacterial co-inoculation on enzyme activity and metal immobilization in serpentine soil. J. Soils Sedim. 17 (3), 665–673. Available from: https://doi.org/10.1007/s11368-015-1243-y.

Bas, A.D., Deveci, H., Yazici, E.Y., 2014. Treatment of manufacturing scrap TV boards by nitric acid leaching. Sep. Purif. Technol. 130 (2), 151–159. Available from: https://doi.org/10.1016/j.seppur.2014.04.008.

Behnamfard, A., Salarirad, M.M., Veglio, F., 2013. Process development for recovery of copper and precious metals from waste printed circuit boards with emphasize on palladium and gold leaching and precipitation. Waste Manag. 33 (11), 2354–2363. Available from: https://doi.org/10.1016/j.wasman.2013.07.017.

Bigum, M., Damgaard, A., Scheutz, C., Christensen, T.H., 2017. Environmental impacts and resource losses of incinerating misplaced household special wastes (WEEE, batteries, ink cartridges and cables). Resour. Conserv. Recycl. 122, 251–260. Available from: https://doi.org/10.1016/j.resconrec.2017.02.013.

Birloaga, I., Coman, V., Kopacek, B., Vegliò, F., 2014. An advanced study on the hydrometallurgical processing of waste computer printed circuit boards to extract their valuable content of metals. Waste Manag. 34 (12), 2581–2586. Available from: https://doi.org/10.1016/j.wasman.2014.08.028.

Bloodworth, A., 2014. Resources: track flows to manage technology-metal supply. Nature 505 (7481), 19–20. Available from: https://doi.org/10.1038/505019a.

Brayner, R., Barberousse, H., Hemadi, M., Djedjat, C., Yéprémian, C., Coradin, T., et al., 2007. Cyanobacteria as bioreactors for the synthesis of Au, Ag, Pd, and Pt nanoparticles via an enzyme-mediated route. J. Nanosci. Nanotechnol. 7 (8), 2696–2708. Available from: https://doi.org/10.1166/jnn.2007.600.

Chen, J., Huang, K., 2006. A new technique for extraction of platinum group metals by pressure cyanidation. Hydrometallurgy 82 (3–4), 164–171. Available from: https://doi.org/10.1016/j.hydromet.2006.03.041.

Côrtes, L.N., Tanabe, E.H., Bertuol, D.A., Dotto, G.L., 2015. Biosorption of gold from computer microprocessor leachate solutions using chitin. Waste Manag. 45, 272–279. Available from: https://doi.org/10.1016/j.wasman.2015.07.016.

Cossu, R., 2013. Editorial: the urban mining concept. Waste Manag. 497–498. Available from: https://doi.org/10.1016/j.wasman.2013.01.010.

Cossu, R., Williams, I.D., 2015. Urban mining: concepts, terminology, challenges. Waste Manag. 45, 1–3. Available from: https://doi.org/10.1016/j.wasman.2015.09.040.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272. Available from: https://doi.org/10.1016/j.rser.2015.06.010.

Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electric and electronic equipment: a review. J. Hazard. Mater. 99 (3), 243–263. Available from: https://doi.org/10.1016/S0304-3894(03)00061-X.

Cui, J., Forssberg, E., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31 (1), 45–58. Available from: https://doi.org/10.1016/J.WASMAN.2010.08.014.

Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: a review. J. Hazard. Mater. 158 (2–3), 228–256. Available from: https://doi.org/10.1016/j.jhazmat.2008.02.001.

Davies, E., 2017. Getting the metals out of old phones. Chem. World March. Available from: https://www.chemistryworld.com/feature/smartphone-recycling/2500497.article M4-Citavi.

Deep, A., Kumar, K., Kumar, P., Kumar, P., Sharma, A.L., Gupta, B., et al., 2011. Recovery of pure ZnO nanoparticles from spent Zn-MnO_2 alkaline batteries. Environ. Sci. Technol. 45 (24), 10551–10556. Available from: https://doi.org/10.1021/es201744t.

Deng, J., Wang, X., Duan, X., Liu, P., 2015. Facile preparation of MnO_2/graphene nanocomposites with spent battery powder for electrochemical energy storage. ACS Sustain. Chem. Eng. 3 (7), 1330−1338. Available from: https://doi.org/10.1021/acssuschemeng.5b00305.

Dennis, W.H., 2018. Pyrometallurgy. Metallurgy 55−74. Available from: https://doi.org/10.4324/9781315124414-3 (August 2015).

Ding, Y., Zhang, S., Liu, B., Zheng, H., Chang, C.C., Ekberg, C., 2019. Recovery of precious metals from electronic waste and spent catalysts: a review. Resour. Conserv. Recycl. 141 (August 2018), 284−298. Available from: https://doi.org/10.1016/j.resconrec.2018.10.041.

Dong, H., Zhao, J., Chen, J., Wu, Y., Li, B., 2015. Recovery of platinum group metals from spent catalysts: a review. Int. J. Miner. Process. 145, 108−113. Available from: https://doi.org/10.1016/j.minpro.2015.06.009.

Ficeriová, J., Baláž, P., Gock, E., 2011. Leaching of gold, silver and accompanying metals from circuit boards (PCBs) waste. Acta Montanistica Slovaca 16 (2), 128−131.

Fogarasi, S., Imre-Lucaci, F., Imre-Lucaci, Á., Ilea, P., 2014. Copper recovery and gold enrichment from waste printed circuit boards by mediated electrochemical oxidation. J. Hazard. Mater. 273, 215−221. Available from: https://doi.org/10.1016/j.jhazmat.2014.03.043.

Fontana, D., Pietrantonio, M., Pucciarmati, S., Torelli, G.N., Bonomi, C., Masi, F., 2018. Palladium recovery from monolithic ceramic capacitors by leaching, solvent extraction and reduction. J. Mater. Cycles Waste Manag. 20 (2), 1199−1206. Available from: https://doi.org/10.1007/s10163-017-0684-3.

Fu, Y., He, Y., Qu, L., Feng, Y., Li, J., Liu, J., et al., 2019. Enhancement in leaching process of lithium and cobalt from spent lithium-ion batteries using benzenesulfonic acid system. Waste Manag. 88, 191−199. Available from: https://doi.org/10.1016/j.wasman.2019.03.044.

Ghodake, G., Lee, D.S., 2011. Biological synthesis of gold nanoparticles using the aqueous extract of the brown algae *Laminaria japonica*. J. Nanoelectron. Optoelectron. 6 (3), 268−271. Available from: https://doi.org/10.1166/jno.2011.1166.

Ghosh, B., Ghosh, M.K., Parhi, P., Mukherjee, P.S., Mishra, B.K., 2015. Waste printed circuit boards recycling: an extensive assessment of current status. J. Clean. Prod. 94, 5−19. Available from: https://doi.org/10.1016/j.jclepro.2015.02.024.

Guo, Y., Li, F., Zhu, H., Li, G., Huang, J., He, W., 2016. Leaching lithium from the anode electrode materials of spent lithium-ion batteries by hydrochloric acid (HCl). Waste Manag. 51, 227−233. Available from: https://doi.org/10.1016/j.wasman.2015.11.036.

Guo, X.-Y., Jiang, X.-J., Liu, J.-X., Liu, Y., Liu, Z.-K., 2017. Recovery of metal values from waste printed circuit boards using a cascading alkali leaching process. Zhongguo Youse Jinshu Xuebao/Chin. J. Nonfer. Metals. 27 (2), 199−205.

Gurung, M., Adhikari, B.B., Kawakita, H., Ohto, K., Inoue, K., Alam, S., 2013. Recovery of gold and silver from spent mobile phones by means of acidothiourea leaching followed by adsorption using biosorbent prepared from persimmon tannin. Hydrometallurgy 133, 84−93. Available from: https://doi.org/10.1016/j.hydromet.2012.12.003.

Hadi, P., Xu, M., Lin, C.S.K., Hui, C.W., McKay, G., 2015. Waste printed circuit board recycling techniques and product utilization. J. Hazard. Mater. 283, 234−243. Available from: https://doi.org/10.1016/j.jhazmat.2014.09.032.

He, S., Zhang, Y., Guo, Z., Gu, N., 2008. Biological synthesis of gold nanowires using extract of Rhodopseudomonas capsulata. Biotechnol. Prog. 24 (2), 476−480. Available from: https://doi.org/10.1021/bp0703174.

He, X., Li, Y., Wu, X., Zhao, Y., Wang, H., Liu, W., 2016. Study on the process of enrichment platinum group metals by plasma melting technology. Precious Metals 37 (1), 1−5.

Hilson, G., Monhemius, A.J., 2006. Alternatives to cyanide in the gold mining industry: what prospects for the future? J. Clean. Product. 14 (12-13 SPEC. ISS.), 1158−1167. Available from: https://doi.org/10.1016/j.jclepro.2004.09.005.

Hsu, E., Barmak, K., West, A.C., Park, A.H.A., 2019. Advancements in the treatment and processing of electronic waste with sustainability: a review of metal extraction and recovery technologies. Green Chem. 21 (5), 919−936. Available from: https://doi.org/10.1039/c8gc03688h.

Husseiny, M.I., El-Aziz, M.A., Badr, Y., Mahmoud, M.A., 2007. Biosynthesis of gold nanoparticles using *Pseudomonas aeruginosa*. Spectrochim. Acta - Part A: Mol. Biomol. Spectrosc. 67 (3−4), 1003−1006. Available from: https://doi.org/10.1016/j.saa.2006.09.028.

Ilankoon, I.M.S.K., Ghorbani, Y., Chong, M.N., Herath, G., Moyo, T., Petersen, J., 2018. E-waste in the international context − a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manag. 82, 258−275. Available from: https://doi.org/10.1016/j.wasman.2018.10.018.

Innocenzi, V., De Michelis, I., Vegliò, F., 2017. Design and construction of an industrial mobile plant for WEEE treatment: investigation on the treatment of fluorescent powders and economic evaluation compared to other e-wastes. J. Taiwan Inst. Chem. Eng. 80, 769−778. Available from: https://doi.org/10.1016/j.jtice.2017.09.019.

Işıldar, A., Rene, E.R., van Hullebusch, E.D., Lens, P.N.L., 2018. Electronic waste as a secondary source of critical metals: management and recovery technologies. Resour. Conserv. Recycl. 135, 296−312. Available from: https://doi.org/10.1016/j.resconrec.2017.07.031.

Işıldar, A., van Hullebusch, E.D., Lenz, M., Du Laing, G., Marra, A., Cesaro, A., et al., 2019. Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE) − a review. J. Hazard. Mater. 362, 467−481. Available from: https://doi.org/10.1016/j.jhazmat.2018.08.050.

Jain, D., Kachhwaha, S., Jain, R., Srivastava, G., Kothari, S.L., 2010. Novel microbial route to synthesize silver nanoparticles using spore crystal mixture of Bacillus thuringiensis. Indian J. Exp. Biol. 48 (11), 1152−1156. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21117457.

Jha, M.K., Choubey, P.K., Jha, A.K., Kumari, A., Lee, J.C., Kumar, V., et al., 2012. Leaching studies for tin recovery from waste e-scrap. Waste Manag. 32 (10), 1919−1925. Available from: https://doi.org/10.1016/j.wasman.2012.05.006.

Jha, M.K., Lee, J.C., Kim, M.S., Jeong, J., Kim, B.S., Kumar, V., 2013. Hydrometallurgical recovery/recycling of platinum by the leaching of spent catalysts: a review. Hydrometallurgy 133, 23−32. Available from: https://doi.org/10.1016/j.hydromet.2012.11.012.

Jiang, P., Harney, M., Song, Y., Chen, B., Chen, Q., Chen, T., et al., 2012. Improving the end-of-life for electronic materials via sustainable recycling methods. Proc. Environ. Sci. 16, 485−490. Available from: https://doi.org/10.1016/j.proenv.2012.10.066.

Jing-ying, L., Xiu-li, X., Wen-quan, L., 2012. Thiourea leaching gold and silver from the printed circuit boards of waste mobile phones. Waste Manag. 32 (6), 1209−1212. Available from: https://doi.org/10.1016/j.wasman.2012.01.026.

Jowkar, M.J., Bahaloo-Horeh, N., Mousavi, S.M., Pourhossein, F., 2018. Bioleaching of indium from discarded liquid crystal displays. J. Clean. Product. 180, 417−429. Available from: https://doi.org/10.1016/j.jclepro.2018.01.136.

Kaya, M., 2016. Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manag. 57, 64–90. Available from: https://doi.org/10.1016/j.wasman.2016.08.004.

Khaliq, A., Rhamdhani, M., Brooks, G., Masood, S., 2014. Metal extraction processes for electronic waste and existing industrial routes: a review and australian perspective. Resources 3 (1), 152–179. Available from: https://doi.org/10.3390/resources3010152.

Kim, E.-Y., Kim, M.-S., Lee, J.-C., Jeong, J., Kim, B.-S., 2006. Leaching of copper from waste printed circuit boards using electrogenerated chlorine in hydrochloric acid solution. TMS Ann. Meet. 2006 (3–4), 124–132.

Kim, E.Y., Kim, M.S., Lee, J.C., Pandey, B.D., 2011. Selective recovery of gold from waste mobile phone PCBs by hydrometallurgical process. J. Hazard. Mater. 198, 206–215. Available from: https://doi.org/10.1016/j.jhazmat.2011.10.034.

Kim, K., Dutta, T., Kim, K., Deep, A., Szulejko, J.E., Vellingiri, K., 2017. Recovery of nanomaterials from battery and electronic wastes: a new paradigm of environmental waste management. Renew. Sustain. Energy Rev. 82 (November), 0–1. Available from: https://doi.org/10.1016/j.rser.2017.10.094.

Kim, M.S., Lee, J.C., Park, S.W., Jeong, J., Kumar, V., 2013. Dissolution behaviour of platinum by electro-generated chlorine in hydrochloric acid solution. J. Chem. Technol. Biotechnol. 88 (7), 1212–1219. Available from: https://doi.org/10.1002/jctb.3957.

Kolliopoulos, G., Balomenos, E., Giannopoulou, I., Yakoumis, I., Panias, D., 2014. Behavior of platinum group during their pyrometallurgical recovery from spent automotive catalysts. OALib 01 (05), 1–9. Available from: https://doi.org/10.4236/oalib.1100736.

Kwak, I.S., Won, S.W., Chung, Y.S., Yun, Y.S., 2013. Ruthenium recovery from acetic acid waste water through sorption with bacterial biosorbent fibers. Bioresour. Technol. 128, 30–35. Available from: https://doi.org/10.1016/j.biortech.2012.10.146.

Lecler, M.T., Zimmermann, F., Silvente, E., Masson, A., Morèle, Y., Remy, A., et al., 2018. Improving the work environment in the fluorescent lamp recycling sector by optimizing mercury elimination. Waste Manag. 76, 250–260. Available from: https://doi.org/10.1016/j.wasman.2018.02.037.

Lee, C.H., Tang, L.W., Popuri, S.R., 2011. A study on the recycling of scrap integrated circuits by leaching. Waste Manag. Res. 29 (7), 677–685. Available from: https://doi.org/10.1177/0734242X10380995.

Li, J., Lu, H., Guo, J., Xu, Z., Zhou, Y., 2007. Recycle technology for recovering resources and products from waste printed circuit boards. Environ. Sci. Technol. 41 (6), 1995–2000. Available from: https://doi.org/10.1021/es0618245.

Li, J., Zeng, X., Chen, M., Ogunseitan, O.A., Stevels, A., 2015. "Control-Alt-Delete": rebooting solutions for the e-waste problem. Environ. Sci. Technol. 49 (12), 7095–7108. Available from: https://doi.org/10.1021/acs.est.5b00449.

Lister, T.E., Wang, P., Anderko, A., 2014. Recovery of critical and value metals from mobile electronics enabled by electrochemical processing. Hydrometallurgy 149, 228–237. Available from: https://doi.org/10.1016/j.hydromet.2014.08.011.

Liu, R., Li, J., Ge, Z., 2016. Review on *Chromobacterium violaceum* for gold bioleaching from e-waste. Proc. Environ. Sci. 31, 947–953. Available from: https://doi.org/10.1016/j.proenv.2016.02.119.

Lu, Y., Xu, Z., 2016. Precious metals recovery from waste printed circuit boards: a review for current status and perspective. Resour. Conserv. Recycl. 113 (2016), 28–39. Available from: https://doi.org/10.1016/j.resconrec.2016.05.007.

Ma, E., 2019. Recovery of waste printed circuit boards through pyrometallurgy. Electron. Waste Manag. Treat. Technol. 247–267. Available from: https://doi.org/10.1016/B978-0-12-816190-6.00011-X.

Ma, Y., Tang, H., Lin, X., Jiang, T., Li, G., Li, Z., et al., 2017. Pyrometallurgical recovery of platinum group metals from spent catalysts. JOM 69 (9), 1553−1562. Available from: https://doi.org/10.1007/s11837-017-2450-3.

Mahmoud, A., Cézac, P., Hoadley, A.F.A., Contamine, F., D'Hugues, P., et al., (2017). A review of sulfide minerals microbially assisted leaching in stirred tank reactors, *International Biodeterioration & Biodegradation*, 119, 118−146. Avaliable from: https://doi.org/10.1016/j.ibiod.2016.09.015.

Majumder, D.R., 2012. Bioremediation: copper nanoparticles from electronic-waste. Int. J. Eng. Sci. Technol. 4 (10), 4380−4389.

Majumder, D.R., 2014. Waste to health: Bioleaching of nanoparticles from e-waste and their medical applications. Indian J. Appl. Res. 3 (2), 277−286. Available from: https://doi.org/10.15373/2249555x/feb2013/94.

Maliszewska, I., 2012. Biological synthesis of metal. Wiadomości chemiczne 83 (1−4), 11−12.

Marra, A., Cesaro, A., Rene, E.R., Belgiorno, V., Lens, P.N.L., 2018. Bioleaching of metals from WEEE shredding dust. J. Environ. Manag. 210, 180−190. Available from: https://doi.org/10.1016/j.jenvman.2017.12.066.

Morin, D., Lips, A., Pinches, T., Huisman, J., Frias, C., Norberg, A., et al., 2006. BioMinE - Integrated project for the development of biotechnology for metal-bearing materials in Europe. Hydrometallurgy 83 (1−4), 69−76. Available from: https://doi.org/10.1016/j.hydromet.2006.03.047.

Musariri, B., Akdogan, G., Dorfling, C., Bradshaw, S., 2019. Evaluating organic acids as alternative leaching reagents for metal recovery from lithium ion batteries. Miner. Eng. 137, 108−117. Available from: https://doi.org/10.1016/j.mineng.2019.03.027.

Naghavi, Z., Ghoreishi, S.M., Rahimi, A., Hadadzadeh, H., 2016. Kinetic study for platinum extraction from spent catalyst in cyanide solution at high temperatures. Int. J. Chem. React. Eng. 14 (1), 143−154. Available from: https://doi.org/10.1515/ijcre-2015-0046.

Namias, J., 2013. The Future of Electronic Waste Recycling in the United States: Obstacles and Domestic Solutions. Columbia University, New York, p. 66. Available from: http://dx.doi.org/10.1021/acs.jpclett.8b00176.

Nangia, Y., Wangoo, N., Goyal, N., Shekhawat, G., Suri, C.R., 2009. A novel bacterial isolate *Stenotrophomonas maltophilia* as living factory for synthesis of gold nanoparticles. Microb. Cell Factor 8 (1), 39. Available from: https://doi.org/10.1186/1475-2859-8-39.

Natarajan, K., Selvaraj, S., Murty, V.R., 2010. Microbial production of silver nanoparticles. Digest J. Nanomater. Biostruct. 5 (1), 135−140.

Nowakowski, P., 2017. A proposal to improve e-waste collection efficiency in urban mining: Container loading and vehicle routing problems − a case study of Poland. Waste Manag. 60, 494−504. Available from: https://doi.org/10.1016/j.wasman.2016.10.016.

Ongondo, F.O., Williams, I.D., Whitlock, G., 2015. Distinct urban mines: exploiting secondary resources in unique anthropogenic spaces. Waste Manag. 45, 4−9. Available from: https://doi.org/10.1016/j.wasman.2015.05.026.

Park, Y., Fray, D., 2009. Recovery of high purity precious metals from printed circuit boards. J. Hazard. Mater. 164 (2−3), 82−88.

Perkins, D.N., Brune Drisse, M.N., Nxele, T., Sly, P.D., 2014. E-waste: a global hazard. Ann. Global Health 80 (4), 286−295. Available from: https://doi.org/10.1016/j.aogh.2014.10.001.

Petter, P.M.H., Veit, H.M., Bernardes, A.M., 2014. Evaluation of gold and silver leaching from printed circuit board of cellphones. Waste Manag. 34 (2), 475−482. Available from: https://doi.org/10.1016/j.wasman.2013.10.032.

Pimprikar, P.S., Joshi, S.S., Kumar, A.R., Zinjarde, S.S., Kulkarni, S.K., 2009. Influence of biomass and gold salt concentration on nanoparticle synthesis by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. Colloid. Surf. B: Biointerfaces 74 (1), 309−316. Available from: https://doi.org/10.1016/j.colsurfb.2009.07.040.

Pradhan, N., Nayak, R.R., Pradhan, A.K., 2011. Green synthesis of silver nanoparticle by *Penicillium purpurogenum* NPMF: the process and optimization in situ synthesis of entrapped silver nanoparticles by a fungus—*Penicillium purpurogenum*. Nanoscience 3 (July 2015), 3129−3137. Available from: https://doi.org/10.1166/nnl.2011.1235.

Priya, A., Hait, S., 2018. Extraction of metals from high grade waste printed circuit board by conventional and hybrid bioleaching using *Acidithiobacillus ferrooxidans*. Hydrometallurgy 177, 132−139. Available from: https://doi.org/10.1016/j.hydromet.2018.03.005.

Ramani, R., Srinivas, V., Kumar, R., Ahmad, A., Sastry, M., Khan, M.I., et al., 2004. Intracellular synthesis of gold nanoparticles by a novel alkalotolerant actinomycete, Rhodococcus species. Nanotechnology 14 (7), 824−828. Available from: https://doi.org/10.1088/0957-4484/14/7/323.

Ravi Naidu, M.H.W., 2013. Electronic waste management: an overview. Waste Manag. 33 (5), 1237−1250. Available from: http://nanoimmondzia.ge.ibf.cnr.it/userFiles/ElectronicWaste.pdf.

Rocchetti, L., Vegliò, F., Kopacek, B., Beolchini, F., 2013. Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. Environ. Sci. Technol. 47 (3), 1581−1588. Available from: https://doi.org/10.1021/es302192t.

Singaravelo, G., Arockiyamari, J., Ganesh Kuma, V., 2007. A novel extracellular biosynthesis of monodisperse gold nanoparticles using marine algae. Colloids Surf. B, Biointerfaces 57 (1), 97−101.

Sinha, A., Singh, V.N., Mehta, B.R., Khare, S.K., 2011. Synthesis and characterization of monodispersed orthorhombic manganese oxide nanoparticles produced by Bacillus sp. cells simultaneous to its bioremediation. J. Hazard. Mater. 192 (2), 620−627. Available from: https://doi.org/10.1016/j.jhazmat.2011.05.103.

Suresh, A.K., Pelletier, D.A., Wang, W., Broich, M.L., Moon, J., Gu, B., et al., 2011. Acta Biomaterialia Monodispersed biocompatible silver sulfide nanoparticles: facile extracellular biosynthesis using the c −proteobacterium, *Shewanella oneidensis*. Acta Biomater. 7 (12), 4253−4258. Available from: https://doi.org/10.1016/j.actbio.2011.07.007.

Tesfaye, F., Lindberg, D., Hamuyuni, J., Taskinen, P., Hupa, L., 2017. Improving urban mining practices for optimal recovery of resources from e-waste. Miner. Eng. 111, 209−221. Available from: https://doi.org/10.1016/j.mineng.2017.06.018.

Thakkar, K.N., Mhatre, S.S., Parikh, R.Y., 2009. Biological synthesis of metallic nanoparticles. Nanomed.: Nanotechnol. Biol. Med. 6, 257−262. Available from: https://doi.org/10.1016/j.nano.2009.07.002.

Tiwary, C.S., Kishore, S., Vasireddi, R., Mahapatra, D.R., Ajayan, P.M., Chattopadhyay, K., 2017. Electronic waste recycling via cryo-milling and nanoparticle beneficiation. Materials Today 20 (2), 67−73. Available from: https://doi.org/10.1016/j.mattod.2017.01.015.

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25 (1), 28−37. Available from: https://doi.org/10.1016/j.mineng.2011.09.019.

Upadhyay, A.K., Lee, J.C., Kim, E.Y., Kim, M.S., Kim, B.S., Kumar, V., 2013. Leaching of platinum group metals (PGMs) from spent automotive catalyst using electro-generated chlorine in HCl solution. J. Chem. Technol. Biotechnol. 88 (11), 1991−1999. Available from: https://doi.org/10.1002/jctb.4057.

Usha, R., Prabu, E., Palaniswamy, M., Venil, C.K., Rajendran, R., 2010. Synthesis of metal oxide nano particles by Streptomyces sp. for development of antimicrobial textiles. Global J. Biotechnol. Biochem. 5 (3), 153−160.

Vahabi, K., Mansoori, G.A., Karimi, S., 2011. Biosynthesis of silver nanoparticles by fungus *Trichoderma reesei* (a route for large-scale production of AgNPs). Insci. J. 1 (1), 65−79. Available from: https://doi.org/10.5640/insc.010165.

Vakilchap, F., Mousavi, S.M., Shojaosadati, S.A., 2016. Role of Aspergillus niger in recovery enhancement of valuable metals from produced red mud in Bayer process. Bioresour. Technol. 218, 991−998. Available from: https://doi.org/10.1016/j.biortech.2016.07.059.

De Vargas, I., Macaskie, L.E., Guibal, E., 2004. Biosorption of palladium and platinum by sulfate-reducing bacteria. J. Chem. Technol. Biotechnol. 79 (1), 49−56. Available from: https://doi.org/10.1002/jctb.928.

Veit, H.M., Diehl, T.R., Salami, A.P., Rodrigues, J.S., Bernardes, A.M., Tenório, J.A.S., 2005. Utilization of magnetic and electrostatic separation in the recycling of printed circuit boards scrap. Waste Manag. 25 (1), 67−74. Available from: https://doi.org/10.1016/j.wasman.2004.09.009.

Vera, M., Schippers, A., Sand, W., 2013. Progress in bioleaching: fundamentals and mechanisms of bacterial metal sulfide oxidation − part A. Appl. Microbiol. Biotechnol. 97 (17), 7529−7541. Available from: https://doi.org/10.1007/s00253-013-4954-2.

Vidyadhar, A., 2016. A review of technology of metal recovery from electronic waste. E-Waste in Transition - From Pollution to Resource. IntechOpen, Rijeka, Ch. 6. http://doi.org/10.5772/61569.

Wang, J., Chen, C., 2006. Biosorption of heavy metals by Saccharomyces cerevisiae: a review. Biotechnol. Adv. 24 (5), 427−451. Available from: https://doi.org/10.1016/j.biotechadv.2006.03.001.

Wang, J., Chen, C., 2009. Biosorbents for heavy metals removal and their future. Biotechnol. Adv. 27 (2), 195−226. Available from: https://doi.org/10.1016/j.biotechadv.2008.11.002.

Wentzien, S., Sand, W., Albertsen, A., Steudel, R., 1994. Thiosulfate and tetrathionate degradation as well as biofilm generation by *Thiobacillus intermedius* and *Thiobacillus versutus* studied by microcalorimetry, HPLC, and ion-pair chromatography. Arch. Microbiol. 161 (2), 116−125. Available from: https://doi.org/10.1007/BF00276471.

De Windt, W., Boon, N., Van den Bulcke, J., Rubberecht, L., Prata, F., Mast, J., et al., 2006. Biological control of the size and reactivity of catalytic Pd(0) produced by *Shewanella oneidensis*. Antonie van Leeuwenhoek, Int. J. Gen. Mol. Microbiol. 90 (4), 377−389. Available from: https://doi.org/10.1007/s10482-006-9088-4.

Wu, J.Y., Chang, F.C., 2016. Recovery of nano-Al_2O_3 from waste aluminum electrolytic solution generated during the manufacturing of capacitors. Desalin. Water Treat. 57 (60), 29479−29487. Available from: https://doi.org/10.1080/19443994.2016.1171171.

Wu, Y., Fang, Q., Yi, X., Liu, G., Li, R.W., 2017. Recovery of gold from hydrometallurgical leaching solution of electronic waste via spontaneous reduction by polyaniline. Prog. Nat. Sci.: Mater. Int. 27 (4), 514−519. Available from: https://doi.org/10.1016/j.pnsc.2017.06.009.

Xiang, Y., Wu, P., Zhu, N., Zhang, T., Liu, W., Wu, J., et al., 2010. Bioleaching of copper from waste printed circuit boards by bacterial consortium enriched from acid mine drainage. J. Hazard. Mater. 184 (1−3), 812−818. Available from: https://doi.org/10.1016/j.jhazmat.2010.08.113.

Xiaotang, H., Huan, W., Xilong, W., Yong, L.I., Yu, Z., Shouli, H.A.N., et al., 2012. Study on the recovery of rhodium from spent organic rhodium catalysts of acetic acid industry using pyrometallurgical process. Precious Metals 33 (S1), 24–27.

Xie, F., Lu, D., Yang, H., Dreisinger, D., 2014. Solvent extraction of silver and gold from alkaline cyanide solution with LIX 7950. Miner. Process. Extract. Metall. Rev. 35 (4), 229–238. Available from: https://doi.org/10.1080/08827508.2013.825615.

Xiu, F.R., Zhang, F.S., 2012. Size-controlled preparation of Cu2O nanoparticles from waste printed circuit boards by supercritical water combined with electrokinetic process. J. Hazard. Mater. 233–234, 200–206. Available from: https://doi.org/10.1016/j.jhazmat.2012.07.019.

Xiu, F.R., Qi, Y., Zhang, F.S., 2015. Leaching of Au, Ag, and Pd from waste printed circuit boards of mobile phone by iodide lixiviant after supercritical water pre-treatment. Waste Manag. 41, 134–141. Available from: https://doi.org/10.1016/j.wasman.2015.02.020.

Yang, Y., Chen, S., Li, S., Chen, M., Chen, H., Liu, B., 2014. Bioleaching waste printed circuit boards by *Acidithiobacillus ferrooxidans* and its kinetics aspect. J. Biotechnol. 173 (1), 24–30. Available from: https://doi.org/10.1016/j.jbiotec.2014.01.008.

Yang, Y., Xu, S., He, Y., 2017. Lithium recycling and cathode material regeneration from acid leach liquor of spent lithium-ion battery via facile co-extraction and co-precipitation processes. Waste Manag. 64, 219–227. Available from: https://doi.org/10.1016/j.wasman.2017.03.018.

You, G.B., Fang, W.B., Li, Q.B., Ma, Y.B., Yang, X.-T., Yang, H.B., 2016. Study on enrichment method of platinum, palladium and rhodium in spent auto-catalysts. Yejin Fenxi/Metallurg. Anal. 36 (5), 7–11. Available from: https://doi.org/10.13228/j.boyuan.issn1000-7571.009680.

Zhang, W., Chen, Z., Liu, H., Zhang, L., Gao, P., Li, D., 2011. Biosynthesis and structural characteristics of selenium nanoparticles by *Pseudomonas alcaliphila*. Colloid. Surf. B: Biointerfaces 88 (1), 196–201. Available from: https://doi.org/10.1016/j.colsurfb.2011.06.031.

Zhao, F., Wang, S., 2019. Bioleaching of electronic waste using extreme acidophiles. In: Prasad, M.N.V., Vithanage, M.B.T.-E.W.M. (Eds.), Electronic Waste Management and Treatment Technology. Butterworth-Heinemann, pp. 153–174. Available from: http://doi.org/10.1016/b978-0-12-816190-6.00007-8.

Zhou, J., Zhu, N., Liu, H., Wu, P., Zhang, X., Zhong, Z., 2019. Recovery of gallium from waste light emitting diodes by oxalic acidic leaching. Resour. Conserv. Recycl. 146, 366–372. Available from: https://doi.org/10.1016/j.resconrec.2019.04.002.

Biochemical hazards associated with unsafe disposal of electrical and electronic items

3

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3.1 Introduction

Many elements (some of them are relatively rare) are used in electronic and electrical instruments. Table 3.1 shows some common elements that are found in many electrical and electronic instruments.

All these elements are not distributed uniformly in nature, but the table is useful in the general sense. Today mining activities are more carefully regulated worldwide but disposal and recycling are not.

Broadly speaking, all electrical and electronic items are made up of (1) electrically conducting or semiconducting functional part, (2) insulating stuff (mostly plastic or ceramic), and (3) enclosure meant for physical protection of the device (can be metal or plastic). At the end of service life, these parts may be segregated so that an efficient recycle can be attempted. It is most economical if the desired segregation is done at an early stage when the parts can be visually identified.

Many elements, compounds and polymers are commonly used in electrical and electronic industries. Every known element, compound, and molecules of biological origin have been assigned a number (this is not a number in the mathematical sense) by the American Chemical Society as a CAS (Chemical Abstracts Service) number that is unique. According to the official site maintained by the American Chemical Society, "CAS REGISTRY is the most authoritative collection of disclosed chemical substance information, containing more than 141 million organic and inorganic substances and 67 million sequences . . ." (http://support.cas.org/content/chemical-substances/faqs). Although this number is widely used all over the world, several other countries have their own system of classification (Beilstein is widely used in Germany). However, the CAS Registry Number is only a unique identifier and there may be several linked references present in the Registry. The toxicity data are maintained (in the United States) by the safety data sheets (SDS) [material safety data sheets (MSDS)] that is maintained by the Occupational Safety and Health Administration (OSHA) of the US government, Department of Labor. They use the CAS number as a reference to identify any given chemical. The basic objective is, simply stated, "The Hazard Communication Standard (HCS) (29 CFR

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00001-2

Table 3.1 Abundance of common elements in Earth's crust (ppm).

Z	Symbol	Name	Abundance (ppm)	Comments
3	Li	Lithium	20	Less common alkali metal, used in modern cells
4	Be	Beryllium	2.0	Low density reactive metal, used in X-ray tubes
5	B	Boron	7.0	Toxic to insects and lower forms of life
13	Al	Aluminum	80×10^3	Widely distributed, nontoxic
14	Si	Silicon	270×10^3	One of the most common elements on earth
24	Cr	Chromium	96	Used in many ferrous alloys
25	Mn	Manganese	1.0×10^3	Used in many ferrous alloys
26	Fe	Iron	58×10^3	Widely distributed, nontoxic
27	Co	Cobalt	28	Less common iron group element
28	Ni	Nickel	72	Less common iron group element
29	Cu	Copper	58	Widely used in electrical and electronic items
30	Zn	Zinc	82	Widely used in batteries
31	Ga	Gallium	17	Used in LEDs
32	Ge	Germanium	1.3	Used in semiconductors, detectors
33	As	Arsenic	2.0	Used in semiconductors
34	Se	Selenium	50×10^{-3}	Rare element; used in light detectors
42	Mo	Molybdenum	1.2	Used in tool steels
46	Pd	Palladium	3×10^{-3}	Rare element; used as catalysts
47	Ag	Silver	0.08	Used in some solders
48	Cd	Cadmium	0.18	Used in some special cells
49	In	Indium	0.2	Used in semiconductors; soldering
50	Sn	Tin	1.5	Electroplating; soldering
51	Sb	Antimony	0.2	Special detectors
52	Te	Tellurium	X	special semiconductor detectors
53	I	Iodine	0.5	High energy detectors (gamma ray)
55	Cs	Cesium	1.6	Photosensitive detectors
74	W	Tungsten	1.0	Incandescent lamp filaments; crucibles
78	Pt	Platinum	X	Rare and precious metal; used in resistance sensors
79	Au	Gold	2×10^{-3}¶	Rare and precious metal; contact surface plating
80	Hg	Mercury	20×10^{-3}¶	Used in batteries; discharge lamps
81	Tl	Thallium	0.47	Used in gamma ray detectors
82	Pb	Lead	10	Most common solder; some special detector

(*Continued*)

Table 3.1 (Continued)

Z	Symbol	Name	Abundance (ppm)	Comments
83	Bi	Bismuth	4×10^{-3}¶	Used in semiconductors; soldering
90	Th	Thorium	5.8	Used in vacuum tubes (not completely obsolete)
92	U	Uranium	1.6	Nuclear reactors (not common in electronics)

Abundances of the elements, <http://www.kayelaby.npl.co.uk/chemistry/3_1/3_1_3.html> (accessed 29.04.18.). (The numbers above are average values suggesting that typical concentrations of the above elements in commercial ores are significantly higher that the numbers reported above. They are usually present in much smaller amounts in a typical habitable environment. Very few elements are uniformly distributed over the earth's surface). It has been suggested that urban dumps of electrical and electronic items may be practical source of several of the above elements (in particular, for rare and precious elements, e.g., Ag, Au, Pt, or Pd).

1910.1200(g)), revised in 2012, requires that the chemical manufacturer, distributor, or importer provide SDSs (formerly MSDSs or material safety data sheets) for each hazardous chemical to downstream users to communicate information on these hazards." Although these rules and guidelines are specific to the United States, most countries use these guidelines provided in the SDS. The information available in the SDS is rather detailed and contains 16 sections: (1) identification, (2) hazard(s) identification, (3) composition/information on ingredients, (4) first-aid measures, (5) fire-fighting measures, (6) accidental release measures, (7) handling and storage, (8) exposure controls/ personal protection, (9) physical and chemical properties, (10) stability and reactivity, (11) toxicological information, (12) ecological information (non-mandatory), (13) disposal considerations (non-mandatory), (14) transport information (non-mandatory), (15) regulatory information (non-mandatory), and (16) other information.

Safety requirements of various chemicals are often conveyed via pictograms in accordance with International Standards Organization (ISO) recommendations (e.g., ISO 7010 describes graphical symbols related to hazardous and safety related matters). In the United States, the practice is similar, but the picture is often supplemented with a minimal text. The department of transportation (in the United States) requires that all vehicles must have suitable stickers describing the nature of the substance being transported. European chemical bureau (ECB) also have several pictograms recommended for hazardous materials (vide infra Fig. 3.1).

3.2 Life cycle of various elements

None of the elements are uniformly distributed over the earth's surface. Many are locally concentrated and occur at specific places. If the concentration is suitable (economic value), the deposits are treated as ores and minerals are extracted by several physical and chemical processes. Some of the elements are associated with other elements (e.g., Zn and Cd; Se and Te) and are often separated at a later stage. The isolation is never perfect, and the process leaves a large amount

Figure 3.1 A selection of ECB recommended pictograms for hazardous materials. *Source*: Adapted from Wikimedia Commons. The pictograms are expected to be self-explanatory.

of waste (that still contains the desired element but at a concentration that is economically unviable). Waste is produced both at the mining site and at the factory. Waste is a manufacturing by-product that can often be used for extraction of other elements (e.g., Cd is a by-product in Zn refining; Ag is often recovered during Pb and Cu refining). A large amount of waste is produced during this extraction phase and the effect on the environment is appreciable. At the end of the service life, most electronic and electric products are simply discarded (particularly if the item is physically small) but they still contain elements that can be economically reused. Such parts are often recycled [e.g., Cu and Au are often recovered from printed circuit boards removed from discarded electronic products; Cu, Al, and Fe are often removed from electric items for recycling]. The case (a case study) for the recycling of LCD TVs has also been reported in literature (Vanegas et al., 2017). The cycle can be schematically described in Fig. 3.2.

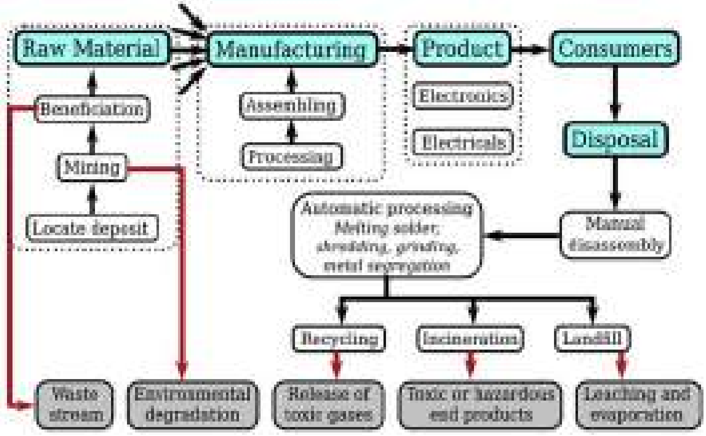

Figure 3.2 Life cycle of common elements used in electrical and electronics. All the stages are energy intensive and produce large entropy. In modern electronics and electrical industry, recycling is relatively small.

3.3 Toxicity values and their significance

Toxicity values are meaningful for a particular molecular species; even the oxidation state may be important. Individual elemental composition may also be meaningless. For example, hydrogen, carbon, and nitrogen are not toxic by themselves but the molecule containing hydrogen, carbon, and nitrogen, hydrogen cyanide, is a highly toxic compound. For a species to be biochemically toxic, it must be able to seriously interfere with the metabolic (life cycle) processes. Toxicity often manifests at specific organs and the agent must reach the target organ to show its effect. Many toxic agents are themselves subject to metabolism and they are often made inactive after some time due to biochemical processing. For elements, they are most commonly present in their oxidized form (Li^{+} ion rather than Li metal) and similarly for the anions (Cl^{-} rather than gaseous Cl_2). However, in the environment they can be transformed into different forms (microbial activity in the soil or geothermal effects over longer periods).

Toxicity of a molecule also depends on the specific route of administration. The same agent may be less toxic if administered orally rather than being injected. If the compound can be metabolized by the biochemical machinery, then the same dose administered over a period may be less toxic compared to the same being administered in one go. Many elements (e.g., Pb^{+2} and Hg^{+2}) cannot be efficiently processed and they tend to accumulate in specific organs. Often the elements form complex with other biomacromolecules and indirectly interfere with the metabolic subsystem. If the toxic compound is made insoluble, it shows much-reduced effect because of reduced bioavailability.

We often report the toxic effects in terms of lethal dose (LD50 being most common) but toxic effects can manifest in sublethal doses too. Therefore we also have safe or permissible limits for various elements that are experimentally determined to have no observable side effects. Some of the toxic agents manifestly do not show short-term activity but effects can be seen over several generations.

Common metals like Fe, Al, Cu, Be, Mn, Ni, and Cr are used in electrical power transmission. They individually have different degrees of toxicity. Biochemical toxicity is dose-dependent and therefore it is relevant to know the relative proportions of toxic elements in electric and electronic items. Where ever available, we have attempted to provide the annual global production of the element and its overall share to the electric and electronic industries.

3.3.1 Biochemical toxicity of copper (Cu)

Nineteen million tons of copper were produced in 2015 globally (Mineral Commodity Summaries 2017—Copper, <https://minerals.usgs.gov/minerals/pubs/commodity/copper/mcs-2017-coppe.pdf> accessed 29.04.18) and approximately 9% of this came from recycling. Therefore more than 90% (minus the growth) of the Cu produced annually is lost into the environment and is not recoverable. For power transmission, Al is steadily replacing Cu and 18% of the annual production of Cu is consumed by electrical and electronic industries. Electronic printed circuit boards are a major consumer of the metal. In 2015 the global sale value of printed circuit boards was USD 69.3 billion (contain both Cu and plastic) (sales worldwide 2010−18 <https://www.statista.com/statistics/674137/printed-circuit-board-product-sales-value-worldwide/>, accessed 29.04.18). Cu is an essential trace element required in both plants and animals for several enzymatic reactions as catalyst and cofactors. However, an excess of Cu can result in copper toxicity. The effect of environmental Cu on plants is more pronounced when compared to human and other mammals, as it is not readily bioaccumulated. Cu is relatively safe when compared to several other metals (cf. mercury, lead, and cadmium). In human, presence of excess Cu in system leads to production of metallothionein, which binds to Cu to form a water-soluble complex which can be eventually excreted. Further, the presence of organic and inorganic colloids in soil reduces Cu mobility and thereby the exposure of land plants to copper is reduced. However, aquatic plants are vulnerable to Cu toxicity. Studies indicate that Cu toxicity in plants depends on its bioavailability, which in turn is dependent on the physicochemical characteristics of the environment, such as pH, redox potential, soil and sediment type, water hardness, and organic content (Flemming and Trevors, 1989). Higher levels of Cu may result in inhibition of enzymes leading to interference in metabolic pathways. One of the major toxic effects on plants includes inhibition of chloroplast photosynthesis (Pádua et al., 2010). Excess of Cu leads to formation of hydroxyl radical, which initiate peroxidative chain reaction, thus degrading membrane lipids (Sandmann and Böger, 1980). Excess Cu inhibits overall vegetative growth in plants (Fernandes and Henriques, 1991). Aquatic species are vulnerable to copper toxicity about 10−100 folds more than mammals (Okocha and Adedeji, 2012).

As mentioned earlier, Cu is relatively safe for higher animals and studies on domesticated or laboratory animals showed a high tolerance limit of 300−800 μg/g dry weight feed in diet. Cu being an essential trace element is supplemented in diet to fulfill dietary requirements. The maximum permitted levels of Cu in complete feed varies from animal to animal that also depends upon their age (metabolic activity). However, for farm animals, an optimum concentration of 20 mg/kg dry matter in total diet is recommended by Advisory Committee on Animal Feedingstuffs (ACAF), United Kingdom (Guidance Note for Supplementing Copper to Bovines <https://acaf.food.gov.uk/sites/default/files/multimedia/pdfs/committee/guidancesuppcopperbovines.pdf> accessed 29.04.18).

3.3.2 Biochemical toxicity of beryllium (Be)

United States is the single major producer of this rare element and produced 190 metric tons of Be in 2015 (with China a distinct second with 20 metric tons of production in the same year) out of the world production of 275 metric tons (Mineral Commodity Summaries 2016—Beryllium <https://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2016-beryl.pdf> accessed 29.04.18). Less than 10% of this came from recycling and most of the production went into copper-based alloys (Shah et al., 2016). Be−Cu alloy is widely used in many electrical and electronic devices. In plants, Be interferes with various physiological and morphological processes resulting in reduction the plant growth. Be significantly affects seed germination, biomass, and root length (Kaplan et al., 1990). The effect on various plants and the critical levels is reviewed by Shah et al. (Shah et al., 2016). It has been well documented that Be interferes with mineral uptake in plants and therefore growth and yield.

Individuals exposed to Be show increase in the total number of lymphocytes, however, there is no evident immune dysfunction as a result of short-term exposure to Be (Kim et al., 2013). A more severe effect of Be exposure is Berylliosis, or *chronic beryllium disease* (CBD), a chronic lung disease caused by sustained exposure to Be in genetically susceptible individuals. Noncaseating granulomas are formed as a result of aggregation of $CD4^+$ T-lymphocytes and macrophages following each instance of Be exposure and may ultimately lead to lung fibrosis. The effect of Be is attributed to its ability to induce posttranslational modification to create neo-antigens (Fontenot et al., 2016; Jakubowski and Palczyński, 2015; McCanlies et al., 2003).

The lowest observed adverse effect level for Be sensitization and CBD progression was suggested as 0.55 μg Be/m^3 (Kreiss et al., 1996). Further in 2005, Schuler et al. suggested the occupational exposure limits to be $<0.2\ \mu g/m^3$ (Schuler et al., 2005).

3.3.3 Biochemical toxicity of manganese (Mn)

More than 17 million tons of Mn was produced in 2015 and about one-third of the metal came from South Africa. China is the second largest producer of this metal and it is poorly recycled because of lower volume of production. Most of the metal is used as a component of steel (Mn alloy—ferromanganese) but there are other minor uses in electrical and electronic industries (most common being the resistance heating element in most electrical heaters). Unlike Al, Mn is found in several enzymes as a cofactor.

Mn is required for normal development and physiological processes both in plants and animals. It is critical to maintain Mn homeostasis, which is required for regulation of several enzymes as arginase, superoxide dismutase and glutamine synthetase. However, any imbalance in the Mn homeostasis leads to disease conditions. Mn deficiency has been shown to be linked to skin lesions and bone malformation (including osteoporosis), whereas an overexposure to Mn may lead to neurodegenerative diseases. Level of Mn in serum of healthy human individuals is indicated as 0.05−0.12 μg/dL (Crossgrove and Zheng, 2004). The safe upper limit of Mn intake in humans is suggested to be 11 mg/day based on the study on Canadian women by Greger in 1998 (Greger, 1998), where the participants consumed 0.7−10.9 mg/day of Mn with no observable side effects and thus this was stated as the NOAEL (no observed adverse effect level). According to the American Conference of Governmental Industrial Hygienists (ACGIH) guidelines 2013, the threshold limit value (TLV) as a time-weighted average (TWA) for respirable Mn particulate is restricted to 0.02 mg/m^3, that is, an individual should not breather more than 0.02 mg/m^3 of air of Mn over an 8-h work shift. The new recommended TLV-TWA for inhalable Mn (which may not be inhaled into deeps lungs due to size) is 0.1 mg/m^3 (Revised TLV for Manganese <http://www.lincolnelectric.com/en-us/education-center/welding-safety/Pages/revised-tlv-manganese.aspx>, accessed 29.04.18). Manganism is a toxic condition resulting from chronic exposure to excessive levels of Mn.

3.3.4 Biochemical toxicity of chromium (Cr)

Chromium is only indirectly used in electrical and electronic industries as stainless steel in various forms. It is also used as an alloy in resistance heating elements. Cr plating is widely used (instead of Ni-plating) as an anticorrosion measure. In 2015 more than 30 million metric tons of Cr was produced worldwide with South Africa producing about half of the total. Cr is considered highly toxic and is a possible carcinogen.

Toxicity of Cr depends on the oxidation state, trivalent and hexavalent states being the most prevalent ones. Hexavalent chromium (Cr(VI)) compounds are powerful oxidizing agents and therefore more toxic compared to trivalent chromium. Further, Cr(III) compounds are poorly absorbed in the body, whereas Cr(VI) is absorbed by the lung and gastrointestinal tract (Wilbur et al., 2012).

3.3.5 Biochemical toxicity of aluminum (Al)

In 2015 the world production of Al was more than 51.5 million metric tons of which more than 50% was produced in China. The single major use of the metal is in transportation (body parts) but an 8% of the metal produced went to electrical industry (power conductor). (Mineral Commodity Summaries 2017—Aluminum

<https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/mcs-2017-alumi.pdf> accessed 29.04.18). Because of its lower cost (compared to Cu), Al has virtually displaced copper completely in power transmission applications. Al is highly recyclable and about 30% of the production comes from scrap (Global Aluminum Recycling <http://www.world-aluminium.org/media/filer_public/2013/01/15/fl0000181.pdf>, accessed 29.04.18). The metal is highly reactive, but the exposed metal gets a thin oxide protective film that makes it less active and highly useful in diverse applications.

Al is not needed for life and is not an essential requirement for either plants or animals. The toxicity of Al depends mainly on the pH owing to its higher solubility in acidic environments. Mobilization of Al ions is facilitated by increasing acidification of the environment leading to toxic effects in living systems. Al interferes with the activity of metabolic enzymes as hexokinase, alkaline phosphatase, phosphodiesterase, and phosphoxidase, due to its high affinity to RNA and DNA. It is particularly harmful for nervous, osseous, and hematopoietic systems (Barabasz et al., 2002). Al exhibits both beneficial and detrimental effects on plants. On one hand, it stimulates iron absorption by the roots, negates the toxic effects of other metals as Cu and Mn and imparts protection against phytopathogenic fungi and adverse environmental conditions as drought and high soil salinity. On the other hand, Al toxicity may lead to inhibition of root growth. It hinders calcium uptake and translocation, induces oxidative stress and changes cell wall and plasma membrane properties and nutritional imbalance (Silva, 2012).

3.3.6 Biochemical toxicity of lead (Pb)

About 5 million metric tons of Pb was produced in 2015 and the production of Pb is steadily but slowly decreasing because of its toxicity. Major part of the production goes into storage cells (lead acid batteries) and a significant part of the Pb present in storage cells is recycled. About 50% of the world production comes from China and the mining, production, and refining of Pb are associated with large scale environmental damages. Pb was earlier used as an antiknock compound [tetraethyl lead (TEL)] in petrol and it was transported into the atmosphere with the exhaust. Today the use of leaded (TEL) fuel has virtually stopped all over the world. Pb toxicity is often termed as lead poisoning due to the severe symptoms seen due to toxicity. They pose a range of effects on individuals exposed to Pb. However, the effects may vary depending on acute or chronic exposure. Acute toxicity may result in short-term effects as loss of appetite, headache, hypertension, abdominal pain, renal dysfunction, fatigue, sleeplessness, arthritis, hallucinations, and vertigo, whereas chronic exposure may lead to long-term effects including mental retardation, birth defects, psychosis, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis, muscular weakness, brain damage, kidney damage, and may even cause death (Jaishankar et al., 2014).

3.3.7 Biochemical toxicity of arsenic (As)

Arsenic is used only in very small amounts in electronic (GaAs is used in Light Emitting Diodes) and electrical industries. In 2015 the value of global GaAs device sales increased slightly to an estimated $7 billion (Mineral Commodity Summaries 2018—Arsenic <https://minerals.usgs.gov/minerals/pubs/commodity/arsenic/mcs-2017-arsen.pdf>, accessed 29.04.18). World production of the element in 2015 was 36,500 metric tons and about 70% of this came from China. Both natural and anthropogenic sources cause As toxicity (water pollution being the most common). Elevated levels of As in the body leads to arsenic poisoning. A short-term exposure generally results in vomiting, abdominal pain, and diarrhea (Ratnaike, 2003). However, chronic exposure results in arsenicosis [chronic arsenic toxicity (CAT)], usually caused due to the consumption of As contaminated ground water. CAT causes skin lesions like pigmentation, keratosis, pulmonary diseases, liver diseases like noncirrhotic portal fibrosis and other problems like neurological disorders, peripheral vascular disease, hypertension and ischemic heart disease, diabetes mellitus, nonpitting edema of feet/hands, weakness, and anemia; it is also associated with cancer of skin, lung, and urinary bladder (Mazumder, 2008).

Arsenate (As(V)) and arsenite (As(III)) are the two inorganic forms of arsenic (different oxidation states) that are easily taken up by root cells in plants. Arsenate is readily converted to arsenite, which is more toxic of the two forms. Arsenic causes oxidative stress in plants leading to membrane damage following lipid peroxidation. As(V) is an analog of inorganic phosphate and therefore is often easily transported by phosphate transporter proteins. Further, As(V) competes with phosphate during phosphorylation (glycolysis, oxidative phosphorylation), thus decreasing the cellular ability to produce ATP, and thereby hindering normal metabolism. As(III) is a dithiol reactive compound and binds to enzymes with closely spaced cysteine residues or dithiol cofactors and thus interfering with their native functionality (Finnegan and Chen, 2012).

3.3.8 Biochemical toxicity of lithium (Li)

Lithium has been widely used in humans for treating mood disorders, but inadequate information about its adverse effects is still a concern. In 2015, 31,500 metric tons of Li was produced and 80% of the production came from Australia and Chile. A major part of the production goes into modern batteries (mobile phones are the major user). The element is not an essential trace element for plants or animals but because of the small size of the cation (Li^+) it interferes with a number of metabolic processes. Commonly seen side effects include increased thirst, increased urination, and weakness. As the concentration of serum Li increases, toxicity increases. Serum concentration of <1.5 mEq/L is advised during the treatment phase. Early signs of Li toxicity may be seen at serum concentrations <2 mEq/L, such as diarrhea, vomiting, drowsiness, muscular weakness, and lack of coordination. Higher levels may result in giddiness, ataxia, blurred vision, tinnitus, and a large output of dilute urine, followed by damage to multiple organs and organ systems at levels above 3 mEq/L (Lithium salts monograph for professionals <https://www.drugs.com/monograph/lithium-salts.html>, accessed 29.04.18). Episodes of acute lithium toxicity were termed as the Syndrome of Irreversible Lithium-Effected Neurotoxicity, SILENT, with the most common symptom as persistent cerebellar dysfunction (Munshi and Thampy, 2005). Depending on the concentration of Li in the growth medium, it can stimulate or inhibit plant growth. Li interferes with numerous physiological processes including photosynthesis, DNA biosynthesis, and enzyme metabolism leading to alteration in overall metabolism.

Discarded Li batteries are the major source of Li into soil, which leads to its entry in food chain (Shahzad et al., 2016). Because of the relatively low volume, the metal is poorly recycled. It is strongly recommended that the Li-cells from mobile (and other) devices should be collected and segregated for recycling. Li batteries are also used in passenger aircrafts and also in modern electric cars as auxiliary power source.

3.3.9 Biochemical toxicity of boron (B)

Global production of boron was 9.4 million metric tons in 2015. Both borax and boric acids, two most important B compounds, are widely used in various industries (ceramics and detergents are the most important ones). Use of B in electrical and electronic industries is rather limited (used as a doping agent for Si semiconductors). Because of the low cost of the mineral, and the difficulty and cost of recovering, borates are rarely recycled. B is generally considered nontoxic to animals and humans, with LD50 at 6 g/kg body weight. A 4 g/day dose of boric acid was reported to be nontoxic; however, multiple doses of higher concentration are considered toxic. Boric acid is used as insecticide as it is more toxic to insects than to mammals. B is essential for plant growth, but excessive exposure to boron is toxic for plants. The initial symptoms include yellowing of leaves and may result in stunted growth. Growth inhibition in plants was seen with increased internal B concentration in the range of 1−5 mM across various plants. However, it was seen that mature cells in plants can withstand up to 60 mM of B for several days. This was further corroborating with a study in wheat, where rapid growth inhibition was observed when high B concentration was applied to the root tip but not when applied to mature root areas (Reid et al., 2004).

3.3.10 Biochemical toxicity of silicon (Si)

Silicon is generally considered nontoxic in its natural forms, that is, silica and silicates. It is one of the most widely distributed elements on the earth's crust. In 2015, 7.6 million metric tons of elemental Si was produced worldwide. In 2013, 70,000 metric tons of Si was discharged into waste (in the production of thin slices of Si to produce photovoltaic solar cells, approximately 40% of the material is lost). It is estimated that by 2030, 6.3 million metric tons of Si waste will be produced and will be the largest consumer of elemental Si. A large fraction of the Si production went for several Fe (ferrosilicon) and Al alloys. Silicon carbide is also widely used as a commercial abrasive. Si dust has been shown to have adverse effects on lungs, but no significant toxicity is reported for limited exposure. Inhalation of large quantity of silicon dioxide (crystalline silica) can pose as a potent respiratory hazard leading to silicosis. The LD50 of 3160 mg/kg body weight was obtained for crystalline silica when administered orally in rats (Lauwerys and Hoet, 2001).

Occupational exposure to crystalline silica has been attributed to several systemic autoimmune diseases, including scleroderma, rheumatoid arthritis, systemic lupus erythematosus, sarcoidosis, and some of the small vessel vasculitides with renal involvement (e.g., Wegener granulomatosis) (Parks et al., 1999). It can cause irritation in skin and eyes, when in contact, leading to redness and watering in eyes and skin inflammation. Si is known to stimulate plant growth and reduces heavy metal stress. It is the second most abundant element in the soil and is beneficial in reducing heavy metal stress both in plants and in soil. It acts by reducing active heavy metal ions present in the growth media, reducing metal uptake and stimulating antioxidant system in plants (Adrees et al., 2015).

3.3.11 Biochemical toxicity of iron (Fe)

Iron, because of its magnetic properties, is used in electrical motors, generators, and transformers. But the most important use, as steel, is to provide enclosure and support (construction industry is one of the major consumers). Because of the large volume of production (1.4 billion metric tons globally in 2015), the metal is widely recycled (as scrap).

Fe is essential for growth and development of most organisms, but high tissue concentrations can lead to physiological imbalance resulting in liver and heart diseases, certain cancers, and immune system dysfunction. Chronic inhalation of iron oxide fumes may result in siderosis and may increase the risk of lung cancer. Fe overload can lead to oxidative damage resulting in lipid peroxidation followed by membrane impairment, mainly in mitochondria and lysosomes. Excess of Fe can result in damage to various metabolic processes, most of which are downstream effects of oxidative stress caused by Fe overload (Britton et al., 2002). LD50 for iron in rats was reported as 30 g/kg (Iron—Chemical properties, health and environmental effects <https://www.lenntech.com/periodic/elements/fe.htm>, accessed 29.04.18).

3.3.12 Biochemical toxicity of cobalt (Co)

In 2015, 126,000 metric tons of cobalt was produced globally and half of this came from Congo (Mineral commodity Summaries 2017—Cobalt <https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2017-cobal.pdf>, accessed 29.04.18). Co is used in permanent magnets, superalloys, batteries, and in some chemical applications. Co is part of vitamin B_{12} and is therefore beneficial for humans. Humans may be exposed to Co through air, water, or food. Breathing air containing high concentrations of Co can result in lung problems, such as asthma and pneumonia. High intake of Co can cause vomiting, nausea, neurological deficits (hearing and visual impairment), heart problems, and thyroid malfunctioning (Leyssens et al., 2017). Chronic exposure to Co may lead to considerable weight loss, dermatitis, and respiratory disorders. LD50 for cobalt when administered orally was found to be 6171 mg/kg body weight. Plants grown on soil with high levels of Co may accumulate Co, which may be passed to human consuming those plant products. Co has been listed as possible carcinogen to human by International Agency for Research on Cancer (IARC) (Cobalt—chemical properties, health, and environmental effects <https://www.lenntech.com/periodic/elements/co.htm>, accessed 29.04.18).

3.3.13 Biochemical toxicity of nickel (Ni)

Global production of Ni in 2015 was 2.3 million metric tons and Philippines is a major producer of the metal. The metal is widely used as a component of stainless steel (alloy), but a small part is used in consumer electronics in batteries. The metal is also a popular choice for electroplating (steel) to enhance corrosion resistance. The metal is widely recycled at the scrap level but active recovery from consumer items is low. Exposure of Ni to skin produces skin irritation; a further oral exposure may lead to erythema, eczema, and lichenification of the areas of skin in contact with Ni. Studies have indicated that Ni metal dusts and some Ni compounds are potent carcinogens, which may be due to facilitation of oxygen-free radical reactions by nickel oxides. The carcinogenicity of nickel compounds depends on their ability to enter cells and therefore water-soluble compounds exhibit less potency when compared to water-insoluble compounds (Cempel and Nikel, 2006).

High Ni concentrations in soil can hamper plant growth. Common symptoms of Ni toxicity in plants include chlorosis, necrosis, and wilting. It interferes with enzymatic activity of antioxidant enzymes such as superoxide dismutase and catalase, thereby enhancing oxidative stress. It interferes with significant processes such as photosynthesis, respiration, germination, and chlorophyll synthesis (Bhalerao et al., 2015).

3.3.14 Biochemical toxicity of zinc (Zn)

Zinc is a widely used metal and the world production in 2015 was 12.8 million metric tons and China is a major supplier. Zn is widely used in several nonferrous alloys (e.g., brass), paints, and disposable batteries. Zn is an essential trace metal and is present in several enzymes as cofactors. Zn when taken orally in high concentration may lead to symptoms such as nausea, vomiting, epigastric pain, lethargy, and fatigue. Metabolically, Zn may interfere with copper and iron utilization and may negatively affect blood lipoprotein levels and cholesterol concentrations. US Recommended Dietary Allowance is 15 mg Zn/day; however, a much higher concentration close to 10 times the US RDA has been used for therapeutic purposes with no adverse effects (Fosmire, 1990).

3.3.15 Biochemical toxicity of gallium (Ga)

Gallium is a relatively rare metal and the 2015 production was 470 metric tons (produced as a by-product during Al mining) and most of it was used by the semiconductor industry. Ga is used in LEDs and related optoelectronic devices and some specialized integrated circuits. Ga is present in body in very trace amounts and is not considered to be toxic or carcinogenic. A case of accidental exposure to gallium halide resulted in dermatitis initially, followed by severe episodes of tachycardia, tremors, dyspnea, vertigo, and unexpected blackouts (Ivanoff et al., 2012). Acute exposure to gallium chloride can result in throat irritation and chest pain, and fume inhalation can be dangerous causing pulmonary edema and partial paralysis. Because of the low volume, Ga is not recycled from electronic devices.

3.3.16 Biochemical toxicity of germanium (Ge)

Germanium is another element that is widely used in semiconductor industry and the world production in 2015 was 165 metric tons (China is again the major producer). The metal is extracted as a by-product in Zn, Cu, or Pb refining. Use of Ge in semiconductor devices is steadily decreasing (being replaced by Si) but the Ge is also used in optical fibers (and production of optical fibers is steadily increasing). Ge is also used in specialized detectors (GeLi and SiLi detectors) and some optical devices. The amount present in consumer items is small and hence the element is not recycled from electronic and electric devices. It is not a requirement for living systems. Intake of inorganic Ge preparations for a long time has been shown to negatively affect renal functions and cause gastrointestinal symptoms as vomiting, anorexia, and weight loss. Kidney damage was shown by tubular degeneration and interstitial fibrosis with minor glomerular abnormalities (Obara et al., 1991).

Another report has indicated that prolonged intake of Ge products has resulted in renal failure and may lead to death. Ge overdose can also cause anemia, muscle weakness, peripheral neuropathy, and myopathy (Tao and Bolger, 1997).

3.3.17 Biochemical toxicity of selenium (Se)

Annual global production of Se is about 2000 metric tons and a major part of it is used by the glass industry. It is usually obtained as a by-product during Cu refining. About 12% of the total production is used in the electronics industry, mostly as a photosensitive element. CdSe is also used in IR devices. Se is essential as a trace element for growth (both plants and animals) but higher concentrations are toxic. Selenosis is caused by chronic exposure to selenium and the adverse effects of Se range from brittle hair and deformed nails, to even death in severe cases (Yang et al., 1983). A chronic Se poisoning is characterized by changes in the appearance of the nails and the early effects include brittle nails with longitudinal streaks and severe poisoning is indicated by breakage in nails, followed by regrown deformed nails or nails lost repeatedly. Overexposure to Se fumes may lead to garlic breath, conjunctivitis, vomiting, abdominal pain, diarrhea, and enlarged liver. Symptoms of acute toxicity include hypotension and tachycardia. It can also cause cardiac abnormalities and further leading to refractory hypotension from peripheral vasodilatation and direct myocardial depression leading to death (Nuttall, 2006). There may be serious symptoms as pulmonary edema or other neurological symptoms as tremor, muscle spasms, restlessness, confusion, delirium, and coma. Excessive accumulation of selenium in plants can induce oxidative stress and can lead to distorted protein structure and function (Gupta and Gupta, 2017).

3.3.18 Biochemical toxicity of molybdenum (Mo)

In 2000 the world production of Mo was 129,000 metric tons. The major used is in metallurgy (ferromolybdenum used for alloying for special steels) and in chemical form in other industries (MoS_2 is a popular lubricant). Its use in electrical and electronic industries is rather limited (used in some resistance heater elements). It is an essential trace element for both animals and plants and is a cofactor for some enzymes (nitrate reductase; xanthine dehydrogenase) but can be toxic at higher dose. In experiments conducted on rodents, reproduction and fetal development were critically affected at a concentration of 10 mg/L or higher, resulting in delayed fetal development (Fungwe et al., 1990; Vyskocil and Viau, 1999). The recommended dietary allowances for Mo were fixed at 4.45 μg/kg per day for infants, 1.95−5.36 μg/kg per day for children and 1.5−3.6 μg/kg per day for adults (Vyskocil and Viau, 1999). Molybdenum is applied to the soil as a micronutrient often mixed with fertilizers. Mo exhibits little to no toxicity to *Isochrysis galbana*, a tropical microalga (Trenfield et al., 2015).

3.3.19 Biochemical toxicity of palladium (Pd)

In 2015, 216 metric tons of Pd was mined worldwide. The major use of the platinum group elements (Pt, Pd, Rh, Ru, Ir, Os) are as catalysts and automobile industry is one of the major users (Pd is preferred because it is the cheapest). Pd is used in the making printed circuit boards (plated through holes) but the amount used is rather small. It is mostly recycled from the automobile catalytic converters. All the platinum group elements are relatively inert (they are also rare) and they do not pose significant threat to the environment. Pd is known to inhibit enzymes such as creatine kinase, aldolase, succinate dehydrogenase, carbonic anhydrase, alkaline phosphatase, and prolyl hydroxylase (Liu et al., 1979). Pd toxicity majorly affects mitochondria, it increases ROS production in mitochondria, collapses mitochondrial membrane potential, causes a negative effect on mitochondrial respiratory system that may lead to apoptosis (Hosseini et al., 2016). Another study on rats indicated that inorganic Pd compound can significantly induce drop in diastolic and mean blood pressure and a decrease in heart rate. However, Pd bound in an organic compound does not show any significant cardiotoxicity in isolated rat hearts (Peric et al., 2012).

3.3.20 Biochemical toxicity of silver (Ag)

The annual global production of silver is 27,000 metric tons, Mexico being the major supplier. Ag is also obtained as a by-product in the refining of Pb, Cu, and Au. It is widely used in several electrical and electronic industries. It is also used in chemical industries and photographic films. Ag is not a normal trace metal (micronutrient) needed for animal or plant life. Ag is toxic and the TLV for metallic silver and soluble Ag compounds was fixed at 0.1 and 0.01 mg/m^3, respectively, by ACGIH. The recommended exposure limit (REL) established by the National Institute for Occupational Safety and Health (NIOSH) is set at 0.01 mg/m^3 for all forms of Ag (Drake and Hazelwood, 2005).

The commonly known adverse effect of prolonged exposure to Ag is irreversible pigmentation of the eyes (argyrosis) or skin (argyria), resulting in bluish-gray pigmentation of the affected area. Other toxic effects of Ag include damage to liver and kidneys, irritation in eyes, skin, throat, or lungs. Chronic overexposure may lead to cardiac abnormalities, anemia, and permanent damage to nervous system (Drake and Hazelwood, 2005).

3.3.21 Biochemical toxicity of cadmium (Cd)

In 2015, 23,200 metric tons of Cd were mined worldwide (China is the largest producer of the metal). Cd is mainly used in rechargeable batteries (NiCd cells), paints and pigments, electroplating for corrosion resistance, and in chemical industries. Cd is a nonessential element (it is not present in living systems and is not required). Cd is considered toxic and prolonged exposure can affect multiple organs such as skeletal, urinary, reproductive, cardiovascular, central and peripheral nervous, and respiratory systems. Cd interferes with several physiological processes such as cell proliferation, differentiation, and apoptosis (Rani et al., 2014). It causes oxidative stress by inhibiting activity of antioxidant enzymes such as catalase, manganese-superoxide dismutase, and copper/zinc-dismutase. Cd is reported as a potent carcinogen (Rahimzadeh et al., 2017). It tends to accumulate in kidneys and affects excretory mechanisms.

3.3.22 Biochemical toxicity of tin (Sn)

Two hundred and eighty-nine thousand tons of Sn were produced globally in 2015 and China was the single largest producer of the metal. The metal is used as a protective layer (tin plating) to improve corrosion resistance, in chemical industries (organo-tin as a reagent in various chemical synthesis), and also as an alloy component in solder (with or without Pb; current trend is to use lead-free solder in all electronic applications). Sn is not an essential element for life and is considered nontoxic. *The Provisional Tolerable Weekly Intake for tin is 14 mg/kg body weight and recommended maximum permissible levels of tin in food are typically 250 mg/kg (200 mg/kg United Kingdom) for solid foods and 150 mg/kg for beverages* (Blunden and Wallace, 2003). Higher levels of Sn may accumulate in liver, bone, lymph nodes, and kidneys. Chronic exposure to Sn can cause liver damage, immune disorder, depression, and brain damage (Torack et al., 1960; Winship, 1988). Acute effects of tin overexposure include nausea, dizziness, diarrhea, eye and skin irritations, headaches, stomach aches, and breathlessness (Winship, 1988). The toxic effects of Sn can be attributed to its interaction with the absorption and excretion of Fe, Cu, and Zn (Westrum and Thomassen, 2002).

3.3.23 Biochemical toxicity of antimony (Sb)

In 2015, 142,000 metric tons of Sb were mined globally, and China is the single major producer (77% of the world production). Sb is used as (1) an alloy in lead acid batteries (used widely in transport vehicles) and (2) in paints and chemicals, and also as (3) a flame retardant. The metal is highly toxic and attempts are being made to find less toxic substitutes. Chronic exposure to Sb in the air at levels of 9 mg/m^3 may cause irritation of the eyes, skin, and lungs. Long-term inhalation of Sb can potentiate pneumoconiosis, altered electrocardiograms, stomach pain, diarrhea, vomiting, and stomach ulcers (Cooper and Harrison, 2009). Sb overexposure has been shown to cause adverse effects on respiratory, cardiovascular, gastrointestinal, and reproductive system (Sundar and Chakravarty, 2010). Sb has not been established as a carcinogen for humans but has been shown to cause lung tumors in rats. It is classified as a possible carcinogen by the IARC.

3.3.24 Biochemical toxicity of tellurium (Te)

Global annual production of Te is about 220 metric tons and, like Se, is obtained as a by-product during Cu refining. Most of the Te is used for alloying and a small amount is used in electronics (special detectors; also in thermoelectric devices). Studies to identify Te effect on transformed and nontransformed cells indicate cytotoxic effects (Vij and Hardej, 2012). When inhaled, body converts Te to dimethyltelluride, $(CH_3)_2Te$, which produces pungent-smelling garlic-like odor, termed as "tellurium breath" (Blackadder and Manderson, 1975). Inhalation of Te may also lead to headache, drowsiness, nausea, dry mouth, and metal taste. Ingestion of Te may lead to gastrointestinal illness and can affect liver and central nervous system. The permissible exposure limit as established by OSHA for Te exposure in workplace is 0.1 mg/m^3 over an 8-h workday, which is same as the REL given by NIOSH.

3.3.25 Biochemical toxicity of iodine (I)

In 2015, 30,600 metric tons of Iodine was produced and two-thirds of the production came from Chile and the rest from Japan. It is used in several detectors (gamma counters), X-ray contrasting agents (medical imaging), LCD monitors, and special lamps (halogen lamps).

Iodine is an essential micronutrient for humans, required for synthesis of thyroid hormones and other physiological processes. Elemental iodine is toxic when taken orally with a lethal dose of 30 mg/kg and can cause irritation and damage to skin. A solution of iodine is often used as an antiseptic. Most common electrical and electronic equipment do not contain any iodine.

For adults who are not lactating or pregnant, the US Institute of Medicine, jointly with WHO, United Nations Children's Fund (UNICEF), and the International Council for the Control of Iodine Deficiency Disorders (ICCIDD), recommend a daily iodine intake of 150 μg and state a tolerable upper level (the approximate threshold below which notable adverse effects are unlikely to occur in the healthy population) of 1100 μg/day in adults (Leung and Braverman, 2014).

Farm animals fed with excessive dietary iodide displays symptoms of iodism such as hyperglycemia, hypercholesterolemia, and a neutrophilic-lymphopenic shift in blood leukocytes, besides lacrimation, coryza, conjunctivitis, coughing, hair loss, and exophthalmos. Excessive iodide interferes with body metabolism and affects immune functions (Hillman and Curtis, 1980).

The permissible exposure limit for iodine exposure at workplace is set at 1 mg/m^3 by OSHA for an 8-h workday, which is same as the REL set by NIOSH. However, 20 times this level, 20 mg/m^3 can prove to immediately detrimental to health and life.

3.3.26 Biochemical toxicity of tungsten (W)

Eighty-nine thousand metric tons of W was mined in 2015, and China accounted for more than 80% of the production. The metal is used for filament in various incandescent lamps (and also in vacuum tubes) but the major part of the world production goes into the tungsten carbide bits that are widely used in various engineering applications (gas and oil field drilling is a major consumer). W has toxic attributes similar to those of other heavy metals. These include hindering of seedling growth, reduction of root and shoot biomass, ultrastructural malformations of cell components, aberration of cell cycle, disruption of the cytoskeleton, and deregulation of gene expression related with programmed cell death (Adamakis et al., 2012). Because of the low volume of the metal in use, it does not pose a threat.

Experiments conducted on rats by implanting W pellets resulted in aggressive tumors indicating potential carcinogenic effect of W (Kalinich et al., 2005). Various studies have indicated ill effects of W exposure on reproduction, immune system, cardiovascular function, and neurobehavior (Witten et al., 2012).

3.3.27 Biochemical toxicity of platinum (Pt)

One hundred and eighty-nine tons of Pt was produced in 2015 and more than 70% of it came from South Africa. The metal is used in various chemical industries as a catalyst (also in automobiles with the same purpose) and to a small extent in electronic and in the manufacturing of precision glass. It is not an essential element and is also used in several cancer drugs (chemotherapy). The metal is rather inert chemically but an acute exposure to Pt may cause irritation of eyes, nose, and throat, whereas a chronic exposure can result in respiratory disorders and skin allergies. The permissible exposure limit as per OSHA standard is 2 μg/m^3 averaged over an 8-h workday, and the REL set by NIOSH for platinum exposure is 1 mg/m^3 over an 8-h workday.

3.3.28 Biochemical toxicity of mercury (Hg)

The global annual production of Hg in 2015 was 3270 metric tons and 85% of this came from China. Hg is widely used in batteries, pesticides, fireworks, and in some fairness (cosmetic) creams. Hg is a highly toxic element and is a cumulative poison. Small but significant amount of Hg is also present in all fluorescent lamps (that also makes the disposal of fluorescent lamps a hazardous process). There is a systematic attempt to replace major uses of Hg with less toxic products. Inorganic Hg salts can cause irritation in the gut and can damage kidneys. Organic Hg salts are capable of crossing the blood–brain barrier as they are fat-soluble and can cause neurological and behavioral disturbances (Langford and Ferner, 1999). Methylmercury is a potent neurological poison and can damage brain by affecting cerebellum and the visual cortex. Prenatal exposure to methylmercury can result in retarded development and cognitive impairment in children (Grandjean et al., 1997). Metallic Hg can evaporate at room temperature and thus is considered harmful. Also, it can be biotransformed to organic Hg in lakes and other water bodies, thus entering the food chain eventually reaching human. One such infamous incident was Hg poisoning which affected thousands of people in Minamata Bay in Japan and the disease was termed as Minamata disease. Dangerous amounts of Hg were found in fishes caught near Bombay (now Mumbai) that came from caustic soda manufacturing plants (using Castner–Kellner process; now being phased out). Major symptoms include numbness in limbs, impaired peripheral vision, hearing and speech, and muscle weakness. Severe toxicity may lead to insanity, paralysis, coma, and even death.

3.4 Plastics used in electronics and electrical items

Plastics are widely used in electrical and electronics devices. In electrical cables, plastics are used as insulators and as physical protection from the environment. Mechanical strength is often provided by a covering (cladding) of steel wires or tapes just below the outermost plastic sheath. Electronic items contain plastics as (1) protection to the component device and wires; (2) enclosure material (item can be enclosed in either plastic or metal); and in much smaller amounts as (3) special purpose adhesives. Polyvinylchloride (PVC) is one of the most common plastics that finds numerous applications (drain pipes to insulation for electrical wires). In 2016 the global production of the PVC was 62 million metric tons. The global production of electrical and electronic waste in 2012 was 42 million metric tons (of which 9.4 million metric tons were contributed by the United States and 7.3 million metric tons were contributed by China) (Vouvoudi et al., 2017). Although environment unfriendly, PVC is popular because the characteristics of the final product can be relatively easily manipulated by using special additives (often plasticizers) and it costs low. Most plastics are inflammable and for use in electronic and electrical items, some form of flame retardants is often used. Unfortunately, these compounds (brominated organic compounds that slow down, but do not completely prevent fire) are also toxic to the environment (because of the presence of bromine). Current trend is to reduce the use of PVC in both electrical and electronic items. Fig. 3.3 shows extensive use of plastic random assortment of electronic components.

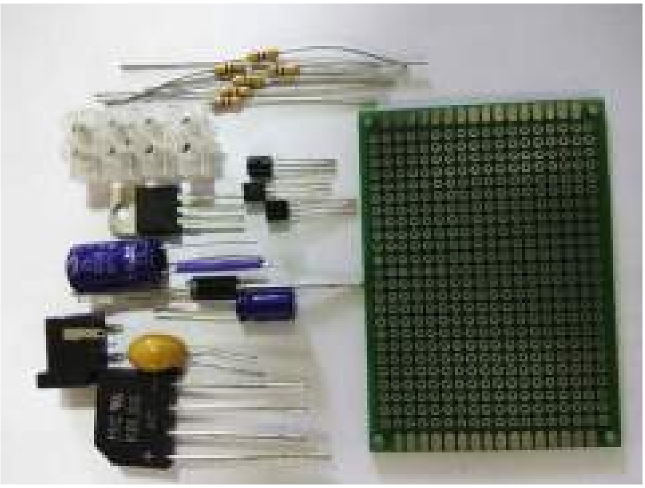

Figure 3.3 A random assortment of electronic components showing the extensive use of plastics.

Almost all domestic electric wires are insulated with PVC and at the end of their service life the cables are burnt to remove the plastic and recover the Cu (that can be recycled). However, PVC produces highly toxic fumes (unless burnt under controlled conditions in an incinerator) which causes air pollution. Phthalate esters are often used as plasticizers for PVC, but they too are environment unfriendly. Pyrolysis of the plastics present in the waste can produce a liquid fuel fraction but this has not been tried on a large scale (Vouvoudi et al., 2017). Polyethylene and cross-linked polyethylene are slowly replacing PVC for electric cable insulation. Polycarbonate plastics are popular for enclosures but recent concerns about the effects of bisphenol-A (substance of very high concern) have restricted their use.

Plastics are known for their long degradation process and therefore when disposed in landfill pose environmental risk. Brominated flame retardants (BFRs), PVC, and polychlorinated biphenyls (PCBs) are particularly toxic.

PCBs are used in capacitor and transformers. They affect systems including immune, endocrine, and nervous systems. IARC classified PCBs as a definite carcinogen in human in 2013 (Lauby-Secretan et al., 2013). Exposure to extremely high level of PCBs may lead to skin conditions as rashes, dermal and ocular lesions, and irregular menstrual cycles and lowered immune response (Aoki, 2001). Further, in children, it is reported to cause poor cognitive development. Pregnant women exposed to PCBs may give birth to children with compromised immune function and motor control problems (Jacobson and Jacobson, 1996). In animals, even a short exposure to PCBs can cause liver damage and can be fatal. Long-term exposure to small amounts of PCBs can cause ill effects to skin, liver, stomach, and immune system. It can also lead to hearing loss (Goldey et al., 1995).

PVC contains components as vinyl chloride monomer, which is a noted carcinogen in humans. Further, the presence of plasticizers is a prime concern; the most commonly used plasticizer is phthalate which is a known carcinogen in rodents and is reported as a potential endocrine disruptor in humans (Kajta and Wójtowicz, 2013). Dioxins, released when PVC is incinerated, are toxic in nature and can cause nervous system disorder, birth defects, and even cancer (Matés et al., 2010). It is also found to cause reproductive, immune, and developmental system dysfunction (Thornton, 2002).

BFRs are ubiquitously used in various industry chemicals. Different BFRs have varying effect on humans and animals. Brominated diphenyl ethers (BDEs) are the most widely used category. It has been reported that PentaBDEs cause adverse effects even in lower doses, followed by OctaBDEs and DecaBDEs, which are harmful in comparatively higher doses only. They are reported to affect neurobehavioral development and thyroid, kidney and liver morphology (Darnerud, 2003). Several BFRs are linked to memory and learning problems, retarded physical and mental growth, lower IQ, and reduced fertility. These components tend to persist in environment and bioaccumulate. They have been detected in the tissue of sperm whales, which mostly inhabit in deep oceans, suggesting the long-distance transport and bioaccumulation (Boon et al., 2002).

A modern electronic consumer device may contain most of the possible elements mentioned above but they are in a sealed environment and do not appear to pose any direct hazard to the user. However, when disposed improperly, they (e.g., mercury from fluorescent lamps or lead present in solders) can seep into the environment and can pose a threat for many years to come (because the elements change their chemical form, but the toxic effects persist). Most plastics, by their commercial design, are essentially resistant to degradation and pose a direct threat to the environment (rather than humans) and modern economics makes recycling of plastics unattractive.

3.5 Current disposal methods

Major biochemical hazards are mediated by inappropriate disposal of electrical and electronic goods, where the individual components, especially the toxic elements (mentioned in the previous sections) which make its way in living systems. Once these goods are out-of-use and are discarded, the process of their disassembly starts. Post disassembly the individual components are either recycled, incinerated, or are deposited in a landfill. However, the choice of final disposal depends on the nature and characteristic of individual elements and should be taken into consideration before proceeding with disposal. It is generally a combination of these methods, where recycling marks the first step followed by incineration or landfilling or both.

It has been suggested that urban E-wastes can be mined to extract several rare and precious metals (Li, Au, Ag, Pd, In) since they have a much higher concentration compared to the natural mines (Wang et al., 2017). Considerable efficiency enhancement can be expected if some preliminary segregation can be done (e.g., Li can be used for batteries; Cu, Ag, Au, and Pd can be used in making printed circuit boards and In can be used for LCD panels). Both Pd and Pt can be recovered with high yield from catalytic converters of automobiles.

Recycling is supposed to be the most intensive step as it requires manual disassembly followed by several steps depending upon the item to be recycled, such as melting solder, shredding, grinding, and metal segregation. Recycling is opted to recover valuable components which can be repurposed and used further. During recycling may also release hazardous substances causing toxicity in living systems. For example, heating plastics (e.g., PVC) which contain bromine or chlorine leads to formation of dioxins and furans, which are released into the air; however, measures are being taken to reduce these emissions using proper handling techniques. The remaining components after recycling are either incinerated and landfilled or landfilled directly. Incineration is advantageous in some cases, whereas in others it might lead to further toxic and hazardous end products in the form of fly ash, slag, or wastewater being released into air, water, or land. Landfilling may sound to be a safe option for waste management, but the problem arises when the filled waste leaches or evaporates from the landfill.

3.6 Current recycling practices

Recycling can be undertaken at several places: (1) at the point of production, (2) at the assembly point, and (3) at the consumer level after the end of life of the item. At the factory where the material is produced, recycling makes the most economic sense. A part that could not be used becomes a waste and can be safely returned to the previous (or still earlier) stage where the recycled material will act as an input. This is a routine practice because it costs the least and reduces waste. This sometimes is not even considered as a recycling step.

Recycling at the assembly point is also easy to implement because of the volume involved. An automobile factory, for example, produces lots of steel scrap that can be sold back to the factory at a discount. An electronic assembly line can (and does) segregate all faulty circuit boards that are sold to a scrap dealer at a price. The scrap dealer has an idea of the rough composition of the lot and passes on the material to the factory that can make the most use of the material (e.g., a lot containing mostly printed circuit boards can be sent to a copper recovery agent who will also recover smaller amounts of Ag, Au, and Pd from the same boards). However, for economic reasons, the assembly line must reduce waste production and maximize efficiency. Hence the production of scrap at this stage is rather small ($<1\%$).

The picture changes completely at the last step when the final user, at the end of life of the item, wishes to discard the item. The final product is distributed over many people and over a large geographical area. Recycling at this step is most important but is also difficult. Therefore a large amount of the material ends up as E-waste in a potential landfill.

Because of economic reasons, many countries decide to export their E-waste to other countries for final disassembly and disposal. Therefore E-waste disposal has become a major concern particularly in developing nations. E-wastes from developed countries are being shipped to developing countries, such as India and Bangladesh, for recycling due to low-cost labor and weak environmental regulations (Agoramoorthy and Chakraborty, 2012).

For example, it has been reported that in 2016, over 2 million metric tons of E-waste was produced in India. It does not include the E-waste that India received in the same period (import of E-waste is officially banned in India). Because of lack of suitable infrastructure, only about 1%−2% of the E-waste was effectively recycled. One of the main reasons for the low efficiency of recycling is the lack of economic incentives. Economics dictate that wealthier countries that do have a decent E-waste collection system in place prefer to export them to third countries where the laws and regulations are rather lax or nonexistent (or not enforced). The E-waste in poorer countries is manually processed by women and children (two rather vulnerable groups) without proper safety safeguards.

References

Adamakis, I.-D.S., Panteris, E., Eleftheriou, E.P., 2012. Tungsten toxicity in plants. Plants 1, 82−99.

Adrees, M., Ali, S., Rizwan, M., Zia-ur-Rehman, M., Ibrahim, M., Abbas, F., et al., 2015. Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: a review. Ecotoxicol. Environ. Saf. 119, 186−197.

Agoramoorthy, G., Chakraborty, C., 2012. Environment: control electronic waste in India. Nature 485, 309.

Aoki, Y., 2001. Polychlorinated biphenyls, polychloronated dibenzo-*p*-dioxins, and polychlorinated dibenzofurans as endocrine disrupters—what we have learned from Yusho disease. Environ. Res. 86, 2−11.

Barabasz, W., Albinska, D., Jaskowska, M., Lipiec, J., 2002. Ecotoxicology of aluminium. Pol. J. Environ. Stud. 11, 199−204.

Bhalerao, S.A., Sharma, A.S., Poojari, A.C., 2015. Toxicity of nickel in plants. Int. J. Pure Appl. Biosci. 3, 345−355.

Blackadder, E.S., Manderson, W.G., 1975. Occupational absorption of tellurium: a report of two cases. Occup. Environ. Med. 32, 59−61.

Blunden, S., Wallace, T., 2003. Tin in canned food: a review and understanding of occurrence and effect. Food Chem. Toxicol. 41, 1651−1662.

Boon, J.P., Lewis, W.E., Tjoen-A-Choy, M.R., Allchin, C.R., Law, R.J., de Boer, J., et al., 2002. Levels of polybrominated diphenyl ether (PBDE) flame retardants in animals representing different trophic levels of the North Sea food web. Environ. Sci. Technol. 36, 4025−4032.

Britton, R.S., Leicester, K.L., Bacon, B.R., 2002. Iron toxicity and chelation therapy. Int. J. Hematol. 76, 219−228.

Cempel, M., Nikel, G., 2006. Nickel: a review of its sources and environmental toxicology. Pol. J. Environ. Stud. 15.

Cooper, R.G., Harrison, A.P., 2009. The exposure to and health effects of antimony. Indian J. Occup. Environ. Med. 13, 3.

Crossgrove, J., Zheng, W., 2004. Manganese toxicity upon overexposure. NMR Biomed. 17, 544−553.

Darnerud, P.O., 2003. Toxic effects of brominated flame retardants in man and in wildlife. Environ. Int. 29, 841−853.

Drake, P.L., Hazelwood, K.J., 2005. Exposure-related health effects of silver and silver compounds: a review. Ann. Occup. Hyg. 49, 575−585.

Fernandes, J.C., Henriques, F.S., 1991. Biochemical, physiological, and structural effects of excess copper in plants. Bot. Rev. 57, 246−273.

Finnegan, P., Chen, W., 2012. Arsenic toxicity: the effects on plant metabolism. Front. Physiol. 3, 182.

Flemming, C.A., Trevors, J.T., 1989. Copper toxicity and chemistry in the environment: a review. Water. Air. Soil Pollut. 44, 143−158.

Fontenot, A.P., Falta, M.T., Kappler, J.W., Dai, S., McKee, A.S., 2016. Beryllium-induced hypersensitivity: genetic susceptibility and neoantigen generation. J. Immunol. 196, 22−27.

Fosmire, G.J., 1990. Zinc toxicity. Am. J. Clin. Nutr. 51, 225−227.

Fungwe, T.V., Buddingh, F., Demick, D.S., Lox, C.D., Yang, M.T., Yang, S.P., 1990. The role of dietary molybdenum on estrous activity, fertility, reproduction and molybdenum and copper enzyme activities of female rats. Nutr. Res. 10, 515−524.

Goldey, E.S., Kehn, L.S., Lau, C., Rehnberg, G.L., Crofton, K.M., 1995. Developmental exposure to polychlorinated biphenyls (aroclor 1254) reduces circulating thyroid hormone concentrations and causes hearing deficits in rats. Toxicol. Appl. Pharmacol. 135, 77−88.

Grandjean, P., Weihe, P., White, R.F., Debes, F., Araki, S., Yokoyama, K., et al., 1997. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicol. Teratol. 19, 417−428.

Greger, J.L., 1998. Dietary standards for manganese: overlap between nutritional and toxicological studies. J. Nutr. 128, 368S−371S.

Gupta, M., Gupta, S., 2017. An overview of selenium uptake, metabolism, and toxicity in plants. Front. Plant Sci. 7, 2074.

Hillman, D., Curtis, A.R., 1980. Chronic iodine toxicity in dairy cattle: blood chemistry, leukocytes, and milk iodide. J. Dairy Sci. 63, 55−63.

Hosseini, M.-J., Jafarian, I., Farahani, S., Khodadadi, R., Tagavi, S.H., Naserzadeh, P., et al., 2016. New mechanistic approach of inorganic palladium toxicity: impairment in mitochondrial electron transfer. Metallomics 8, 252−259.

Ivanoff, C.S., Ivanoff, A.E., Hottel, T.L., 2012. Gallium poisoning: a rare case report. Food Chem. Toxicol. 50, 212−215.

Jacobson, J.L., Jacobson, S.W., 1996. Intellectual impairment in children exposed to polychlorinated biphenyls in utero. N. Engl. J. Med. 335, 783−789.

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N., 2014. Toxicity, mechanism and health effects of some heavy metals. Interdiscip. Toxicol. 7, 60−72.

Jakubowski, M., Palczyński, C., 2015. Beryllium, Handbook on the Toxicology of Metals, fourth ed. Elsevier, pp. 635−653.

Kajta, M., Wójtowicz, A.K., 2013. Impact of endocrine-disrupting chemicals on neural development and the onset of neurological disorders. Pharmacol. Rep. 65, 1632−1639.

Kalinich, J.F., Emond, C.A., Dalton, T.K., Mog, S.R., Coleman, G.D., Kordell, J.E., et al., 2005. Embedded weapons-grade tungsten alloy shrapnel rapidly induces metastatic high-grade rhabdomyosarcomas in F344 rats. Environ. Health Perspect. 113, 729.

Kaplan, D.I., Sajwan, K.S., Adriano, D.C., Gettier, S., 1990. Phytoavailability and toxicity of beryllium and vanadium. Water. Air. Soil Pollut. 53, 203−212.

Kim, K.-W., Kim, D., Won, Y.L., Kang, S.-K., 2013. Effects of beryllium on human serum immunoglobulin and lymphocyte subpopulation. Toxicol. Res. 29, 115.

Kreiss, K., Mroz, M.M., Newman, L.S., Martyny, J., Zhen, B., 1996. Machining risk of beryllium disease and sensitization with median exposures below 2 μg/m^3. Am. J. Ind. Med. 30, 16–25.
Langford, N.J., Ferner, R.E., 1999. Toxicity of mercury. J. Hum. Hypertens. 13, 651.
Lauby-Secretan, B., Loomis, D., Grosse, Y., El Ghissassi, F., Bouvard, V., Benbrahim-Tallaa, L., et al., 2013. Carcinogenicity of polychlorinated biphenyls and polybrominated biphenyls. Lancet Oncol. 14, 287–288.
Lauwerys, R.R., Hoet, P., 2001. Industrial Chemical Exposure: Guidelines for Biological Monitoring. CRC Press.
Leung, A.M., Braverman, L.E., 2014. Consequences of excess iodine. Nat. Rev. Endocrinol. 10, 136.
Leyssens, L., Vinck, B., Van Der Straeten, C., Wuyts, F., Maes, L., 2017. Cobalt toxicity in humans: a review of the potential sources and systemic health effects. Toxicology 387, 43–56.
Liu, T.Z., Lee, S.D., Bhatnagar, R.S., 1979. Toxicity of palladium. Toxicol. Lett. 4, 469–473.
Matés, J.M., Segura, J.A., Alonso, F.J., Márquez, J., 2010. Roles of dioxins and heavy metals in cancer and neurological diseases using ROS-mediated mechanisms. Free Radic. Biol. Med. 49, 1328–1341.
Mazumder, D.G., 2008. Chronic arsenic toxicity & human health. Indian J. Med. Res. 128, 436.
McCanlies, E.C., Kreiss, K., Andrew, M., Weston, A., 2003. HLA-DPB1 and chronic beryllium disease: a HuGE review. Am. J. Epidemiol. 157, 388–398.
Munshi, K.R., Thampy, A., 2005. The syndrome of irreversible lithium-effectuated neurotoxicity. Clin. Neuropharmacol. 28, 38–49.
Nuttall, K.L., 2006. Evaluating selenium poisoning. Ann. Clin. Lab. Sci. 36, 409–420.
Obara, K., Saito, T., Sato, H., Yamakage, K., Watanabe, T., Kakizawa, M., et al., 1991. Germanium poisoning: clinical symptoms and renal damage caused by long-term intake of germanium. Jpn. J. Med. 30, 67–72.
Okocha, R., Adedeji, O., 2012. Overview of copper toxicity to aquatic life. Rep. Opin. 4, 57–68.
Pádua, M., Cavaco, A.M., Aubert, S., Bligny, R., Casimiro, A., 2010. Effects of copper on the photosynthesis of intact chloroplasts: interaction with manganese. Physiol. Plant. 138, 301–311. Available from: https://doi.org/10.1111/j.1399-3054.2009.01335.x.
Parks, C.G., Conrad, K., Cooper, G.S., 1999. Occupational exposure to crystalline silica and autoimmune disease. Environ. Health Perspect. 107, 793.
Peric, T., Zivkovic, V., Krkeljic, J., Petrovic, Z.D., Simijonovic, D., Novokmet, S., et al., 2012. Toxic effects of palladium compounds on the isolated rat heart. Med. Chem. 8, 9–13.
Rahimzadeh, M.R., Rahimzadeh, M.R., Kazemi, S., Moghadamnia, A., 2017. Cadmium toxicity and treatment: an update. Casp. J. Intern. Med. 8, 135.
Rani, A., Kumar, A., Lal, A., Pant, M., 2014. Cellular mechanisms of cadmium-induced toxicity: a review. Int. J. Environ. Health Res. 24, 378–399.
Ratnaike, R.N., 2003. Acute and chronic arsenic toxicity. Postgrad. Med. J. 79, 391–396.
Reid, R.J., Hayes, J.E., Post, A., Stangoulis, J.C.R., Graham, R.D., 2004. A critical analysis of the causes of boron toxicity in plants. Plant Cell Environ. 27, 1405–1414.
Sandmann, G., Böger, P., 1980. Copper-mediated lipid peroxidation processes in photosynthetic membranes. Plant Physiol. 66, 797–800.
Schuler, C.R., Kent, M.S., Deubner, D.C., Berakis, M.T., McCawley, M., Henneberger, P.K., et al., 2005. Process-related risk of beryllium sensitization and disease in a copper–beryllium alloy facility. Am. J. Ind. Med. 47, 195–205.

Shah, A.N., Tanveer, M., Hussain, S., Yang, G., 2016. Beryllium in the environment: whether fatal for plant growth? Rev. Environ. Sci. Biotechnol. 15, 549−561.
Shahzad, B., Tanveer, M., Hassan, W., Shah, A.N., Anjum, S.A., Cheema, S.A., et al., 2016. Lithium toxicity in plants: reasons, mechanisms and remediation possibilities − a review. Plant Physiol. Biochem. 107, 104−115.
Silva, S., 2012. Aluminium toxicity targets in plants. J. Bot. 2012.
Sundar, S., Chakravarty, J., 2010. Antimony toxicity. Int. J. Environ. Res. Public. Health 7, 4267−4277.
Tao, S.-H., Bolger, P.M., 1997. Hazard assessment of germanium supplements. Regul. Toxicol. Pharmacol. 25, 211−219.
Thornton, J., 2002. Environmental impacts of polyvinyl chloride building materials. Healthy Building Network, Washington DC, p. 110.
Torack, R.M., Terry, R.D., Zimmerman, H.M., 1960. The fine structure of cerebral fluid accumulation: II. Swelling produced by triethyl tin poisoning and its comparison with that in the human brain. Am. J. Pathol. 36, 273.
Trenfield, M.A., van Dam, J.W., Harford, A.J., Parry, D., Streten, C., Gibb, K., et al., 2015. Aluminium, gallium, and molybdenum toxicity to the tropical marine microalga *Isochrysis galbana*. Environ. Toxicol. Chem. 34, 1833−1840.
Vanegas, P., Peeters, J.R., Cattrysse, D., Dewulf, W., Duflou, J.R., 2017. Improvement potential of today's WEEE recycling performance: the case of LCD TVs in Belgium. Front. Environ. Sci. Eng. 11, 13.
Vij, P., Hardej, D., 2012. Evaluation of tellurium toxicity in transformed and non-transformed human colon cells. Environ. Toxicol. Pharmacol. 34, 768−782.
Vouvoudi, E.C., Rousi, A.T., Achilias, D.S., 2017. Thermal degradation characteristics and products obtained after pyrolysis of specific polymers found in waste electrical and electronic equipment. Front. Environ. Sci. Eng. 11, 9.
Vyskocil, A., Viau, C., 1999. Assessment of molybdenum toxicity in humans. J. Appl. Toxicol. 19, 185−192.
Wang, M., Tan, Q., Chiang, J.F., Li, J., 2017. Recovery of rare and precious metals from urban mines: a review. Front. Environ. Sci. Eng. 11, 1.
Westrum, B., Thomassen, Y., 2002. 130. Tin and Inorganic Tin Compounds. National Institute for Working Life.
Wilbur, S., Abadin, H., Fay, M., Yu, D., Tencza, B., Ingerman, L., et al., 2012. Toxicological Profile for Chromium, Agency for Toxic Substances and Disease Registry (ATSDR) Toxicological Profiles. Agency for Toxic Substances and Disease Registry (US), Atlanta, GA.
Winship, K.A., 1988. Toxicity of tin and its compounds. Adverse Drug React. Acute Poisoning Rev. 7, 19−38.
Witten, M.L., Sheppard, P.R., Witten, B.L., 2012. Tungsten toxicity. Chem. Biol. Interact. 196, 87−88.
Yang, G.Q., Wang, S.Z., Zhou, R.H., Sun, S.Z., 1983. Endemic selenium intoxication of humans in China. Am. J. Clin. Nutr. 37, 872−881.

Policy issues for efficient management of E-waste in developing countries

4

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4.1 E-waste and its management

Electronic (e-) waste is globally regarded as a subset of waste electrical and electronic equipment (WEEE). The most prominent definition of E-waste/WEEE can be referred through the description given by the European Commission as "the end-of-life (EoL) commodity/gadgets that have been used for generating, measuring, and transferring the electrical or magnetic current, and/or functioned by supplying the current during their service life." In this ways, certainly not limited to, the discarded electronic goods (e.g., personal computers and hand/telephones), electrical appliances (e.g., air conditioners, refrigerators, and washing machines), and power storage batteries are belonging the E-waste. Another definition given by the Association of Plastics Manufacturers in Europe (APME) has stated E-waste as the multifarious combination of ferrous, nonferrous, ceramic, and plastic materials.

A rapidly changing technology and its unprecedented use in our daily life are generating a large volume of EoL materials those have been kept within the boundary of E-waste. With an annual growth rate of more than 4%, E-waste is the enormously growing waste volume around the globe. In 2014, approximately 41.8 Mt (million tons) of E-waste was generated worldwide, which reached 44.7 Mt in 2016 (equivalent to 6.1 kg/inhabitant), and estimated to touch 50 Mt by the end of year 2018 (https://tcocertified.com/news/global-e-waste-reaches-record-high-says-new-un-report/; https://www.forbes.com/sites/lamsharon/2017/11/23/global-e-waste-to-hit-49-8m-tons-by-2018-heres-what-japan-is-doing-to-combat-it/#6489acd335ca). At the regional level, Asia is the top generator of E-waste (~41%), followed by the United States (~29%), and Europe (~27%); however, Europe is top in the generation by per inhabitant. The gap in E-waste generation between the developed and developing countries is very wide. The richest country is generating 19.6 kg/inhabitant against the poorest country of only 0.6 kg/inhabitant. Although the developed countries have covered themselves from the adversaries of E-waste under the umbrella of advanced technology and management system, developing and

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00002-4

underdeveloped countries are still struggling to get proper guidelines for effective management of E-waste. In those countries, specifically low and middle income-group countries, a large proportion of E-waste is either disposed in landfill sites or, fed to the informal recycling sector. The burning of end-of-life wires and printed circuit boards (PCBs) are a common practice to separate metal and polymer substance. Rudimentary methods, including the hand-picking and dismantling, nitrate/aqua-regia leaching, and throwing the residual and effluent streams in an open environment is also practiced to retrieve the precious metals from E-waste. Therefore lacking safeguard to the environment and public health with an inappropriate efficiency of resource recycling (Leung et al., 2006; SEPA, 2011).

4.2 Current practices of E-waste management

In the global framework for an effective E-waste management, the collection, handling, processing (recycling and recovery), and final disposal are accepted as the main factors (E-waste management rule, 2016). On the other side, threats from improper handling of greater volume by the informal recycling with weak/absent of E-waste legislation are the major issues identified for developing countries (Heeks et al., 2015). However, the role of informal sectors in low and middle income countries cannot be ignored (Pathak et al., 2017). Fig. 4.1 depicts the current practices of E-waste management system where it is collected from sales, households, business, and public sectors after attaining the EoL. Below the aggravated management of thus generated E-waste volume in developing countries of more relevance is discussed.

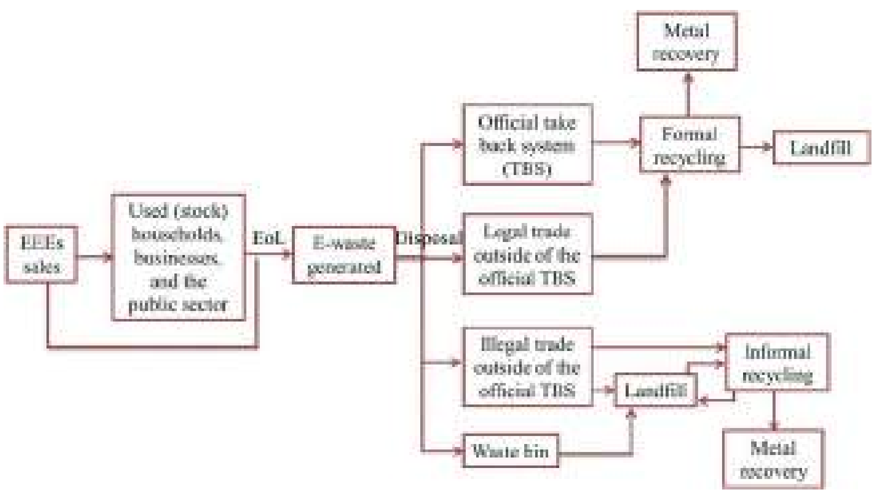

Figure 4.1 Pictorial representation of a typical E-waste management system (Balde et al., 2015; Pathak et al., 2017).

4.2.1 China

In the last 5 years, the Asia-Pacific region has 63% jumped in global E-waste generation that accounted for 16 Mt in weight (https://www.theguardian.com/environment/2017/jan/16/chinas-booming-middle-class-drives-asias-toxic-e-waste-mountains). Amongst all, the domestic E-waste production in China has been recorded more than doubled to 6.7 Mt during the same period (https://www.recycling-magazine.com/2017/10/19/electronics-recycling-china/). It makes China the largest producer of E-waste, alone contributing around 15% of the global volume (https://i.unu.edu/media/unu.edu/news/52624/UNU-1stGlobal-E-Waste-Monitor-2014-small.pdf; https://www.chinadialogue.net/article/show/single/en/9841-China-to-release-plan-for-tackling-e-waste-by-end-of-year-).

Nevertheless, the domestic generation of E-waste has remained smaller if compared to the amount of E-waste being imported from developed countries to China, which has accounted up to 35 Mt (Ongondo et al., 2011). Owing to the problems E-waste carry in terms of quantity and toxicity, China is the largest importer of these challenges. Mostly the imported E-waste ends through practicing the primitive process by the informal sector. The informal recycling sector practices the primitive processes without any proper scientific facilities and safeguards to the environment and human health (Green Peace-Basel Action Network, 2004). Usually, it is a kind of family-run workshop within their house or surroundings where disassembling of E-waste and metals stripping by open acid bath or burning of PCBs and wire/cables are practiced (Leung et al., 2006). Such activities caused severe problems in the form of environmental pollution nearby the informal recycling areas, like Guiyu where the accumulation of heavy metals and hazardous hydrocarbons have been measured in the soil, air, and water (Yu et al., 2010; Bridgen et al., 2005; Zhang and Min, 2009). Notably, Guiyu is an archetype of "backyard" E-waste processing by 1995, employing 150,000 peoples in approximately 5500 shops (Driscoll and Shiheng, 2010).

Time-to-time the environmentalists, researchers, and media has brought attention to its environmental impacts (Hicks et al., 2005; Basel Action Network, 2002). Therefore it is needed for China to develop the systems to handle domestically generated E-waste and its international trade as well. Henceforth, the Chinese government is continuously working to develop the policies, infrastructure facilities, and technologies for the effective management of E-waste. In this direction, the specific and pertinent efforts in the form of regulations and laws enacted by the Chinese government are summarized in Table 4.1.

The Management of Prevention and Control of Pollution from Electronic Information Products (EIPs) referred as China's RoSH and the waste disposal law dealing for the administration of the recovery and disposal of E-waste are of vital importance. They basically target by funding safe E-waste recycling facilities, also the responsibility of E-waste collection is fixed on the manufacturers/retailers/recycling companies.

4.2.2 India

India stands fifth for generating the E-waste worldwide. A compound growth of 25% per annum, generating 1.85 Mt E-wastes has been estimated in 2016 (ASSOCHEM

Table 4.1 Laws and regulations related to E-waste management in China (MEP, 2003, 2007, 2009; MIIT, 2006; Yang et al., 2008; Streicher and Yang, 2007).

Regulations	Status/ date	Major contents
Notification on Importation of the Seventh Category Waste	February 1, 2000	Ban on the import of the seventh category of waste
The circular on strengthening environmental management of waste electrical and electronic equipments (WEEE)	August 26, 2003	Prohibit the environmentally harmful processing of WEEE; encourage electronic product manufacturers to promote cleaner production and eco-design
The Ordinance on Management of Prevention and Control of Pollution from Electronic Information Products [The Ministry of Industry and Information Technology (MIIT), 2006]	November 6, 2006	Aims to reduce the utilization of hazardous and toxic substances in electronic appliances as well as the pollution generated due to the manufacture, recycling and disposal of these products. It is the counterpart of the EU RoHS directive, including requirements for eco-design; restrictions on the use of six hazardous substances
The Technical Policy on Pollution Prevention and Control of WEEE (MEP)	April 27, 2006	Set forth the guiding principles of “3R” and “polluter pays principle”; stipulates the general provisions of eco-design, the information disclosure of products, and provisions environmentally sound collection, for the reuse, recycling and disposal of WEEE
The ordinance on management of prevention and control of pollution from electronic and information products (MIIT)	March 1, 2007	Requirements for eco-design; restrictions on the use of hazardous substances; requirements for producers to provide information about their products
Administrative measure on pollution prevention of waste electrical and electronic equipments (MEP)	February 1, 2008	Intend to prevent the pollution caused during the disassembly, recycling and disposal of E-waste; specifies responsibilities of relevant parties and the licensed scheme for E-waste recycling companies
Circular economy law	January 1, 2009	Specify provisions on reduce, reuse and recycle (3R) of electronic products during the production, consumption and other processes

(*Continued*)

Table 4.1 (Continued)

Regulations	Status/ date	Major contents
Regulation on management of the recycling and disposal of waste electrical and electronic equipments	January 1, 2011	Mandatory recycling of WEEE; implementation of extended producer responsibility; establish of a special fund to assist E-waste recycling; certification for second hand appliances, and recycling enterprises

India report 2016). However, the volume coming from OECD countries contributes 50%−60% of the total E-waste in India that makes its precise quantification a difficult task (Borthakur and Sinha, 2013; Pathak et al., 2017). Mumbai (1.2 Mt) tops in the list, while Delhi-NCR (98,000 t), Bangalore (92,000 t), Chennai (67,000 t), Kolkata (50,000 t), Ahmedabad (36,000 t), Hyderabad (32,000 t), and Pune (25,000 t) are the major metro city in the list (The digital dump, 2013). The main designated E-waste and their generation in India are given in Table 4.2. It has been understood that a rapid economic growth with enhanced purchasing capacity of the expanded middle-income urban society gives exponential rising to E-waste generation. Adopting a predictive mathematical modeling, Pathak et al. (2017) quantified the two most sellable electronic items of the Indian market, computers and mobile phones. It has been found that the E-waste volume of computers will continue to increase until 2022, thereafter, slowly reaching a saturation point by 2028. On the other side, no saturation point could be observed for the E-waste from mobile phones.

Looking at such scenario of E-waste generation and its reported adversity to the sustainability, India has drawn a legislative frame to overcome from this problem. The chronological developments in the legislative framework of E-waste management are summarized by Pathak et al. (2017), which clearly depicts that it took three decades to come with an E-waste specific legislation, E-waste Management Rule 2016. After introducing the extended producer responsibility (EPR) in 2010, the responsibilities of manufactures and refurbishers are incorporated in 2016 (Pathak et al., 2017, 2019).

The advent of E-waste legislation has increased the awareness for its management, and hence, some collection centers, organized recycling companies, and local body's society have started to emerge albeit yet contributing small. Reducing the E-waste volume and recovery of valuable and critical metals are the benefits of recycling are being practiced by several recyclers in organized and scientific manner like Recyclekaro.com, E-Parisaraa, E-waste Recycling India, and Green India E-waste & Recycling Opc Pvt. Ltd. It has been considered a positive but slow start due to still handling of 90% E-waste by the unorganized sector, employing 0.5 million child workers in India (http://assocham.org/newsdetail.php?id = 4633Assocham%20/).

Table 4.2 Types and generation of WEEE in India (Pathak et al., 2017).

E-waste type		Households	IT and communication equipments	Consumer electronics	Total E-waste generation in India (Mt/year)
Description of items included		LCD/plasma TVs, air conditioners, refrigerators, washing machine, microwave oven, and mixture grinder	Monitors, printers, keyboards, central processing units, typewriters, mobile phones, chargers, remotes, compact disks, headphones, batteries, and semiconductors	DVDs and players, video games, iPods, and remote control cars	
E-waste (Mt/year)	2012	0.07	0.35	0.02	0.44
	2014	0.20	1.04	0.07	1.30
	2016	0.28	1.48	0.09	1.85
	2018	0.39	2.09	0.13	2.61
	2020	0.50	2.65	0.17	3.31

Most of the unorganized recycling activities are going on either within the metro cities or, in the nearby smaller towns (Dwivedy and Mittal, 2012).

4.2.3 Brazil

Brazil is the second largest E-waste producer among the American countries. Currently, Brazil produces 1.5 Mt E-wastes, just behind the United States of 6.3 Mt. It was only 0.67 Mt in last decade, mostly in the form of televisions, mobile phones, radios, computers, refrigerators, and washing machines. As estimated, the average per capita E-waste generation in between the years 2001–30 is above 3.4 kg that may require the disposal of an accumulative volume of ~25 Mt of E-waste by 2030.

The increasing volume of E-waste has caused for the concern regarding its proper management, and a national law "Law of the Garbage" has been introduced by stating everyone's responsibility for concerning on E-waste generation. This applies to manufacturers, retails, government organizations and officials, and end-user as well. The Federal Law No. 12.305 approved on August 2010 by the National Solid Waste Policy, ensures a proper treatment of E-waste. The State law (No. 13.576) enacted in São Paulo in July 2010 ensures the procedures responsibility for the formal treatment of E-waste that includes recycling, management, and disposal. Including the principle of shared responsibility (PSR) on the life cycle of EEE, the regulatory framework has recognized the solid waste as the reusable and recyclable waste. However, in Sao Paolo and on the federal level strong opposition from producers was reported (Silva et al., 2008).

Moreover, E-waste has been taken as an economic asset with societal value due to the ability of job creation. Under the umbrellas of federal and state laws, Brazil has specialized E-waste management companies. Ecobraz (specialized in collection and recycling of obsolete electronics), Reciclagem Brasil (specialized in providing E-waste a proper destination for recycling), CEDIR (sends E-waste to recycling companies), Coopermiti (offers management, processing, and recycling of E-waste in cooperation with the Prefeitura Municipal de Sao Paulo), Descarte Certo (offers collection and recycling services at large scale), Estre (recycles all kind of E-waste), Lorene (operates in all part of E-waste treatment), RecicloMetais (provides E-waste treatment at all stages), and Recicladora Urbana (offers reverse logistics and waste management services) are the major players in this field (https://techin-brazil.com/e-waste-management-in-brazil). Once collected, the E-waste goes through a dismantling process for individual classification of each component. Thereafter, the recycling companies do processing for recovering the raw materials like plastics, metals, wires, and cables, while neutralizing the hazardous substances through specific chemical processing.

4.2.4 Argentina

E-waste is also an increasing concern in Argentina that is growing with the pace of technological advancements. A 2.5 kg E-waste per inhabitant is estimated to generate on yearly basis in Argentina, which reflects the generation of a total 0.1 Mt E-waste per year. Approximately 25% of which is belonging to obsolete and telecommunications and computers. Similar to others, the recycling rate of E-waste is also very poor in Argentina that is accounted only a 2% of the total amount of E-waste generated per year. The participation of governmental organization is also very limited to less than 5% of the total amount of E-waste processed. This situation becomes more alarming when the white goods and other consumer electronics are included, which gives the E-waste generation data 7.8 kg/inhabitant for the year 2018 (https://www.statista.com/statistics/727725/ewaste-generation-argentina/). In lacking a specific law on E-waste regulation, Argentina has a robust informal sector for the management E-waste, and recycling is majorly controlled by the social marginal and unemployed groups (https://www.giswatch.org/country-report/2010-icts-and-environmental-sustainability/argentina). E-scrap, EcoGestionar, Scrapy Rezagos, Silkers, and Ecotech are a few names involves in the formal recycling of E-waste in Argentina. Some NGOs works for the refurbishing of computers for charity purposes, while a few operates for the takeback program of obsolete or UEEE, hence, their significant volumes end-up in the municipal waste.

In accordance with the article 41 of the constitution that "all inhabitants have the right to a healthy, balanced environment, suitable for human development" and "the prohibition of entry of actual or potentially hazardous waste into the country" is promised. In absence of EPR-type legislation, Argentina looks E-waste problem in the frameworks of Basel Convention and Mercosur agreement on an environmental management policy for universally generated special wastes and postconsumption responsibility (First Extraordinary Meeting of Environmental Ministers, 29 March, Curitiba, Brazil). Presenting a paradox while keeping the country from becoming a dump-yard of E-waste, the possibility of local enterprises expansion and prevention of E-waste disposal are also hindered. Hence, a national plan on integrated E-waste management in 2005 by ratifying the Basal Convention, and guiding principles on E-waste management for the companies were initiated, but bills pending in the legislature lost parliamentary status (Silva et al., 2008; www.rezagos.com/descargas/Proyecto-Ley-RAEE.pdf; www.rezagos.com/descargas/ProyectoLeyRAEE-UTN.pdf).

4.2.5 Nigeria

Nigeria is also a favorite dumping yard of the E-waste generated by developed countries. The awareness and action in regulatory bodies among the major Asian destination countries China, India, and Pakistan has also caused an increased flow of E-waste to Nigeria. Again in the name of UEEE, Nigeria received 66,000 t of old computers, televisions, and monitors during the year 2015–16. Out of which, approximately 16,900 t of UEEE was already in not-working condition (https://www.ehn.org/how-much-e-waste-is-shipped-to-nigeria-2561214315.html). An interesting study has reported that despite the stringent laws in EU for E-waste trades, around 70% of the total E-waste in Nigeria is coming from Europe. In most of the cases, it is kept inside the old vehicles to trespass E-waste to Nigeria (http://collections.unu.edu/eserv/UNU:6349/PiP_Report.pdf; https://motherboard.vice.com/en_us/article/59jew8/e-waste-smuggling-nigeria).

In such way E-waste reached Nigeria (specifically at the Lagos seaport), the brokers/importers provide the passage for the illegal entry under the umbrella of Computer and Allied Product Dealer Association of Nigeria (CAPDAN, a regulatory body coordinating the affairs of IT industry) (https://ejatlas.org/conflict/e-waste). The importers purchasing containers by its weight, and after shorting the good working gadgets for repairing/refurbishing they are sold either in the Ikeja Computer village or, Alaba International market. The nonworking gadget are directly sent to land-fills spread around the city but officially goes to Lagos Olusosun, Igodun, and Ikorodu dumpsites (Babatunde, 2016; Ideho, 2012). There several thousand individual workers are living on or next to dumping yards, including minor children involved in the collection, sorting, dismantling, and metal stripping from the E-waste. They either directly deal with smelter/refineries or, sell to middle-man. Such informal practice causing the environmental and health loss and creates disputes between individual groups of scavengers. Besides this, the domestic E-waste generation rate of Nigeria is also high albeit that is also largely contributed by the EoL-UEEE. The life of repaired/refurbished mobile phones in Nigeria extends up to 7 years. But at the cost of twice a year replacement of batteries and chargers that generates an additional amount of E-waste, estimated to be more than 1 Mt (Nnorom and Osibanjo, 2008).

Looking at the vulnerable situation, Nigeria has approved the opening of its first formal E-waste recycling plant operated by Hinckley Recycling at Ojota in Lagos state (https://www.dailytrust.com.ng/nigeria-gets-first-e-waste-recycling-facility.html). Although Nigeria does not have potent enforcement of specific regulations on E-waste management (Nnorom and Osibanjo, 2008), the move is an appreciative one. Recently, it has implemented the National Environmental Regulations (Electronics Sector) that explicitly prohibits only the trade of unusable electronic goods.

4.3 Policy comparison between developed and developing countries

Although a slow rate of technological advancement in the developing countries, they are currently consuming the EEE at a faster rate than the developed countries. Therefore they also produce more E-waste, might be in doubled amount than the developed countries (Garlapati, 2016). For example, the discarded units of obsolete computers by developing and developed countries is estimated to be 400−700 million and 200−300 million, respectively, by 2030 (Sthiannopkao and Wong, 2013). But in lack of the proper rules and regulations, the developing countries are facing several-folds higher challenges than the developed countries. Therefore their comparison is worthy to discuss.

4.3.1 Comparison of rules and policies

A comparison of legislative policies between the developed and developing countries is summarized in Table 4.3. Nevertheless, many of the developing countries have started to prepare and enacted their specific policy on E-waste management, the developed countries are one step ahead due to the strict implementation of legislations.

In developed countries, the national registry system, along with the proper collection and logistics system is very strong (Sthiannopkao and Wong, 2013). The Avoidance of Packaging Waste of Germany is the first mandated EPR program that put financial obligations on manufacturers for collection and reduction of packaging waste (Ongondo et al., 2011; Van Rossem et al., 2006). Later, it is adopted and extended to EEE manufacturer by Sweden, Norway, Taiwan, and Switzerland. The EU legislation restricting the use of hazardous substances in EEE and WEEE/E-waste (Directive 2002/95/EC, the RoHS Directive), and promoting their collection and recycling (Directive 2002/96/EC), has been enacted in 2003 (EU RoHS Directive 2002/95/EC). Currently, the legislations in China and India have clearly implemented the EPR system in lacking of a national registry that keeps track of the produced EEE for the purpose of eventual manufacturer take-back, the generation of E-waste is difficult to trace. The big gray markets available for the second-hand UEEE in these countries is also making situation vulnerable, while comparing

Table 4.3 A comparative legislation/regulations in the developed and developing countries for dealing with E-waste (Pathak et al., 2017).

Developed countries	**Developing countries**
The United States: Responsible electronics recycling act came in 2011. Banned the export of WEEE item: PCs, TVs, printers, xerox, phones, CRTs, batteries, containing Pb, Cd, Hg, Cr, Be, and organic solvents	*China*: Restriction on junk electrochemical products and electrical items mainly for copper recycling. Catalog of restricted imports of solid wastes, 2008
The United Kingdom: Under EU directives in 2007. Adopted the EU directives	*India*: Import policy under 2005. Further, transboundary moment and EPR were introduced in E-waste rule 2011. Provided a strategy and method for treatment of E-waste
Belgium: Directive 2002/96/EC on WEEE, 2002. The Public Waste Agency of Flanders controls the waste management and responsibility of producer	*Pakistan*: Import policy order, 2009. Banned the import of refrigerator and air conditioners, and CRT can be imported only with used computers
France, Germany and the Netherland: Under EU directives in 2005. Limited use of toxic materials by the producers; collection and processing of used electronics by distributors and municipalities; France introduced an "eco-cost" for treating WEEE	*Thailand*: Criterion for import of used EEE (UEEE), 2007. Control on the classified UEEE
Japan: Law for the Control of export, import, and others of specified hazardous and other wastes. Export prohibited without consent from the import country	*Vietnam*: Law on environmental protection, 2005. Prohibits the movement of hazardous waste from abroad stipulates responsibilities for waste generator
Norway: The revised EU directives, 2006. A WEEE register established with mandatory membership for every producer and importer of an approved take-back company	*Nigeria*: Guide for importers of UEEE into Nigeria, 2011. Import of WEEE banned with a compulsory registration of importers
South Korea: Showed restriction on export, without consent from the importing country. They have transboundary movement act on hazardous wastes and their disposal	*Hong Kong*: Advice on movement of used EEE, 2011. Legislative control on used EEE

it to the developed countries (Pathak et al., 2017). Among the major destination countries in Asia (China, India, and Pakistan), the domination of informal and private players are a major bottleneck to inventoried the E-waste in these countries (Abbas, 2010; Jain, 2010; Kurian, 2007). Although these countries have a lower labor costs, the large rate of E-waste generation (through both import and domestic production), the transportation cost, and above all the costlier technology for its benign disposal, presents hurdles despite the enactment of environmental regulations. Henceforth, the informal sector keeps growing to handle the majority of E-waste in developing countries.

4.3.2 Socio-economic factors of defendants

The socio-economic factors play vital role in building up policies on E-waste. It is highly dependents on the materials' market price, its weight therein the product, volume of E-waste generation and recycling rate along with the cost of recycling and purity of the recovered material, and environmental benignness of the process (Cucchiella et al., 2015). The recycling of E-waste has been found economic feasible (Azevedo et al., 2017); however, the contribution by the informal sector to the major steps of collection, screening, and treatment causes serious issues on environment and human health. In developing countries, the rag pickers are unavoidable part of recycling practices but practicing without safety measurements. For the sake of little benefits, their life is put in danger. Hence, the earning by these malpractices cannot be allowed on a larger benefit of the society and demands for a sustainable recycling practice through the regulatory bodies.

4.3.3 Environmental consequences

E-waste is a complex mixture of several heavy and hazardous metals (including Cu, Fe, Ni, Co, Pb, Cd, Cr, Au, Ag, and Pd) along with the plastics and ceramics whose composition changes with its manufacturing time (Robinson, 2009). Plenty available studies on the contamination caused by E-waste to the soil, water, and air at recycling or landfill sites have established the hazardous and toxic nature of E-waste (Borthakur and Singh, 2017; Williams, 2011). Moreover, the malpractices by informal recycling is making the situation worst in the developing countries like Nigeria, India, Ghana, China, Thailand, Vietnam, Pakistan, Indonesia, and Bangladesh. The open burning of wire piles, melting of circuit boards, and discard of metal bearing acidic solutions are in usual practice (Borthakur and Singh, 2017). The concentrations of hazardous organic compounds polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) have found to be increased in the air and water and show adverse impact on environment and human health (refer Table 4.4). Through which, it reaches to our food chain and directly affecting the human health (Tue et al., 2014, 2016; Luo et al., 2011).

4.4 Proposed sustainable E-waste management in developing countries

Reverse logistics has been actively implemented to bring sustainability in the developed countries, which is now followed by the developing countries. Three major steps of the reverse logistic for E-waste recycling are (Tsydenova and Bengtsson, 2011) as below.

Table 4.4 Environmental and health consequences due to E-waste recycling (Chen et al., 2011; Ilankoon et al., 2018; Pathak et al., 2017).

Pollutants	Sources	Environmental consequences	Health impact
Pb	PC monitors, batteries, PCBs, light bulbs, lamps	Degrade the soil fertility	Can cause intellectual impairment in children, anemia, and kidney damage
Cd	Rechargeable computer batteries, older CRTs, PCBs, Ni-Cd batteries, infrared detectors, semiconductor chips, ink or toner photocopying machines, and mobile phones	Highly toxic and bioaccumulation occurs in the environment	Affects kidneys and bones, reproductive damage, and lung emphysema
Be	Power supply boxes, computers, x-ray machines, and ceramic components of electronics	Adverse impact on environment	Affect liver, kidneys, heart, nervous system, lymphatic system, and develop beryllium sensitization
Hg	Lighting devices for flat screen displays, CRTs, PCBs, thermostats, monitors, and cold cathode fluorescent lamps	Contaminant soil, air, and water, and bioaccumulation occurs	Damage the central nervous system, anemia, and kidney damage
Cr	Production of metal housings (anticorrosion coatings), data tapes, and floppy disks	Highly toxic, causes severe water pollution	Carcinogens, affects the reproductive and endocrine functions
Ba	CRTs (2%–9% Ba), fluorescent lamps	Get accumulated in soil, water, and plants	Low blood potassium, cardiac arrhythmias, respiratory failure, dysfunction, and paralysis

(*Continued*)

Table 4.4 (Continued)

Pollutants	Sources	Environmental consequences	Health impact
POPs	Used in circuit boards, plastic casings of computers, lubricants and coolants in generators, fluorescent lighting, ceiling fans, electric motors, connectors, and mobile	Bioaccumulation in the environment (very resistant to break down) and air pollution	Neurotoxicity, long-term exposure can lead to impaired learning and memory functions interfere with thyroid and estrogen hormone systems
PVC	For insulation on wires and cables	Incineration produces chlorinated dioxins and furans, which are highly toxic even in very low concentrations, persist long in the environment	Cause pulmonary dysfunctions and lung damage

1. Disassembly: Selective disassembly target hazardous or valuable components for special treatment.
2. Upgrading: Mechanical processing and/or metallurgical processing to increase the content of desirable materials.
3. Refining: purifying the recovered materials using chemical (metallurgical) processing to make them acceptable for the original use.

On the other hand, developing countries are struggling to cover all recommended steps of recycling and disposal due to the limited availability of infrastructure, technological access, and investments. Henceforth, implementation of Best-of-2-Worlds (Bo2W) principle that provides a network and pragmatic solution for E-waste treatment can boost the emerging economies in developing countries (Nnorom and Osibanjo, 2008). Fig. 4.2 depicts the installation for collection center and screening center by municipalities based on the number of inhabitants. It looks for technical and logistic integration of best preprocessing in the developing countries to dismantle E-waste manually and best end-processing to treat hazardous and complex fractions in international state-of-the-art end-processing facilities. Besides, environment cleaner production design, EPR, standards and labeling, product stewardship, recycling, and remanufacturing are some of the good practices adopted by various countries to deal with the E-waste caused problems and bringing up the sustainability (Azevedo et al., 2017). These practices inspire the government/nongovernmental organizations, researchers, and academicians to propose the sustainable some models for E-waste management.

Figure 4.2 Proposed model for government guidelines, collection center (cc), and screening center (sc) (Azevedo et al., 2017).

4.4.1 Proposed mathematical model

Most of the developing countries have the potential to utilize and manage the EEE/UEEE and generated E-waste. Several sustainable and mathematical models have been proposed in this direction (Azevedo et al., 2017; Pathak et al., 2017). 3-R representing the "reduce-reuse-recycle" model for E-waste management (Habib et al., 2015; Parajuly et al., 2017), while for specifying the need and importance of recycling Pathak et al. (2017) have presented a schematic flow of EEE and E-waste (as shown in Fig. 4.3). The description of each process is given in Table 4.5. The flow of the model indicates a positive effect of proper collection and recycling that mitigating the global environmental impacts. However, based on the present scenario of developing countries, a quick shift from informal to formal sector is not easy, therefore formal sector alone cannot display the desired result and indicating for they work together in an integrative manner.

4.4.2 Circular economy

The circular economy is another concept which is able to slow down the rate of EEE consumption by circulating them within the system for the longest possible time and minimizing/eliminating the E-waste generation through smarter product design and business model (Parajuly et al., 2017). It is also involved multi-R system (including reduce, reuse, refuse, recycle, recovery, rethinking, and redesign) that emphasize the social, environmental, and economic aspects (https://www.unido.org/sites/default/files/2017-07/Circular_Economy_UNIDO_0.pdf). The circular economy principle is embedded in the Indian E-waste management rule 2016 and also fulfill the requirement of sustainable development goals of UNIDO 2015. The concept of a circular economy in E-waste management is shown in Fig. 4.4. However, various barriers like technological advancements, poor collection system, need for finance and involvement of private sector, training to the informal sector, the

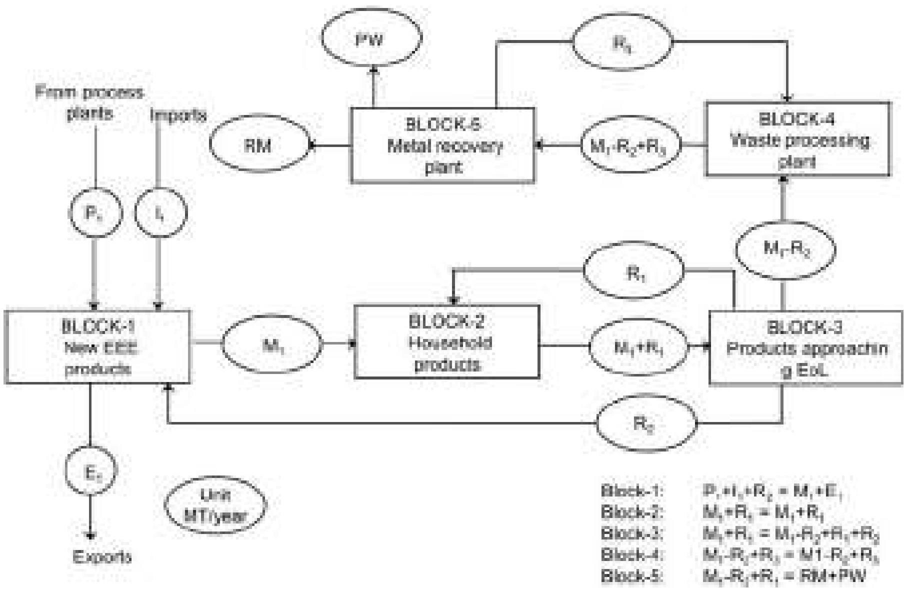

Figure 4.3 Sustainable management model for electrical and electronic equipments (Pathak et al., 2017).

Table 4.5 Estimation of sustainability for E-waste recycling in India, contributed by the formal and informal sectors (Pathak et al., 2017).

Process	Description
Block-1	New EEE product comes to the market
Block-2	Household used product
Block-3	Products approaching EoL
Block-4	Waste processing plant
Block-5	Metal recovery plant
E_1	Exported EEE
I_1	Imported EEE
M_1	New EEE
M_2	EoL completed EEE
R_1	EEE with uncompleted EoL to be reused
R_2	Consumer sending the unused EEE to second hand market
R_3	Metal recycling (formal and informal) of WEEE
RM	Recovered metals
PW	Potential waste

volatile market for recovered materials through the recycling of E-waste have been identified by different researchers (Balde et al., 2017). Keeping in view, it is recommended that the informal sector especially rag pickers should get advance training for collection, dismantlers, and refurbishers, provide incentives and financial support to

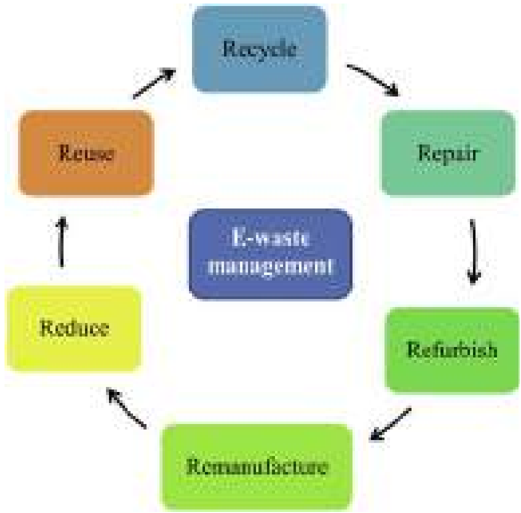

Figure 4.4 Circular economy for E-waste.

attract private sector participation, strict regulations for E-waste imports, monitoring and enforcement of existing regulations, international collaborations, and decentralized E-waste repair/refurbish initiatives. This initiative can be a panacea to build the sustainable E-waste model.

4.5 Conclusions

E-waste is a greater challenge for the sustainability of developing countries, which receives the larger part of this hazards from the developed countries. It is much needed that the developing countries follow the legislative frameworks of developed countries to enact the E-waste specific policies and try to effectively manage this problem of the globe. The control of E-waste flow mostly in the name of UEEE needs an urgent call as the developing countries themselves are generating more domestic E-waste than developed countries. This problem in countries like China, India, Pakistan, Nigeria, Brazil, and Argentina is more serious because a good share of the economy depends on the informal business of E-waste. The discussed cases and current scenario of the E-waste management system and policies of these countries tells about the growing awareness in this field but it is very slow. Only a few developing countries could yet able to establish their own E-waste policy. However, several models on the sustainable management of E-waste have been given but as per the current scenario, negligence of the informal sector is not possible. It has been analyzed that a significant reduction in the E-waste disposal can be obtained in near future only if formal and informal sectors work together to practice an integrative recycling and this practice may lead toward the circular economy.

References

Abbas, Z., 2010. E-waste management in Pakistan. Regional Workshop on E-waste/WEEE Management, Osaka, Japan, July 6−9.

Azevedo, L.P., Gabriel da Silva Araujo, F., Lagarinhos, C.A.F., Tenorio, J.A.S., Espinosa, D.C.R., 2017. E-waste management and sustainability: a case study in Brazil. Environ. Sci. Pollut. Res. Available from: https://doi.org/10.1007/s11356-017-0099-7.

Babatunde, B.I., 2016. Assessment of e-waste in Ikeja local government area of Lagos state. Ph.D. Dissertation. Department of Urban and Regional Planning, Faculty of Environmental Science, Ladoke Akintola University of Technology, Ogbomoso, Oyo State.

Balde, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-Waste Monitor − 2014. United Nations University, IAS − SCYCLE, Bonn, Germany.

Balde, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-Waste Monitor: 2015. United Nations University, Institute for the Advanced Study of Sustainability−Sustainable Cycles (IAS-SCYCLE), Bonn, Germany.

Basel Action Network (BAN) & Silicon Valley Toxics Coalition (SVTC), 2002. Exporting harm: the high-tech trashing of Asia. Seattle & San Jose, <http://www.svtc.org/site/DocServer/technotrash.pdf?docID = 123> (accessed 15.06.18.).

Borthakur, A., Singh, P., 2017. Researches on informal e-waste recycling sector: it's time for a 'Lab to Land' approach. J. Hazard. Mater. 323, 730−732.

Borthakur, A., Sinha, K., 2013. Generation of electronic waste in India: current scenario, dilemmas and stakeholders. Afr. J. Environ. Sci. Technol. 7, 899−910.

Bridgen, K., Labunska, I., Santillo, D., Allsopp, M., 2005. Recycling of Electronic Waste in China and India: Workplace and Environmental Contamination. Greenpeace International, Amsterdam.

Chen, M., Zhang, F.S., Zhu, J., 2011. Leaching toxicity of Pb and Ba containing in cathode ray tube glasses by SEP-TCLP. In: Zhang, L., Krumdick, G.K. (Eds.), Recycling of Electronic Waste II, Proceedings of the Second Symposium, TMS. The Minerals, Metals & Materials Society.

Cucchiella, F., D'Adamo, I., LennyKoh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renewable Sustainable Energy Rev. 51, 263−272.

Driscoll, A., Shiheng, W., 2010. Poverty or poison: China's dire choice in an electronic world. <http://www.vermontlaw.edu/Documents/Driscoll%20WU,%20Poverty%20or%20Poison.pdf> (accessed 28.09.18.).

Dwivedy, M., Mittal, R.K., 2012. An investigation into e-waste flows in India. J. Clean Prod. 37, 229−242.

EU RoHS Directive 2002/95/EC, 2003. <http://eur-lex.europa.eu/homepage.html> (accessed 16.08.18.).

Garlapati, V.K., 2016. E-waste in India and developed countries: management, recycling, business and biotechnological initiatives. Renew. Sustain. Energy Rev. 54, 874−881.

Green Peace-Basel Action Network, 2004. Key finds from Taizhou field investigation. <http://www.ban.org/Library/Taizhou E-waste Research Report.pdf> (accessed 28.04.18.).

Habib, K., Parajuly, K., Wenzel, H., 2015. Tracking the flow of resources in electronic waste − the case of end-of-life computer hard disk drives. Environ Sci Technol. 49, 12441−12449.

Heeks, R., Subramanian, L., Jones, C., 2015. Understanding e-waste management in developing countries: strategies, determinants, and policy implications in the Indian ICT sector. Inf. Technol. Dev. 21, 653−667.

Hicks, C., Dietmar, R., Eugster, M., 2005. The recycling and disposal of electrical and electronic waste in China: legislative and market responses. Environ. Impact Assess. Rev. 25, 459−471.

Ideho, B.A., 2012. E-waste management: a case study of Lagos State, Nigeria. Social and Public Policy Master's Programme in Development and International Cooperation, Department of Social Sciences and Philosophy, University of Jyväskylä, Finland, Autumn.

Ilankoon, I.M.S.K., Ghorbani, Y., Chong, M.N., Herath, G., Moyo, T., Petersen, J., 2018. E-waste in the international context − a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manag. 82, 258−275.

Jain, A., 2010. E-waste management in India: current status, emerging drivers and challenges. Regional Workshop on E-Waste/WEEE Management, Osaka, Japan.

Kurian, J., 2007. Electronic waste management in India: issues and strategies. In: Eleventh International Waste Management and Landfill Symposium. Calgari, Italy, pp. 1−5.

Leung, A., Cai, Z.W., Wong, M.H., 2006. Environmental contamination from electronic waste recycling at Guiyu, southeast China. J. Mater. Cycles Waste Manag. 8, 21−33.

Luo, C.L., Liu, C.P., Wang, Y., Liu, X.A., Li, F.B., Zhang, G., et al., 2011. Heavy metal contamination in soils and vegetables near an e-waste processing site, south China. J. Hazard. Mater. 186, 481−490.

Ministry of Environmental Protection (MEP), 2003. The circular on strengthening the environmental management of waste electrical and electronic equipment. <http://www.mep.gov.cn/gkml/zj/wj/200910/t20091022 172222.htm> (in Chinese) (accessed 18.08 18.).

Ministry of Environmental Protection (MEP), 2007. Administration of environmental pollution control and management of WEEE. <http://www.mep.gov.cn/info/gw/juling/200709/t20070928 109698.html> (in Chinese) (accessed 19.08.18.).

Ministry of Environmental Protection (MEP), 2009. Ordinance on the management of waste household electrical and electronic products. <http://www.sepa.gov.cn/law/fg/xzhg/200903/t20090305 134909.html> (in Chinese) (accessed 19.08.18.).

Ministry of Industry and Information Technology (MIIT) of China, 2006. The ordinance on management of prevention and control of pollution from electronic information products. <http://www.miit.gov.cn/n11293472/n11294912/n11296542/12165064.html> (in Chinese) (accessed 20.08.18.).

Nnorom, I.C., Osibanjo, O., 2008. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour. Conserv. Recycl. 52, 843−858.

Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manage. 31, 714−730.

Parajuly, K., Habib, K., Liu, G., 2017. Waste electrical and electronic equipment (WEEE) in Denmark: flows, quantities and management. Resour. Conserv. Recycl. 123, 85−92.

Pathak, P., Srivastava, R.R., Ojasvi. 2019. Environmental Management of e-waste, Electronic Waste Management and Treatment Technology, Elsevier.

Pathak, P., Srivastava, R.R., Ojasvi, 2017. Assessment of legislation and practices for the sustainable management of WEEE in India. Renew. Sustain. Energy Rev. 78, 220−232.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183−191.

SEPA, 2011. Recycling and Disposal of Electronic Waste: Health Hazards and Environmental Impacts. Stockholm.
Silva, U., Ott, D., Boeni, H., 2008. E-waste recycling in Latin America: overview, challenges and potential. In: Global Symposium on Recycling, Wste Treatment and Clean Technology, Cancun.
Sthiannopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci. Total Environ. 463, 1147–1153.
Streicher, P.M., Yang, J.X., 2007. WEEE recycling in China: present situation and main obstacles for improvement. In: Proceedings of the 2007 International Symposium on Electronics and the Environment. pp. 40–45.
Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31, 45–58.
Tue, N.M., Katsura, K., Suzuki, G., Tuyen, L.H., Takasuga, T., Takahashi, S., et al., 2014. Dioxin-related compounds in breast milk of women from Vietnamese e-waste recycling sites: levels, toxic equivalents and relevance of non-dietary exposure. Ecotoxicol. Environ. Saf. 106, 220–225.
Tue, N.H., Goto, A., Takahashia, S., Itai, T., Asante, K.A., Kunisue, T., et al., 2016. Release of chlorinated, brominated and mixed halogenateddioxin-related compounds to soils from open burning of e-waste in Agbogbloshie (Accra Ghana). J. Hazard. Mater. 302, 151–157.
Van Rossem, C., Tojo, N., Lindhqvist, T., 2006. Extended producer responsibility: an examination of its impact on innovation and greening products, <http://www.greenpeace.org/raw/content/international/press/reports/epr.pdf/> (accessed 26.09.18).
Williams, E., 2011. Environmental effects of information and communications technologies. Nature 479, 354–358.
Yang, J.X., Lu, B., Xu, C., 2008. WEEE flow and mitigating measures in China. Waste Management 28, 1589–1597.
Yu, J., Williams, E., Ju, M., Shao, C., 2010. Managing e-waste in China: policies, pilot projects and alternative approaches. Resour. Conserv. Recycl 54, 991–999.
Zhang, J.H., Min, H., 2009. Eco-toxicity and metal contamination of paddy soil in an e-waste recycling area. J. Hazard. Mater. 165, 744–750.

Further reading

ASSOCHAM India, 2016. India to sit on e-waste pile of 30 lakhs MT with Mumbai on top of heap: ASSOCHAM-Frost & Sullivan Study. <http://www.assocham.org/newsdetail.php?id = 5642/> (accessed 10.09.18.).
Geoff Iyatse, 2016. Mounting e-waste adds to Nigeria's health problems, Punch. <https://punchng.com/mounting-e-waste-adds-to-nigerias-health-problems/>.
The Associated Chambers of Commerce & Industry of India, 2014. <http://assocham.org/newsdetail.php?id = 4633Assocham%20/> (accessed 20.10.18.).
The Digital Dump, 2005. Exporting high-tech re-use and abuse to Africa. Basal Action Network, <http://archive.ban.org/films/TheDigitalDumpTrailer.html/> (accessed 08.12.18.).
Zeng, X., Duan, H., Wang, F., Li, J., 2017. Examining environmental management of e-waste: China's experience and lessons. Renew. Sustain. Energy Rev. 72, 1076–1082.

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E-waste as a challenge for public and ecosystem health

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5.1 The composition, fate, and toxic compounds in E-waste

Recently, the use of electrical and electronic items has been escalated rapidly with the growing importance of information and communication technology to the world economy. However, simultaneously, the life span of those items was reduced along with the drastic changes in features and the capabilities of the electronic and electrical items (Nnorom and Osibanjo, 2008). As a cumulative result of these occurrences the amount of end-of-life electronics and electrical items known as E-waste has been increased steadily. The approximate estimates highlight the average annual global E-waste volume is about 65.4 million tons in 2017 (Alabi and Bakare, 2017). Most of the world's E-waste is from Asian region and during 2014 and it was about 16 metric ton with representing 3.7 kg/inhabitant. However, in the means of waste quantity per inhabitant, the Europe is in the climax with 15.6 kg/inhabitant while in total with 11.6 metric tons (Bob et al., 2017). Developed countries play the leading role on production of E-waste compared to developing and poor countries. The studies show the United States and China are the leading E-waste producers in 2014 with approximately 32% from global E-waste production followed by Japan, Germany, and India. About 80% of E-waste from developed countries are been transported to the developing and poor countries as they have lesser labor cost and minimum legislations (Awasthi et al., 2016). China, India, Pakistan, Nigeria, and Ghana are the top most countries that receive E-waste from developed countries and it is important to note that most of those exports are illegal (Awasthi et al., 2016).

The major substances in the E-waste are ferrous metal, nonferrous metal, glass, plastic, and others (Link, 2014). Iron and steel accountable for most common substances in E-waste by weight and plastics score as second. Mobile phones, personal computers (PCs), entertainment items such as MP3 players, computer games and peripherals, refrigerators, televisions, washing machines, stereo systems, dryers, toys,

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00003-6

toasters, kettles, and other household items are some of the common components that can be seen as E-waste and more of these products are ended up in landfills, rubbish dumps, and recycling centers creating several complications for waste management officials, policy makers, and residents (Bob et al., 2017). The figure becomes more problematic as the entering of E-waste into waste stream is accelerating continuously. Regarding PCs, about 20 million was expired and entered into the waste during 1994 and when it comes to 2004, the amount reached up to more than 100 million (Widmer et al., 2005). This fast growing nature of E-waste has obtained due to the global market for PCs is still away from saturation and the average life span of PCs is declining gradually. CPUs, for example, had 4−6 years of lifetime in 1997 and when in 2005, the lifetime has fallen to 2 years (Widmer et al., 2005). PCs mostly contain with plastic, Pb, Cd, and Hg and it has been calculated that 500 million PCs accommodate for about 2,872,000 ton of plastic, 718,000 ton of Pb, 1363 ton of Cd, and 287 ton of Hg (Widmer et al., 2005). However, mobile phones, calculators, PCs, printers, and other small information technology equipment only account for more or less 7% of E-waste in 2014 (Bob et al., 2017). These facts elaborate that the E-waste is one of the fastest growing and most complex types of solid wastes in this rapid growing economies (Bob et al., 2017).

The types of substances in E-waste can be categorized into two major categories according to their toxicity: hazardous and nonhazardous. Most of heavy metals, in particular, Cd, Cr, Pb and Hg, chlorofluorocarbon, polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and polychlorinated dibenzo-*p*-dioxin furans (PCDD/Fs) are some of the groups that fall into hazardous category. All of these compounds are able to affect the quality of the ecosystem and the improper E-waste handling is the foremost reason to these detrimental effects. There are various techniques that is being used regarding informal E-waste recycling techniques including gold recovery from printed circuit boards with cyanide salt leaching or nitric acid and mercury amalgamation, open burning of printed circuit boards that cables for component separation or for solder recovery, heating and acid leaching of printed circuit boards, toner sweeping, plastic chipping, and melting, burning of wires to recover copper, and manual dismantling of cathode ray tubes, and open burning of plastics (Song and Li, 2014). All of these nonsafe methods are able to generate harmful consequences on environment and human community. During dismantling processes, for instance, dioxins, persistent organic pollutants, PAHs, PCBs, persistent halogenated compounds, hexavalent chromium, PBDEs, and heavy metals are been released and these pollutants persist in the environment for long period of time (Orlins and Guan, 2016).

5.2 Impacts of E-waste on ecosystem health

The impact of E-waste is not limited for a recycling or dumping site and it extends beyond the processing sites creating possible adverse impacts to the whole ecosystem: soil, water, air, and other biota. It is reported that the effluents from E-waste

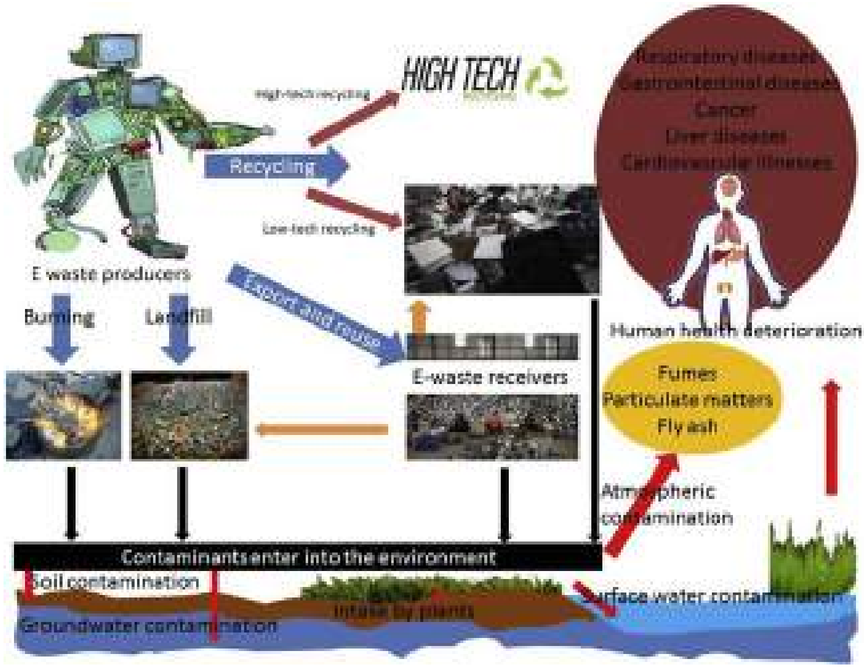

Figure 5.1 General cycling pathway of E-waste and their human and ecosystem impacts.

recycling centers and the dumping sites are rich with heavy metals and suspended particulate matters. The impact of E-waste is not same for all the time even for same E-waste product. The concentration of the contaminants in E-waste depends on the age of the particular E-waste product. Therefore composition of the E-waste is spatially and temporally heterogeneous. Fig. 5.1 shows the general cycling pathways and the ways that E-waste depletes the environment and the human health. Although the recycling is responsible to remove or delay the release of contaminants into the environment, large amount of contaminants may still accumulate in landfills and end up within the environment. It has been documented that the annual Cu production from E-waste is 820,000 and 5000 tons of Cu are annually release into the environment despite recycling (Robinson, 2009). PBDEs are mixed with plastics to form the flame retardants. However, there is no any chemical bond in between plastics and PBDEs and therefore, at the landfill sites and the recycling centers PBDEs may leach into the environment and it may create different human and ecosystem health impacts (Robinson, 2009). As such different contaminants from E-waste have the ability to deplete the quality of the ecosystems.

5.2.1 Impacts of E-waste on soil

Waste recycling centers are one of the most significant sources that affect soil quality as these sites are responsible to release metals and other contaminants with higher concentrations. However, the use of primitive methods to process E-waste is the major problematic reason to contaminate the soil due to E-waste (Awasthi et al., 2016). Most of E-waste dumping in landfills and the chemicals and toxic materials can easily harm to the nature of the natural soil (Dharini et al., 2017). The soil can be contaminated by either direct such as aerial contamination or indirect such as through irrigation processes and thereafter the plants will also be affected as the heavy metals like compounds are persisting for a longer time periods with their nonbiodegradable characteristics. Most of the times the waste from E-waste recycling centers release effluents to the open lands if there are no drain lines or open waters (Link, 2014). It is reported that most of these effluents are in acidic conditions and with having low acidic levels and higher contaminant content, these toxic pollutants become bioavailable state (Link, 2014). Moreover, the Ca contents of the water that coming from the E-waste recycling or dumping cites responsible for changing the pH of the natural soil. This may cause for nutrient depletion in the plants in the particular area (Dharini et al., 2017). Therefore not only creation of harmful health impacts but also the E-waste in soil can cause reduction of harvest in commercial agricultural systems. It may create long term impacts on country's economy. Except from the release of effluent into the open land, the recycling operations that are carried out on open soil also have significant impact for the deterioration of soil quality. It is important to note that Pb, Ba, and Cd have low or zero recycling efficiency and therefore, it is obvious to have higher metal concentrations in the discharges of the E-waste recycling centers which are able to contaminate the nearby soils with an unprecedented scale (Fu et al., 2008). For example, the soil samples that analyzed from nearby areas of E-waste recycling centers that located in Loni, India, has reported with extreme metal concentrations. Almost all the tested soil samples were above the safe concentrations and the highest Pb concentration was 174 times higher than the standards limits. Other than that Cd, Hg, Cr, and Zn have also found with exceeded concentrations in different percentages (Link, 2014). The containing of toxic elements in soil may create nutrient depletion in the plants. With the presence of toxic elements disturbs to the nitrogen absorption by plants. Nitrogen is an essential element for plants as it participates into the photosynthesis process and it is a major building block of the plant proteins. Therefore the contamination of soil by E-waste results the degradation of plant nutrient content (Dharini et al., 2017). Moreover, the studies have been showed that the soils that contaminated by E-waste are also in the deficiency of potassium which is an important component in plant growth and development (Dharini et al., 2017). Most of the E-waste recycling centers experiencing the same incidence as soil are the direct victim of releasing pollutants. In China, the former E-waste recycling centers are the places that have worst soil pollution status. It has been recorded that the metals in soil have greatly exceeded the standard levels and it has been recorded as 17.1 mg/kg of Cd, 11,140 mg/kg of Cu, 4500 mg/kg of Pb, and 3690 mg/kg of Pb. Most of the times the soil is receiving this much of metals due to burning of circuit boards or other metal chips (Luo et al., 2011). Notably, these contaminated statuses are also common to the agricultural lands that situated in nearby areas. Luo et al. (2011) show that the metal concentrations in agricultural soil have exceeded the maximum permissible levels and they warn that these situations are greatly affect agricultural crop production as well as the human population that consume those food items. Further, studies show that these metals are tending to fractionation within the soil and the highest percentages are reported with the residual fraction and the carbonate absorbed phases. The percentage of exchangeable fraction is comparatively low in E-waste contaminated soils. However, the percentage of this fraction in paddy and other agricultural soils are higher than that of the present and former E-waste recycling places (Luo et al., 2011). Therefore it poses higher threat to the whole ecosystem as the exchangeable fraction is responsible to pollute all other ecosystems especially aquatic environment and biota. As for Ni, Cd, and Zn specifically the exchangeable fraction is far higher than other metal fractions and therefore, the mobility of these metals are much greater than other metals and simultaneously their threat to the environment is also high (Luo et al., 2011).

5.2.2 Impacts of E-waste on aquatic ecosystems

Waste water is one of the major transport pathways regarding contamination of aquatic systems with E-waste (Brigden et al., 2005). It has been stated that the E-waste leachate contains several genotoxic and mutagenic substances (Alabi and Bakare, 2017) and most importantly, the underground water has received more mutagenic characters than raw leachate as the underground water table is the place where accumulation took place. Studies have shown that the quality of the water that coming from E-waste recycling and the processing centers do not meet the general water quality requirements in the means of pH, total dissolved solids, hardness, chlorides, and conductivity (Dharini et al., 2017). Apart from the direct contamination of aquatic ecosystems by E-waste leachate, deposition of dust particles that emitted from E-waste recycle or dumping sites also have the potential capability to contaminate the surface waters (Robinson, 2009). Studies show that the presence of dioxins, furans, PAHs, PCBs, and polybrominated diphenyls which are persistence toxins and heavy metals in E-waste have direct involvement with this mutagenesis nature and therefore aquatic organisms fall into a great danger. Moreover, studies show that considering the E-waste recycling cites the highest contamination next to the soil occurs at the pond or available aquatic ecosystems as most of the E-waste combustion processes are taken place at the presence of water source due to the requirement of continuous and easy supply of water for metal extraction processes (Luo et al., 2011). Therefore higher concentration of metals could be found from the water and the sediments. Other than that the most of the mismanaged E-waste recycling centers are tend to dump the waste near to water resources and eventually the pollutants from those E-wastes will be ended up in the aquatic environments (Luo et al., 2011). Nanyang River is one of the rivers that have contaminated with E-waste from different E-waste recycling centers in China and it has been revealed that the sediments have PBDE concentrations up to 16,000 ng/g (Luo et al., 2007b) and most importantly the carp fish from the river also have up to 766 ng/g of PBDE accumulation in fresh weight basis (Luo et al., 2007a). Pb, Ag, Cr, and Se like heavy metals also have been found in the water streams that located near to E-waste centers and the metal concentrations have been found with four or more times compared to drinking water (Pradhan and Kumar, 2014). This fact describes the contamination status of aquatic ecosystems and the whole ecosystem will be contaminated through these waters and the results would be more problematic for the community. Pradhan and Kumar (2014) have studied on heavy metal accumulation in water streams near to E-waste recycling and handling centers and reported that the elevated Cr, Cu, Cd, Fe, Pb, Zn, and Al concentrations as 0.60, 0.70, 0.05, 0.46, 0.04, 1.89, and 3.67 mg/L, respectively. It should be noted that the metal accumulation states are significantly different from these values in the residential area that 500 m away from the E-waste recycling center. The metal concentrations in the area of 500 m away to the E-waste site were reported as 0.02, 0.05, 0.002, 0.32, 0.002, 1.46, and 0.06 mg/L, respectively. Therefore the impact of E-waste is not a simple matter as these metals and all other toxic compounds eventually accumulate in bio systems and at the end the human community and all other ecosystems will be affected badly and irreversibly.

5.2.3 Impact of E-waste on atmosphere

It has been reported that the E-waste recycling centers and open burning sites are the major participants for release different contaminants from E-waste to atmosphere. Most importantly, the atmosphere is the major responsible media for contamination of human body through inhalation, ingestion, and dermal contact pathway. It has been reported that the workers in one of the E-waste recycling sites in China inhale dust containing air and those dust have reported with Cd, In, Sn, Sb, Pb, and Bi and their concentrations as 1.5, 1.3, 91, 13, 89, and 1 mg/m^3, respectively. Most of these heavy metals are carcinogenic and with the time the people may have to suffer with different types of health impacts. Several studies have revealed these point sources are responsible to release heavy metals, particulate matters, dioxines, and many of toxic compounds into the atmosphere that create different detrimental effects to the whole ecosystem (Chan and Wong, 2013). However, the type of contaminants in atmosphere will be different according to the types of work available in the area or near vicinity. For instance, the recycling centers and dumping sites that are mostly involved with circuit boards are tend to release massive amounts of Pb and Cu into the atmosphere, and in a site that located in New Delhi, India, has reported with Pb and Cu as 375,000 and 2670 mg/kg, respectively (Brigden et al., 2005). Also the battery workshops have reported with higher concentrations of Pb and Cd. For example, in an E-waste recycling center in India has reported Pb and Cd as 133,000 and 200,000 mg/kg, respectively, in dust samples (Brigden et al., 2005). As atmosphere is one of the major mediators for suspension of these metals, those contaminants are able to stay for a longer time, transport for a longer distances other than deposition on surfaces (Brigden et al., 2005). These metal particles are tend to adhere with particulate matters and this particulate matters are one of the major pollutants from E-waste, in particular, with open burning of E-waste. All of these metals that adhered to particulate matters tend to deposit on impermeable surfaces, open water bodies, and also intake by plants after deposit on soil surfaces. It has been found that the plants in nearby areas of the E-waste recycling centers are having higher metal concentrations and the weed species are found with the higher metals concentration than agricultural crops. Interestingly, the shoot area of those plants shows the highest metal accumulation (Luo et al., 2011). Therefore it has been suggested that apart from soil and irrigation water the contaminated atmosphere may be one of the major reasons for contamination of soil, aquatic environment, and human population. With the burning of E-waste for different processes, a heavy smoke is formed and the metallic and other compounds are released into the atmosphere. With this release the plants which are growing within the near vicinity are the first victims and with the deposition of metals on plants the folial uptake could take place (Luo et al., 2011). Bi et al. (2009) have found that there is a mechanism to folial uptake of Pb with atmospheric deposition with the presence of metal smelting factories in nearby area. Moreover, this fact could further elaborate the fact of having higher metal concentration in leafy edible parts than that of the root edible parts of a plant which grow near to E-waste recycling, processing, or dumping areas (Luo et al., 2011).

5.3 Impacts and associated risks of E-waste on public health

The improper handling, inadequate processing, and recycling methods are the foremost reasons that pose detrimental health impacts on human beings in particular for the immediate workers in those work lines in E-waste centers (Orlins and Guan, 2016). Almost all of these informal workers do not follow safety guidelines and use standard protective equipment due to their lack of knowledge about E-waste, the lack of knowledge about detrimental impacts, and because of financial issues. Identification of E-waste exposure is complex process as there are many of exposure routes, exposure sources, and different possible exposure time periods. Moreover, these different hazardous chemicals have same inhibitory, synergic, or additive effects (Alabi and Bakare, 2017) and at last a cumulative impact will be taken place. The exposure variability comes from different means: type of the E-waste, quantity of the E-waste, management processes of the E-wastes, age of the site, the human activities within the area, and the physical vulnerability such as pregnant women and children population (Alabi and Bakare, 2017).

However, the main route for heavy metal exposure to human is ingestion (90%), with the chain of soil−crop−food. Also the crop residuals use as foods for livestock and it also promotes the negative impacts on both human and animals and so that the soil contamination by electronic waste is a key start to pose a greater threat to the whole ecosystem (Fu et al., 2008). Table 5.1 depicts some of the studies conducted on human health impacts on E-waste and the pathways of contaminants that affect human health along with the concentrations of the contaminants. It is reported that in China, most of the E-waste recycling centers are located in rural regions and these rural areas are the hotspots for producing the most of food items

Table 5.1 Selected studies on E-waste and the human health impact by different E-waste contaminants.

Country	E-waste related site	Crop or food item/ intake	Contaminant	Concentration	Intake pathway	Health risk	References
China	Taizhou, Zhejiang province	Rice	Cd	0.7 μg/kg/day	Dietary		Chan et al. (2013)
China	Taizhou, Zhejiang province		Pb	3.7 μg/kg/day	Dietary		Chan et al. (2013)
China	Taizhou, Zhejiang province	9 food groups	PBDE	44.7 ng/day/kg	Dietary		Chan et al. (2013)
Indonesia	Astana Anyar district	PM 2.5 dust	Dust	186.75 μg/m^3	Inhalation	Daily repairable particular intake in study area (32.14 μg/kg/day) is higher than that of the control site (10.78 μg/kg/day)	Marselina et al. (2016)
Indonesia	Parung Panjang district	PM 2.5 dust	Dust	229.9 μg/m^3	Inhalation	Daily repairable particular intake in study area (42.36 μg/kg/day) is higher than that of the control site (15.42 μg/kg/day)	Marselina et al. (2016)
China	Taizhou, Zhejiang province	Brest milk	PBDE	572 ng/day/kg	Dietary		Leung et al. (2010)
China	Taizhou, Zhejiang province	Duck eggs	PBDE	52.83 ng/day/kg	Dietary		Leung et al. (2010)

China	Guiya	9 food items	PBDE	931 ng/day/kg	Dietary		Chan et al. (2013)
China	Lin'an	9 food items	PBDE	1.94 ng/day/kg	Dietary		Chan et al. (2013)
Ghana	Agbogbloshie, Accra	Soil	15 PAHs	390 ng/g	Dietary, inhalation, dermal contact	Weakly contaminated	Nishimura et al. (2017)
Philippines	Caloocan	Soil	15 PAHs	2900 ng/g	Dietary, inhalation, dermal contact	Heavily contaminated	Nishimura et al. (2017)
Vietnam	Bui Dau	Soil	15 PAHs	7200 ng/g	Dietary, inhalation, dermal contact	Heavily contaminated	Nishimura et al. (2017)
China	Wenling	Chicken meat	PBDE	1.8 ng/day/kg	Dietary		Qin et al. (2013)
		Eggs		11.7 ng/day/kg	Dietary		
China	San Men Country	Duck eggs	PBDE	0.54 ng/day/kg	Dietary		Labunska et al. (2013)
China	Qingyuan	Egg	PBDE	200.14 ng/day/kg	Dietary		Zheng et al. (2012)
China	Guiya	PM 2.5 dust	Heavy metals		Inhalation	90–91 children (10 years)/million population	Zheng et al. (2016)
South China	Guangdong province	Vegetables	Heavy metals	Cd: 0.4–4.22 mg/kg/DW Cu: 6.54–44.3 mg/kg/DW Pb: 1.21–14.4 mg/kg/DW Zn: 79.9–243 mg/kg/DW	Dietary	Noncarcinogenic risk Cu, Cd, Zn <1 Pb >1	Luo et al. (2011)
India	Varanasi district	Vegetables	Heavy metals	Cd: 1.1–4.5 mg/kg/DW Cu: 20.5–71.2 mg/kg/DW	Dietary		Singh et al. (2010)

to the whole community, in particular rice (Fu et al., 2008). As rice is a staple food for most of the Asians including China and this can be the major source for heavy metal intake of human in the particular regions. Fu et al. (2008) showed that the rice samples received from the fields which are located near vicinity of a E-waste recycling centers exceeded the national standards for heavy metal contents in rice by 15.3%, 31%, and 100% for Hg, Cd, and Pb, respectively. It has been noted that the animal food sources are highly responsible for contamination of human body. For PBDE, the studies showed that the food items such as freshwater fish, seafood, chicken, and other meets and eggs have higher concentrations of PBDE (Song and Li, 2014; Chan and Wong, 2013). It was found that the nonherbivorous fish contain higher levels of PBDE and this fact could be true for most of other persistent pollutants as those could accumulate for a long time and thereafter, the humans who consume those fish species will get more pollutants into their body and finally contaminants will be accumulated in body tissues (Xing et al., 2009). Studies revealed that several food items in some of the countries have exceeded the US EPA reference dosages for dietary intake of PBDEs (100 ng/day/kg): the nine food items received from the Guiya, China, which is one of the popular E-waste recycling centers, have recorded with 931 ng/day/kg of PBDEs which is nine times more higher than the reference dosage (Chan et al., 2013). Moreover, duck eggs from Taizhou, China, and chicken eggs from Qingyuan, China, also have reported with increased PBDEs concentrations with the values of 104 and 200 ng/day/kg, respectively. These values are also exceeded the US EPA reference values (Labunska et al., 2013; Zheng et al., 2012). Both of these areas also have E-waste processing and recycling activities. Table 5.1 shows the records of different food items for different contaminants with their values which are collected from E-waste processing and recycling areas. Most importantly, it has been reported that the infants are also in great danger due to contaminated foods in mothers' diet. Studies conducted with breast feeding mothers in E-waste recycling and dumping areas have revealed that the breast milk which is the only food for 6-month-old infants has increased PBDE concentrations as 572 ng/day/kg. It should be noted that these values are 57 times higher than that of control areas (Song and Li, 2014).

Moreover, apart from dietary intake the inhalation pathway also one of the major reasons for the contamination of human body with E-waste contaminants especially for occupational workers. A study conducted in China has revealed that the mean concentration for PCBs through inhalation has showed fivefold higher than that of the control area (Xing et al., 2009). Not only from the direct exposure but also with the particulate matters that release form the different unsafe processes: grinding, melting, roasting, and open burning have considerable involvement for creating health impacts on the community. These particulates have the ability to create acute and chronic toxicological impacts when deposit on human respiratory track (Zheng et al., 2016). Most importantly the health risk that occurred due to inhalation of E-waste contaminant is severely affected on children rather than adults. This fact has been proved with a respiratory disease analysis done by Li et al. (2008) and it has been reported that 80% of children suffered from respiratory diseases due to bad air quality in the experimental area.

Although the dermal contact pathway has not received a significant research interest, it also serves as one of the pathways that is able to create adverse health impact on the human community. Studies have revealed that the adult people in Taizhou area which is one of the E-waste recycling cites in China has exposed to 0.363 pg/day/kg of toxic equivalents and for children this value was higher as 2.3 pg/day/kg and both have exceeded the value for the control site (Ma et al., 2008). At the same time the workers who are employed in E-waste collection, dumping, and incineration sites are kind of direct victims for the toxic contaminants that release from the E-waste. In China, for instance, there are higher number of incidences with skin damages, headache, vertigo, chronic gastritis, gastric ulcers, and duodenal ulcers on people who worked in a plant that do the incineration of circuit boards and separation of plastics from electrical waste (Alabi and Bakare, 2017). Contamination of groundwater with E-waste leachate reduces its quality and the palatability for human usage. These contaminants such as heavy metals, dioxins, furans, PAHs, PCBs, and polybrominated diphenyls are able to create human gastrointestinal irritation and laxative effects, abnormal sperm quality, chromosome aberration, DNA damage, reduced fecundity, and adverse birth effects (Alabi and Bakare, 2017).

Heavy metals are kind of dangerous compounds that can affect human health in several ways. Most of those heavy metals are potential carcinogens. Kidneys can be damaged by different heavy metals and Cd is one of those metals that creates an impact on the menacing proportion. It is important to note that Cd has long biological half-life in humans and therefore, both short- and long-term impacts can be expected. Pb is a metal that has a direct influence toward central nervous system as well as deterioration of intelligent quotient, and children are therefore one of the greater victims of Pb contamination. Mercury is a potential mutagenic compound and can greatly affect neurons (Fu et al., 2008).

Several studies have conducted experiment on analysis of different body parts for accumulation of contaminants which are common for E-waste recycling and dumping cites (Guo et al., 2010; Ni et al., 2014; Zhao et al., 2013). It is a great indicator for contaminants loading on human body, exposure levels, and human health risk due to E-waste contaminants. The placentas that collected after child birth have reported with different heavy metals such as Cd, Pb, Ni, PCDD, and PBDEs with elevated concentrations (Zhang et al., 2011). For example, placentas collected from mothers who live in Guiya town, China where a well-known E-waste collection center located, has reported 301.4 ng/g of Pb and it is as two times as higher than that of control site (165.8 ng/g). Moreover, in Taizhou, China the placental PBDE concentrations were reported as 19 times higher than that of control site (19.5 and 1.02 ng/g, respectively) (Leung et al., 2010). Similarly, the umbilical cord that collected from the people that live near to E-waste collection and recycling centers also showed increased pollutant concentrations such as heavy metals, PCDD, and PBDEs than that of control cites. Most importantly the Cd concentration in umbilical cords has exceeded even the WHO safety limits (5 μg/L) (Li et al., 2011). The foremost factors to these accumulation statuses could be the mother's involvements in E-waste recycling activities and living near to those E-waste collections and recycling centers during pregnancy and before the pregnancy and father's involvements with E-waste recycling and handling activities (Song and Li, 2014). Therefore the exposure of parents to the E-waste could create adverse health impacts on future generation and the continuous exposure therefore should be eliminated as much as possible even the lifestyles of those people are adhered with their occupation. Assessing of human blood and serum is one of the most common methods to detect the human body burden due to E-waste contaminants as human blood represents the body condition than any other specimen. Among several E-waste contaminants blood Pb level has gained considerable interest and those studies have reported that most of the people who are associated with E-waste are victims of escalated blood Pb levels, particularly, in children. According to US center for disease control, the blood Pb content higher than 100 μg/L, is considered as elevated blood Pb condition and most of the studies that conducted blood assessment for children in E-waste handling sites have found elevated blood Pb levels for children. Interestingly, with the increment of age the blood Pb level also has increased creating more detrimental health burdens on older children than younger ones (Zheng et al., 2008). Other than heavy metals PCB, PBDEs, and dechlorine also have found with elevated concentrations in human blood and among the different human groups, the occupational human group, who are integrated with E-waste recycling and handling are in greater danger (Ren et al., 2009). Other than blood, the human urinary fluids also show elevated contaminant concentrations as the urinary system is also responsible for detoxification and accumulation of contaminants. Zhang et al. (2016) have showed that the persons who are living near to the E-waste dismantling sites are having accumulated bisphenols in their urine and this has been interconnected with the elevated oxidative stress in those people. Overall study shows that 90% of people from affected area are having bisphenols in their urine and the concentrations are significantly higher than that of the urine samples from reference areas. Therefore these E-wastes have ability to disturb human health, living condition, and the physical fitness.

As a metabolic end product, human hair is gaining significant interest since it has the ability to represent contamination status of the human body. Several studies are there that focused on human hair to determine the E-waste contaminant levels in the human body (Zheng et al., 2011a,b; Leung et al., 2010). It has been found that the hair samples collected from workers and residents form E-waste recycling centers and nearby are having heavy metals such as Cd, Cu, Ni, Cr, Mn, As, PBDEs, and PCDD/Fs with increased concentrations than the control population (Leung et al., 2010; Zheng et al., 2011b; Ma et al., 2011). Children and neonates are the most sensitive group for the body burden due to E-waste exposure as they have number of intake pathways such as through breast milk and placental exposure, hand to mouth activities, and up taking of comparatively higher volume of air and lower toxic elimination rates. This fact has been showed clearly with the study conducted in Guiya E-waste recycling center in China. It shows, due to exposure of heavy metals in PM 2.5 particulate matters, the female adult population bears carcinogenic health risk as 59−60 cancer cases/million population and under the same conditions children under 10 years bear 90−91cancer cases/million population (Zheng et al., 2016).

The exposure to the toxic chemicals is not the only health problems that related with the E-waste. Studies have showed that suffering with hearing problems also a kind of detrimental health impact that is related to the E-waste handing, processing, and recycling workers (Carlson, 2016).

5.4 Safety measures for final disposal and future perspectives

At the end of a use of E-waste most of E-wastes do not recycle but reuse and dump in landfills. It has been noted that 80% of electrical and electronic items are transported to the poor and developing countries as illegal transfers or donations. However, after end of the use of electronic and electrical items the best method is recycling as that E-waste bulk contains numerous valuable metals and some other economically valuable components. Recycling have the ability to recover 95% of useful materials from a computer and therefore recycling has high positive impact on economic status of a country. However, the way in which the recycling is done have many of environmental impacts. E-waste recycling integrates with the disassembly and destruction of the equipment to recover new materials (Cui and Zhang, 2008). Most of the times the recycling is done without following a standard or safety procedure and therefore most of contaminants release from those E-wastes are subjected to create problems on different ecosystems. However, the recycling is always better than landfilling of E-waste and incinerated E-waste (Hischier et al., 2005).

Meanwhile, concerning the potential environmental and health issues, the management policies and legislations on E-waste have been raised as an important matter. Therefore from recent decades, the policies and legislations have been extended where they applied throughout the product lifetime: design, manufacture, consumption, and end-of-life, focusing a major responsibility on producers based on extended producer responsibility (Nnorom and Osibanjo, 2008). The government involvement of a particular country is a basic need in E-waste recycling sector in order to avoid the illegal E-waste transportation and handling. For example, since several decades, China has stated as one of the major country that receives illegal E-waste and therefore they have implemented number of E-waste recycling centers that do not follow basic safeguard techniques and so that the human exposure is critical in China. However, the Chinese government has involved into some extent on this issue and as a result of their management practices and the legislations, they could achieve the positive results. The percentage of children that has increased blood Pb levels, than WHO recommended levels was reduced with above government action (Huo et al., 2007; Zheng et al., 2008; Liu et al., 2011). Apart from the government responsibility to increase the effectiveness of the recycling, reuse, and disposal mechanisms of E-waste it is needed to have strong interactions among electrical and electronic item producers of the particular country. Because most of production processers are located out of the countries and for the recycling process the connection and the integration with the producers is highly required. It is true that some of large companies such as Apple, Philips, and Samsung have their own reverse logistic processes and however, this independence makes disadvantages at the point of reuse of those electrical and electronic items (Azevedo et al., 2017). Most importantly the public awareness is a basic need in order to mitigate the health risks that is created by E-waste exposure.

The future of the E-waste will be more complicated with the present procedures of recycling and the disposal. The global production of the E-waste will be changed along with the economic developments of the countries. It is strongly accepted that the total number of electrical and electronic waste production is highly correlated with the country's GDP (Robinson, 2009). Therefore the economic growth will be supported for more E-waste production. With the presence of this growing trend, the high tech mechanisms and more safeguards for the E-waste handling and management are required to establish the stability of ecosystems and human health quality despite of detrimental impacts from E-wastes.

References

Alabi, A.O., Bakare, A.A., 2017. Genetic damage induced by electronic waste leachates and contaminated underground water in two prokaryotic systems. Toxicol. Mech. Methods 27, 657–665.

Awasthi, A.K., Zeng, X., Li, J., 2016. Environmental pollution of electronic waste recycling in India: a critical review. Environ. Pollut. 211, 259–270.

Azevedo, L.P., Da Silva Araújo, F.G., Lagarinhos, C.A.F., Tenório, J.A.S. & Espinosa, D.C. R. 2017. E-waste management and sustainability: a case study in Brazil. Environ. Sci. Pollut. Res., 1–12.

Bi, X., Feng, X., Yang, Y., Li, X., Shin, G.P., Li, F., et al., 2009. Allocation and source attribution of lead and cadmium in maize (*Zea mays* L.) impacted by smelting emissions. Environ. Pollut. 157, 834–839.

Bob, U., Padayachee, A., Gordon, M., Moutlana, I., 2017. Enhancing Innovation and technological capabilities in the management of e-waste: case study of South African government sector. Sci. Technol. Soc. 22, 332–349.

Brigden, K., Labunska, I., Santillo, D., Allsopp, M., 2005. Recycling of Electronic Wastes China and India: Work Place & Environmental Contamination Amsterdam. Greenpeace Research Laboratories, UK, The Netherlands, pp. 1–56.

Carlson, K., 2016. Electronic waste worker health: studying complex problems in the real world. Proceedings of the Eighth International Conference on Information and Communication Technologies and Development. ACM, p. 35.

Chan, J.K.Y., Wong, M.H., 2013. A review of environmental fate, body burdens, and human health risk assessment of PCDD/Fs at two typical electronic waste recycling sites in China. Sci. Total Environ. 463, 1111–1123.

Chan, J., Man, Y., Wu, S., Wong, M., 2013. Dietary intake of PBDEs of residents at two major electronic waste recycling sites in China. Sci. Total Environ. 463, 1138–1146.

Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: a review. J. Hazard. Mater. 158, 228–256.

Dharini, K., Cynthia, J.B., Kamalambikai, B., Celestina, J.A.S., Muthu, D., 2017. Hazardous E-waste and its impact on soil structure, IOP Conf. Ser.: Earth Environ. Sci., 80. p. 012057.
Fu, J., Zhou, Q., Liu, J., Liu, W., Wang, T., Zhang, Q., et al., 2008. High levels of heavy metals in rice (*Oryza sativa* L.) from a typical e-waste recycling area in southeast China and its potential risk to human health. Chemosphere 71, 1269−1275.
Guo, Y., Huo, X., Li, Y., Wu, K., Liu, J., Huang, J., et al., 2010. Monitoring of lead, cadmium, chromium and nickel in placenta from an e-waste recycling town in China. Sci. Total Environ. 408, 3113−3117.
Hischier, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25, 525−539.
Huo, X., Peng, L., Xu, X., Zheng, L., Qiu, B., Qi, Z., et al., 2007. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ. Health Perspect. 115, 1113.
Labunska, I., Harrad, S., Santillo, D., Johnston, P., Yun, L., 2013. Domestic duck eggs: an important pathway of human exposure to PBDEs around e-waste and scrap metal processing areas in Eastern China. Environ. Sci. Technol. 47, 9258−9266.
Leung, A.O., Chan, J.K., Xing, G.H., Xu, Y., Wu, S.C., Wong, C.K., et al., 2010. Body burdens of polybrominated diphenyl ethers in childbearing-aged women at an intensive electronic-waste recycling site in China. Environ. Sci. Pollut. Res. 17, 1300−1313.
Li, Y., Xu, X., Wu, K., Chen, G., Liu, J., Chen, S., et al., 2008. Monitoring of lead load and its effect on neonatal behavioral neurological assessment scores in Guiyu, an electronic waste recycling town in China. J. Environ. Monit. 10, 1233−1238.
Li, Y., Huo, X., Liu, J., Peng, L., Li, W., Xu, X., 2011. Assessment of cadmium exposure for neonates in Guiyu, an electronic waste pollution site of China. Environ. Monit. Assess. 177, 343−351.
T Link, 2014. Impact of E-Waste Recycling on Water and Soil. New Delhi, India.
Liu, J., Xu, X., Wu, K., Piao, Z., Huang, J., Guo, Y., et al., 2011. Association between lead exposure from electronic waste recycling and child temperament alterations. Neurotoxicology 32, 458−464.
Luo, Q., Cai, Z.W., Wong, M.H., 2007a. Polybrominated diphenyl ethers in fish and sediment from river polluted by electronic waste. Sci. Total Environ. 383, 115−127.
Luo, Q., Wong, M., Cai, Z., 2007b. Determination of polybrominated diphenyl ethers in freshwater fishes from a river polluted by e-wastes. Talanta 72, 1644−1649.
Luo, C., Liu, C., Wang, Y., Liu, X., Li, F., Zhang, G., et al., 2011. Heavy metal contamination in soils and vegetables near an e-waste processing site, south China. J. Hazard. Mater. 186, 481−490.
Ma, J., Kannan, K., Cheng, J., Horii, Y., Wu, Q., Wang, W., 2008. Concentrations, profiles, and estimated human exposures for polychlorinated dibenzo-*p*-dioxins and dibenzofurans from electronic waste recycling facilities and a chemical industrial complex in Eastern China. Environ. Sci. Technol. 42, 8252−8259.
Ma, J., Cheng, J., Wang, W., Kunisue, T., Wu, M., Kannan, K., 2011. Elevated concentrations of polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans and polybrominated diphenyl ethers in hair from workers at an electronic waste recycling facility in Eastern China. J. Hazard. Mater. 186, 1966−1971.

Marselina, M., Roosmini, D., Salami, I., Cahyadi, W., 2016. Analysis of respirable particulate exposure and its effect to public health around lead smelter and e-waste processing industry in West Java, Indonesia. J. Phys. Conf. Ser. IOP Publishing, p. 012071.

Ni, W., Huang, Y., Wang, X., Zhang, J., Wu, K., 2014. Associations of neonatal lead, cadmium, chromium and nickel co-exposure with DNA oxidative damage in an electronic waste recycling town. Sci. Total Environ. 472, 354–362.

Nishimura, C., Horii, Y., Tanaka, S., Asante, K.A., Ballesteros Jr, F., Viet, P.H., et al., 2017. Occurrence, profiles, and toxic equivalents of chlorinated and brominated polycyclic aromatic hydrocarbons in E-waste open burning soils. Environ. Pollut. 225, 252–260.

Nnorom, I.C., Osibanjo, O., 2008. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour. Conserv. Recycl. 52, 843–858.

Orlins, S., Guan, D., 2016. China's toxic informal e-waste recycling: local approaches to a global environmental problem. J. Clean. Prod. 114, 71–80.

Pradhan, J.K., Kumar, S., 2014. Informal e-waste recycling: environmental risk assessment of heavy metal contamination in Mandoli industrial area, Delhi, India. Environ. Sci. Pollut. Res. 21, 7913–7928.

Qin, X., Qin, Z., Li, Y., Zhao, Y., Xia, X., Yan, S., et al., 2011. Polybrominated diphenyl ethers in chicken tissues and eggs from an electronic waste recycling area in southeast China. J. Environ. Sci. 23, 133–138.

Ren, G., Yu, Z., Ma, S., Li, H., Peng, P., Sheng, G., et al., 2009. Determination of dechlorane plus in serum from electronics dismantling workers in South China. Environ. Sci. Technol. 43, 9453–9457.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–191.

Singh, A., Sharma, R.K., Agrawal, M., Marshall, F.M., 2010. Risk assessment of heavy metal toxicity through contaminated vegetables from waste water irrigated area of Varanasi, India. Trop. Ecol. 51, 375–387.

Song, Q., Li, J., 2014. A systematic review of the human body burden of e-waste exposure in China. Environ. Int. 68, 82–93.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on E-waste. Environ. Impact Assess. Rev. 25, 436–458.

Xing, G.H., Chan, J.K.Y., Leung, A.O.W., Wu, S.C., Wong, M., 2009. Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environ. Int. 35, 76–82.

Zhang, X., Ruan, X., Yan, M., Zhao, Y., Wei, W., Qin, Z., et al., 2011. Polybrominated diphenyl ether (PBDE) in blood from children (age 9–12) in Taizhou, China. J. Environ. Sci. 23, 1199–1204.

Zhang, T., Xue, J., Gao, C.-Z., Qiu, R.-L., Li, Y.-X., Li, X., et al., 2016. Urinary concentrations of bisphenols and their association with biomarkers of oxidative stress in people living near e-waste recycling facilities in China. Environ. Sci. Technol. 50, 4045–4053.

Zhao, Y., Ruan, X., Li, Y., Yan, M., Qin, Z., 2013. Polybrominated diphenyl ethers (PBDEs) in aborted human fetuses and placental transfer during the first trimester of pregnancy. Environ. Sci. Technol. 47, 5939–5946.

Zheng, L., Wu, K., Li, Y., Qi, Z., Han, D., Zhang, B., et al., 2008. Blood lead and cadmium levels and relevant factors among children from an e-waste recycling town in China. Environ. Res. 108, 15–20.

Zheng, J., Luo, X.-J., Yuan, J.-G., He, L.-Y., Zhou, Y.-H., Luo, Y., et al., 2011a. Heavy metals in hair of residents in an E-waste recycling area, South China: contents and assessment of bodily state. Arch. Environ. Contamin. Toxicol. 61, 696−703.

Zheng, J., Luo, X.-J., Yuan, J.-G., Wang, J., Wang, Y.-T., Chen, S.-J., et al., 2011b. Levels and sources of brominated flame retardants in human hair from urban, e-waste, and rural areas in South China. Environ. Pollut. 159, 3706−3713.

Zheng, X.-B., Wu, J.-P., Luo, X.-J., Zeng, Y.-H., She, Y.-Z., Mai, B.-X., 2012. Halogenated flame retardants in home-produced eggs from an electronic waste recycling region in South China: levels, composition profiles, and human dietary exposure assessment. Environ. Int. 45, 122−128.

Zheng, X., Xu, X., Yekeen, T.A., Zhang, Y., Chen, A., Kim, S.S., et al., 2016. Ambient air heavy metals in PM2. 5 and potential human health risk assessment in an informal electronic-waste recycling site of China. Aerosol Air Qual. Res. 16, 388−397.

Electrochemical enhanced metal extraction from E-waste

6

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6.1 Introduction

The rapid development of technology and requirement of high performance electronic and electrical equipment has reduced the life expectancy's of electronic equipment's as everybody wants to have access to the latest technology. With progressive innovations and inventions, the life span of electronic equipment has become short and end up as obsolete waste products. This waste is now termed as electronic waste (E-waste) or waste electronic and electrical equipment (WEEE) and is one of the fastest growing waste streams in the past few decades (Frazzoli et al., 2010; Kaya, 2016; Zeng et al., 2017). With the rapid growth in the demand on new electronic equipment and the ability to cater a wider public with accessibility reaching to every corner of the world involves stress created on the natural resources that need to be used in making the electronics. This is evident from the exponential raise the prices of some of the metals that are used in the electronic industry (Graedel et al., 2015). The world has generated approximately 41.8 Mt of E-waste in 2014 and is expected to reach 49.8 Mt in 2018 (Cui and Anderson, 2016). Although WEEE constitutes only 8% of municipal solid waste, the amount of metals present in it exceeds than any other form of waste (Hossain et al., 2015). However, only 10%−15% of this waste is recycled and the majority end-up in landfills.

Electronic and electrical equipments uses a significant amount of valuable metals, precious metals, and rare earth which impart unique properties to this equipment and when discarded will become a waste of these resources. It is becoming increasingly difficult to source these metals especially rare earth metals to be used in the electronic industry (Boudesocque et al., 2019; Yazici and Deveci, 2013). The U.S. environmental protection agency suggests that recycling electronic waste would benefit in energy savings than the extraction of metals from the natural ores (EPA, 2007). Some of these metals are extremely toxic and adversely affect the

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00004-8

environment when discarded to the environment without proper care. Hence, these metals from WEEE should be recycled both as resource point of view and environmental view.

Electronic waste is categorized as hazardous waste due to the presence of toxic metals, organics which have a detrimental effect on the human health, environment, and imbalance the ecosystem due to improper handling during disposal (Pinto, 2008). Waste electronics and electrical equipments pose significant issues for its management for both the government and industry. The absence of strict government regulations made it difficult to handle or manage the growing WEEE (Salhofer et al., 2016). The efficiency of WEEE waste recycling involves many steps such as government legislation, consumer participation, the amount of waste that can be handled, and safe handling procedures. The handling practices of WEEE are not the same across the boards, making it difficult to coordinate the efforts. The majority of the WEEE is being dumped into developing countries like Indonesia, India, Bangladesh, Sri Lanka, Philippines, Nigeria and Liberia from the developed countries like United States, Australia, Japan, and European Union (Baldé et al., 2015). This calls for the requisite to treat the wastes that are valuable enough to go further for recovery to be in use as a secondary source.

6.1.1 Waste electronic and electrical equipment types

Electronic and electrical equipment can be classified into different types depending on their source, usage, and recyclability of these materials. The WEEE include batteries, lightbulbs and lamps, television, laptop, computers, tablets, and mobile phones with screens, fridges, freezers, chillers and air-condition units, printed circuit boards (PCBs), ink or toner cartridges, capacitors, cameras, power tools, lawn movers, photocopiers, projectors, display panels, microwaves, and printers (Khaliq et al., 2014; Vidyadhar, 2016). It is well known that the metals can be recycled infinitely irrespective of the form it is available. It is also identified that recovering metals from WEEE has significant advantages such as lesser secondary pollution and energy requirement compared to extracting the metals from natural resources (Zhang and Xu, 2016).

6.1.2 Metallic components in E-waste

The WEEE contains many components such as plastics, ceramics, metals, cables, CRT and LCD screens, cables, fire retardants, wires, and others, of which the metals constitute 60% by weight followed by plastics $\sim$15% and CRT and LCD screens at $\sim$11.8% (Zhang and Xu, 2016). The significant component of WEEE is the metals which can be recovered for reuse in the same industry. There are close to 54 metals that are identified in personal computers (Oguchi et al., 2013). However, the major components of metals include Cu, Al, Fe, Ni, Sn, Zn, Pb, Ag, Au, Li, Co, and others are present in ppm levels. Oguchi et al. (2013) have summarized different types of metals present in 24 different equipment types, as summarized in Table 6.1 (Oguchi et al., 2013). However, there are more metals used in the

Table 6.1 Hazardous and useful materials present in different WEEE.

Component	Useful materials	References
PCBs	Cu	Rajagopal et al. (2016)
CRT	Pb, REEs: Y and Eu	Önal and Binnemans (2019)
LCD panel	In_2O_3	Swain et al. (2016)
Wire	Copper, Aluminum	Vegliò et al. (2003)
Li-ion battery	Al, Cu, Li, Co	Li et al. (2012)
Ni-MH battery	Fe, Ni, Ce, La, Mn	Sobianowska-Turek (2018)

electronic equipment's in trace compositions. In WEEE precious metals contribute to the significant economic value, and the efforts are focused on extracting those metals during recycling operations. The primary hazardous and useful materials associated with WEEE are summarized in Table 6.1.

Apart from metals, the electronic waste is composed of ceramics which include SiO_2 and Al_2O_3 and plastics such as polyethylene, polypropylene, polyesters, epoxies, polyvinylchloride, nylon, and poly tetraflouroethane (Khaliq et al., 2014). In particular, PCBs constitute approximately 40% metals, 30% plastics, and 30% ceramics (Ogunniyi et al., 2009).

There are multiple approaches investigated in the literature to extract the metals from electronic waste. The methods include smelting, pyrometallurgical, vacuum pyrolysis, hydrometallurgical, and microalgal treatment, electrowinning, electrodeposition, and electroextraction. Each approach has its own advantages and disadvantages in relation to operation parameters and energy requirement (Ashiq et al., 2019; Veit et al., 2015). The complex composition of electronic waste warrants high-tech technologies to selectively extract these metals and reuse them. It is known that the metals can be recycled any number of times and recovering from the waste equipment gives an incentive of conserving the natural resources. Pyrometallurgy and hydrometallurgy are the most common methods used for the recovery of metals from WEEE. However, pyrometallurgy requires high temperatures to extract the metals from WEEE, which release toxic gases which need to be cleaned before releasing into the environment (Wang et al., 2017).

On the other hand, hydrometallurgy does not require high temperatures, high operation costs, reduced environmental impact, and reasonable metal recovery rates. Hydrometallurgical treatment of WEEE typically uses mineral acids such as HCl, H_2SO_4, or HNO_3 for the recovery of metals. Apart from that, it uses several reagents to such as cyanides, halide, thiosulfate, or thiourea for the extraction of precious metals. The section below provides a broad overview of the extraction of metals from WEEE using hydrometallurgical methods (Abdelbasir et al., 2018; Awasthi and Li, 2017).

6.1.3 Hydrometallurgical recovery methods

Conventionally, in hydrometallurgy, mostly acids are utilized to selectively leach out the targeted metals. Then, through a series of refining processes as in

Table 6.2 Leaching of WEEE from source and their recovery.

Leaching types	Leaching agents	Elements recovered	References
Thiourea leaching	$CS(NH_2)_2$, Fe(III)/H_2SO_4 as the oxidizing agent	82% Au	Zhang et al. (2012)
Thiosulphate leaching	$(NH_4)_2S_2O_3$, $CuSO_4$ Copper sulphate, NH_4OH Ammonium hydroxide	100% Ag, Au> 95%	Oh et al. (2003)
Acidic leaching	HCl/NaCl with HNO_3/H2O_2 leaching	9%−95% Pd	Quinet et al. (2005)

electrorefining, precipitation, and cementation, the metals get further concentrated (Abdelbasir et al., 2018). The valuable metals exist as complexes which become further demanding to extract them for secondary use. However, leaching has proven to be more promising than pyrometallurgical processes as it utilizes no external energy source and requires just the right solvents. The recovery rates are much higher compared to the pyrometallurgical processes. Table 6.2 shows a few examples of the different solvents used for the recovery of a few metals.

6.1.4 Electrowinning and electrorefining processes

Precious base metals are usually recovered through electrodeposition with lesser use of auxiliary materials as in leaching agents, lower environmental impacts, higher efficiency compared to energy requisites pyrometallurgical process and highly cost-effective (Ashiq et al., 2019; Fogarasi et al., 2015). Usually, the leaching process is followed by an electrorefining step. An electrochemical reaction that takes place spontaneously in the system, generates the requires ions for the current transfer, thereby, the noble metal of high purity gets migrated at the cathode and the less noble metal get oxidized at the anode. This is a normal scenario for any kind of electrochemical cell, involving electrodes and electrolytes and sometimes with an external power source for initial of the cell reactions (Işıldar et al., 2018; Roslan et al., 2017).

Electrowinning is a process by which the metal gets separated and recovered from the solution by electrolysis. The required metal gets deposited from the solution at the cathode, and the anode remains inert throughout the reaction. Whereas, electrorefining is another electrolytic process that involves the removal of impurities from the metal. The impure metal either gets deposited at the anode or remains in the electrolyte as insoluble sludge (Ozgur et al., 2016). Only the metal again gets migrated to the cathode. The rate of the electrolytic process is highly dependent on the current imparted by the half-cell reactions and can be enhanced through increasing the conductivity in the cell through maintaining the concentration of the metal ion solution, adding some salts, providing heat, or even increasing the surface area of the electrodes (Walker, 1979).

6.2 Electrochemical enhancement methods for metal recovery

Electrochemical enhancement of elements from electronic scrap using electrolytic cells has gained tremendous attention over the last few years. Conventional cells utilizing aqueous solutions cannot be employed as electrolytes due to the high rates of electrolysis in the media and nonselective to the required elements to be extracted, lower stability in the cell due to heating and thereby less efficient (Simka et al., 2009). Thus, technologists and researchers focus on coming with electrochemical pathways to selectively refine the metals from leached solutions and by the use of nonaqueous solutions to selectively extract or electrodeposit the metal or the element. A brief graphics of electronic waste recovery is shown in Fig. 6.1.

6.2.1 Copper recovery

Metal wires in electronics appliances consist of copper, that has high electrical conductivity, thermal conductivity, and readily available. However, copper is a multivalent metal that oxidizes to copper oxides, viz., cuprite or cuprous oxide or cupric oxides. These oxides possess different physical properties that make them apt to be used in different applications as in varying from optical devises to high thermally resistant devices (Mezine et al., 2018). Lithium-ion batteries, photodetectors, solar cells, electronic equipments are some of the sources where these oxides have been applied. As is it a p-type semiconductor, copper oxides crystallize and thus suitable for many applications. PCBs contain polymers, metals, and certain amounts of ceramics. Of the 40% metals present in the circuit board, approximately 20% of copper can be found in a typical computer PCB whose quantity is much higher than the ore present naturally (around 0.6%). Copper recovery is of great economic interest in terms of its recovery as its degree of purity of obtaining is high and is of the declining market over the past decade (Zhang et al., 2017). Few recovery processes using electrochemical pathway is shown in Table 6.3.

The challenge revolves around the heterogeneity of the materials being used with copper in the manufacturing of the electronic equipment. Due to the formation of dioxins and furans from the halogenated flame retardants used in the PCBs processing, pyrometallurgical methods has its limitations and an added-costs in its high energy-driven processes (Guimarães et al., 2014; Puente-Siller et al., 2017; Wu et al., 2009). Moreover, the consumption of leaching agents for hydrometallurgy is high and leaches out large quantities of untreated wastewaters in the environment (Jha et al., 2012; Tuncuk et al., 2012). For these reasons, electrolysis is an efficient method for recovering copper and capable of obtaining high purity copper powders

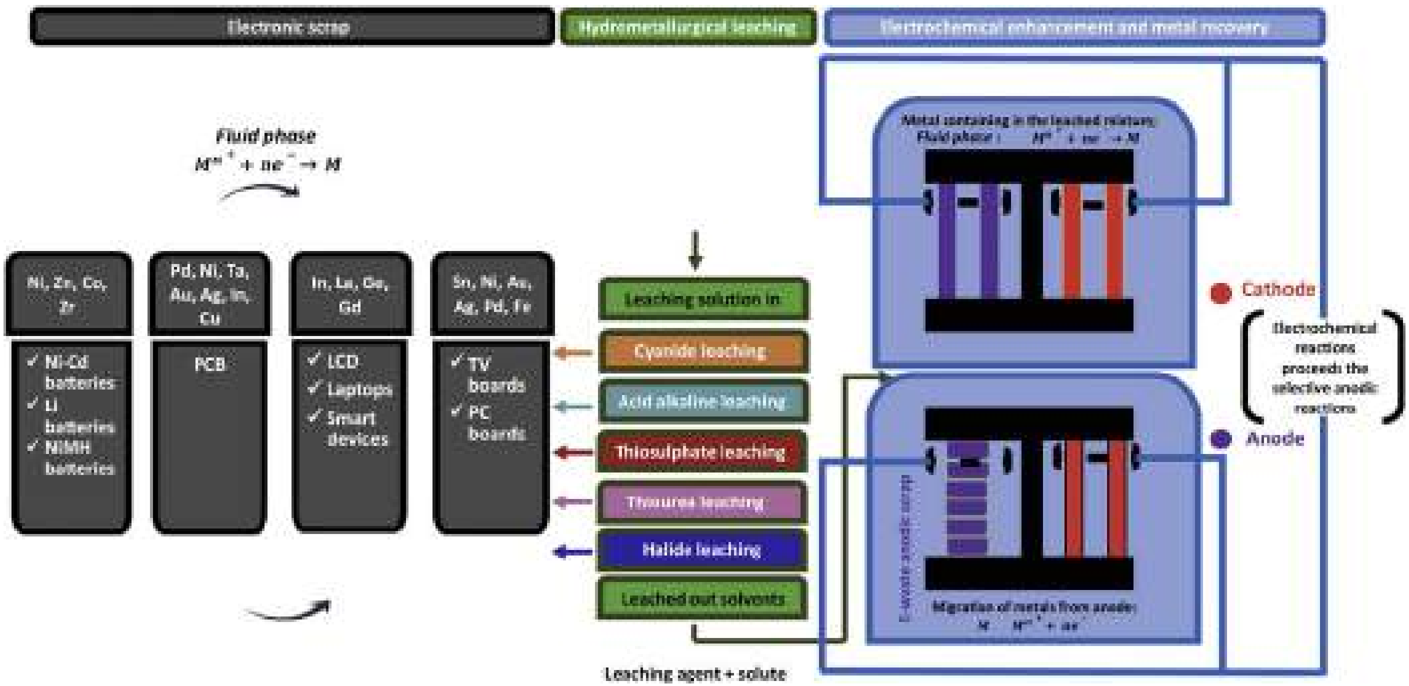

Figure 6.1 Graphical representation of electrochemical recovery of WEEE from leaching to electrowinning processes.

from the electronic wastes. The simultaneous leaching-electrodeposition process has been employed for a quick recovery of copper from PCBs.

Ideally, in the hydrometallurgical process, copper in the wastes gets leached out as Cu (1) utilizing Cu (II) through reduction. The purified Cu (I) reduced to copper metal at the cathode through electrowinning and leftover Cu (I) passes through the anode as Cu (II) and then further purified at the leaching process. This process recovers about 93% of copper and can be further improved while converting into final ultrafine powders of copper rather than copper collected on the cathode utilizing the right leaching agent (Oishi et al., 2008; Yang et al., 2012). Previous studies to further optimized the efficiency of the copper recovery by using ammonia-ammonium sulfate/chloride/carbonate were used as a leaching agent with supplied air for oxidation, achieved a recovery of 98% (Liu et al., 2010; Yang et al., 2012).

Another hydrometallurgical process known as slurry electrolysis is one of a kind recovery methods of pristine metals from electronic wastes and it utilizes chemical and electrochemical process combinations (i.e., leaching, solution purification, and electrowinning) in one reactor, all at once (Zhang et al., 2017). Copper recovered from these methods are mostly in particle size ranging from micropowders or even nanopowders depending on the conditions utilized. According to Li et al. (2019), ruthenium-plated titanium was used as the cathode and anode and a DC supply for current. A portion of CPU sockets containing a mixture of several elements are added to the anode chamber where 200 mL of a mixture of hydrochloric acid, sodium chloride, and hydrogen peroxide as an electrolyte were introduced into the cell (Li et al., 2019). The effects in the current density, pulp of CPU sockets dosage, and the residence time were all studied concerning the copper recovery rate. Hydrochloric acid leaches out copper to its chloride complexes and copper recovery rate significantly increased when hydrochloric acid concentration is increased (H^+ and Cl^- availability increases that contribute to the metal dissolution) up to a certain degree and show a declination in the recovery (Li et al., 2019; Zhu and Gu, 2002). Increasing the acid concentration recovered the other metals in the cell cathode, nickel powders being the impurity with the copper cathode (Ashiq et al., 2018; Li et al., 2019).

Electrolyzed copper powders were obtained from concentrated metal scraps of wasted PCBs, compressed and held at the anode were studied in Chu et al. (2015). Copper (99.5% purity) sheets were used as a cathode with copper sulfate pentahydrate, sodium chloride, and sulfuric acid as electrolytes were used with constant DC applied across. In this study, the rates of nucleation of copper have been further studied to see the mechanisms involved in the migration of copper from the scraps with respect to the particle sizes. Copper sulfate pentahydrate has a diverse effect on the migration of copper ions from the anode. The particle size increases to almost five-fold when the concentration of copper sulfate increases up to 90 g/L which is explained as a process called electro-crystallization which composed of rates: nucleation and growth throughout which the particle size differs in both the rates (Wang et al., 2010). If the rate of nucleation is faster than the growth rate, more crystals of copper formed that are fine in powders. However, when the concentration of the copper sulfate pentahydrate concentration increases, the rate of growth enhances but producing a coarser copper particle (Yazici and Deveci, 2013). An optimum concentration is studied for these reasons, based on a constant current density supplied and the purity of the copper formed (Chu et al., 2015; Zhang et al., 2018a). Electronic items as in mixed motherboards and graphics cards are in high content of both copper and gold. These high valued materials are recycled via slurry electrolysis method that follows.

6.2.2 Gold recovery

Gold leaching process using cyanide were the norms for extraction from ores and has been carried over to extraction of gold from secondary resources as in electronic wastes. The toxicity in the environment leads to drastically reducing its usage and utilizes the applicability of using other leaching agents or other extraction pathways as in the electrochemical process. The recovery of gold using electrowinning and simultaneously leaching using copper ammoniacal thiosulfate solutions has been studied widely over the usage of cyanide (Ashiq et al., 2019; Bisceglie et al., 2017; Kasper et al., 2018). Because of the interference of copper ions in the recovery of gold, usage of this copper salt with additives such as sulfates, chlorides, and phosphate reduced the reduction rates of copper and thereby keeping the copper intact and increasing the volume of gold at the cathode. For instance, usage of EDTA stabilizes the thiosulphate by forming complexes with copper, and thus gold leaching was substantially achieved through the addition of EDTA. Amino acids have also been used as an excellent complexing agent for the selective gold recovery (Feng and Van Deventer, 2011; Kasper et al., 2011, 2018).

The rate of dissolution of gold in thiosulfate solutions that show poor solubility with gold is improved by the use of cupric amines or ferric oxalate or addition of sodium sulfite to the electrolytes. The presence of these sulfite ions prevents the thiosulfate from decomposing, which otherwise disproportionate to elemental sulfur and thereby decreasing the concentration of thiosulfate (Zelinsky, 2015; Zhang et al., 2012). Gold plated is used as a rotating disk electrode with the solution of sulfite and thiosulfate with the gold-containing solutions that need to be leached out (Zelinsky, 2015). Zelinsky and Novgorodtseva (2013) studied the gold anodic dissolution with additive thiourea on the graphite electrode. Graphite electrodes with Ag/AgCl (in saturated KCl) as a reference electrode and varying solutions concentrations of gold mixed with other elements of the waste electronic equipment were studied in Kasper et al. (2018).

Yap and Mohamed (2007) studied the usage of a galvanic cell for recovery of gold where different materials were utilized as a cathode. The drawback of utilizing an external cell that requires a power consumption has been addressed in this work and studied the use of the electrogenerated system without the use of an external supply (Hor and Mohamed, 2005; Spitzer and Bertazzoli, 2004; Yap and Mohamed, 2007). In an electro generative cell, the spontaneous cell reaction occurs, and the noblest of the elements deposits on the cathode and less noble metal is oxidized in the electrolyte, thereby creating the external current. The batch system is coupled with carbon-based porous materials as cathode along with the zinc in the galvanic cell for recovery of gold from cyanide solutions. Reticulated vitreous carbon (RVC) has proven the most effective cathode in recovering 99% of gold from the solution and most of the gold been deposited exhibited the smallest grain size at nanolevel particles (Yap and Mohamed, 2007; Yap and Mohamed, 2008).

6.2.3 Silver recovery

As was the case of gold recovery, cyanidation is the most widely used hydrometallurgical technique to leach out precious metals like silver from different sources. It is due to the repercussions it created to the environment, an alternative of thiourea or thiosulfate to be used as lixiviants have been studied extensively (Ashiq et al., 2019; Zhang et al., 2012). The major drawbacks of using thiosulphate lixiviants are its oxidative degradation to polythionates through interactions with many oxidizing agents present in the lixiviants. It is also common for the silver particles, as in the case of gold, a coating of Cu-S from the degradation of thiosulphate that further inhibits the deposition of silver any further. Electrodeposition combined with leaching has been utilized for silver recovery from electronic scraps and printed circuits boards using an electrochemical cell. Carbon paste electrodes with electro-active species using graphite powder, silver sulfide as an electro-active species have been used.

Ionic liquids are seen as an alternative for recovery of many of the noble metals from the electronic wastes. Ionic liquids are solvents that consist of ion pairs. They are organic solvents with a low melting point that has low vapor pressure and thus environmentally friendly solvents. They have been used in the recovery of divalent metal ions as in copper, platinum, palladium, and gold. The physicochemical characteristics can be altered through combinations of salts used to tune the different cations and the anions (Sebastián et al., 2018; Zhang et al., 2015). Ionic liquids facilitate the migration of silver cations easily in an electrogenerated cell using the organic solvents (Molodkina et al., 2019). Silver deposition from these solvents is a "greener" alternative to silver electroplating using toxic cyanide-containing electrolyte environments (Zhang et al., 2015). Various polycrystalline substrates as in glassy carbon, polycrystalline gold, and platinum are used with ionic liquids to check the deposition rates from Ag^+ to Ag^0 and silver nucleation studies (Ispas et al., 2011; Molodkina et al., 2019; Simka et al., 2009).

6.2.4 Rare earth elements recovery

Permanent magnets, rechargeable batteries, and lamp phosphors utilize a significant portion of rare earth elements (REEs) due to their unique magnetic and electronic properties. Their shortage and rareness in natural forms led to several studies for its recovery from secondary sources that are otherwise end-of-life (EoL) products (Gutfleisch et al., 2011; Prakash et al., 2015).

6.2.4.1 Neodymium recovery

Neodymium iron is widely used in the synthesis of permanent magnets and are recovered from their EoL magnets using dissolution of the scrap by alkali hydroxides to precipitate into neodymium salts that are further refined to form their oxides. Selective recovery of REEs from these magnets that is composed of several other metals focuses on factors influencing the codissolution of ion and boron that coexists in the magnets. The differences in the standard reduction potential are used to selectively recover the rare metals through selective dissolution and thereby collecting the REEs at the cathode. The dissolution of neodymium or for many REEs, acidic solutions are mostly favored for its dissolution due to the passive layer it forms on the scraps (Lee et al., 2014; Prakash et al., 2015; Vander Hoogerstraete et al., 2014). Codissolution of iron and cobalt, that are also part of the system scraps, is a common phenomenon when attempting to recover neodymium. Sulfamic acids and a certain high current density applied could make the iron smelt at the bottom leaving the neodymium salts present in the leachate whose pH is made to drop to acidic conditions to precipitate to obtain the recovered REEs. The scrap magnets are used as an anode in a simple two-electrode electrochemical system with the REEs gets concentrated in the leachate that can be further recovered and extracted via precipitation by double salt or with hydrogen fluoride (Prakash et al., 2015).

6.2.4.2 Tellurium recovery

Tellurium (Te) is also used widely in electronics, photonics, photovoltaics, and metallurgy as it is a p-type semiconductor with extensive crystalline properties (Halpert and Sredni, 2014; Zhong et al., 2018). It is especially used as photovoltaic cadmium telluride (CdTe) cell of solar origin, Te is of high demand in its synthesis, and even a small level of purity could create a tremendous difference in the energy level for storage. Thus, its purification and recovery is crucial and goes through a series of hydrometallurgical processes that cause high energy consumption for its recovery and high equipment cost and reduction reactions at corrosive acidic media that in turn create repercussions in the environment. The low electrodeposition rate of tellurium and many of the kind semiconductors consumes heavy energy and often leading to loss of purity of the REEs thereby showing low conductivity in the diverse applications used (Chang et al., 2014). At a conventional level, tellurium compounds can be reduced to Te by slime solutions with the presence of hydrochloric acids or sulfuric acid leaching solutions (Jin et al., 2018; Makuei and Senanayake, 2018). Tellurium is recovered by electrodeposition at a large scale where electrowinning is done at an alkaline leach liquor. To increase the electrodeposition rate, photo-assistance is provided, and better film quality is obtained in the recovery electrode (Chang et al., 2014; Fan et al., 2016; Yang et al., 2015). The rate of nucleation and growth of Te deposition has been an interest, especially its film formation of stainless steel plate in an alkaline solution using a three-electrode cell. Stainless steel electrode is kept as a working electrode, a saturated calomel electrode as a reference and pure graphite plate as an auxiliary electrode. A light source was used enhance the deposition rate onto the stainless steel substrate and kept to irradiate at a constant rate in a Te-rich leachate electrolyte containing sodium hydroxide as well (Dergacheva et al., 2014; Fan et al., 2016; Guo et al., 2014).

6.2.5 Ionic liquids for enhanced electrodeposition

Conventional aqueous solutions have its limitations in being selective to recover elements from their compounds and continuous liberation of a hydrogen molecule from the anodic reactions narrow the electrochemical window for elemental enhancement with lower stability and lesser efficient. Hydrogen evolution due to reduction half tends to hydroxylate the cathodic deposits due to pore formations and reduces the quality of the cathode (Simka et al., 2009). To overcome these problems, developments have been attempted to derive newer electrolytes extensively for elemental recovery using the cell and that can successfully reduce the reduction of the solvent to a great extent, maximizing the metal deposition (Sebastián et al., 2018; Su et al., 2010; Zhang et al., 2016).

Ionic liquids are free-water salt that is obtained from the dissolution of salts. They have incredibly high viscosity (20−100 mPa s) much higher than the traditional aqueous electrolytes (Fedorov and Kornyshev, 2014). They have much higher conductivity with low vapor pressure and low thermal stability but higher electrochemical stability which makes them unique to have a wider electrochemical window than the aqueous electrolyte (Conway et al., 1992; Dong and Zhang, 2012). Copper from waste PCBs showed a promising recovery when ionic liquids are utilized. Copper extracted using 1-butyl-3-methyl-imidazolium hydrogen sulfate showed almost full recovery (Huang et al., 2014). The driving force for high recovery rates is high electrochemical stability, electrical conductivity, adjustable polarity, and a wider electrochemical window compared to other electrodeposition methods (Zhang et al., 2009b,c; Zhang et al., 2018b). Zhang et al. (2018a) utilize N-butyl sulfonate pyridinium hydrosulfate, replacing sulfuric acid, to examine the recovery rates of copper in slurry electrolysis. As more sulfuric acid is replaced with IL, more copper is recovered and effectively reduced the particle size of the powder thereby forming fine powders with fine monocrystalline crystals with around 91% recovery (Zhang et al., 2018b).

REEs are progressively recovered using IL both at high and room temperature ILs. Owing to extremely high cathodic reduction potential for high ILs, room temperature ILs are preferred and studied for a varied range of REEs (Liu et al., 2016; Venkatesan et al., 2018; Zhang et al., 2016). In pursuit of recovering the waste elements from WEEEs, and electrochemical pathways to reduce to the base metal using ILs, Bagri et al. (2018) found the limit of using the conventional IL is the lack of reversibility that the metals/elements cannot be reoxidized once been reduced. Metals cannot be oxidized at anode, but they deposit on the cathode. Thus, they created a neutral ligand complexation of metal cations by increasing its size reducing the interactions between the cation and anion in the IL; this reduces the lattice energy which can diversify the recovery of a varied range of elements such as Nd, Dy, Gd, and Pr REEs recovery.

6.2.6 Process summary of the recovery of major elements present in waste electronic and electrical equipment

Table 6.3 Electrochemical recovery of selective metals from WEEEs.

WEEE	Elements in WEEE (weight%)	Recovered purity	Electrochemical conditions	References
Printed circuit boards (PCBs)	Cu 26	98	A mixture of copper sulfate pentahydrate, sodium chloride, and sulfuric acid as an electrolyte. Metal scraps obtained from mechanical processing of PCB are pressed to be used directly as anode and copper sheet of 99% purity as a cathode. The concentration of each of the solutions in the electrolyte was varied with different current density to examine the deposition effects separately	Chu et al. (2015) and Li and Zeng (2012)
		92	Electrowinning of synthetic copper sulfate solution and pregnant leach solution for PCB with polyoxometalate (POM), ammonium metatungstate hydrate as an additive to see the effect of current density on the migration of copper to the cathode. Copper and titanium sheets of the same dimensions were used as cathode and anode, respectively	Ehsani et al. (2016)
		99.6	Shredded WEEE up to 8 mm waste introduced in titanium basket as an anode. Pure copper sheets as cathode and ammonia and ammonium sulfate were used as the electrolyte. Optimum current density was identified, and copper recovered to a significant extent	Haccuria et al. (2017)
	24% Cu, 2% Au	94% Cu, 95% Au	Synthetic solutions containing thiosulfate, ammonia, copper, and gold were used for voltammetry studies with a three-electrode system: Pt rotating disk	Kasper et al. (2018)

(*Continued*)

Table 6.3 (Continued)

WEEE	Elements in WEEE (weight%)	Recovered purity	Electrochemical conditions	References
			electrode as the working electrode, Ag/AgCl as a reference electrode and Pt for the counter electrode	
From leached wastewaters of mobile equipment, laptop, tablets	Ni	99	Electrofloatation technique using both electrodes at aluminum and the electrolytes are synthetic wastewater with concentration series of nickel to check its influence on the current density	Coman et al. (2013)
		94	Electrodialysis and electro-leaching of nickel-containing rinse wastewaters using platinized titanium grids packed in beds of graphite powder. Instead of using a semipermeable membrane or ion exchange membranes, electrostatic shielding zones-ionic current sinks (ESZs- ICSs) were utilized	Dermentzis (2010)

6.2.7 Process flow chart

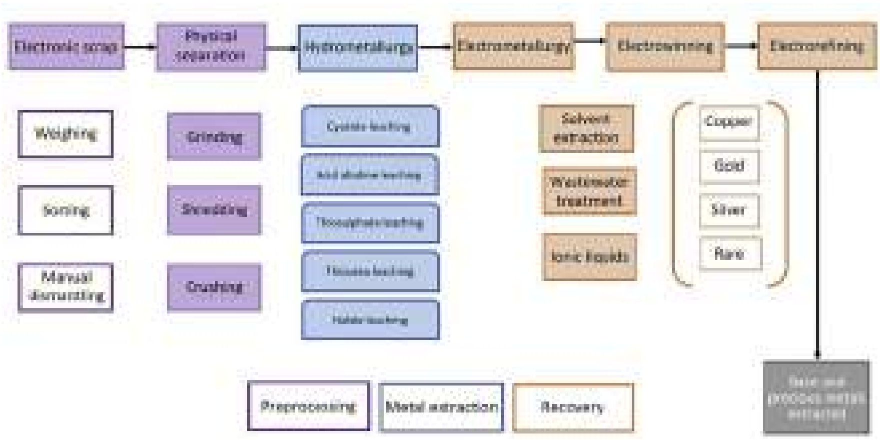

Figure 6.2 General flowsheet of electronic waste recovery to base metals.

6.3 Future outlook

The heterogeneous nature of the waste warrants special requirements for their metal recovery. The recovery of metals usually achieved through manual sorting as in crushing, screening, magnetic or even hydrometallurgical techniques that vary depending on the presence of other materials of the electronic equipment and the ease of separation (Fig. 6.2). Silver and other precious metals are of great importance to recover due to their rising prices and depletion of their parent ores. The most appropriate process must be initiated and studied further to recover these metals (Cortés López et al., 2017; Seisko et al., 2018).

Electrowinning, solvent extraction, precipitation, and ion-exchange are many of the several techniques used for the recovery of valuable metals from leach liquor (Kim et al., 2011; Yi et al., 2016; Yong et al., 2019). Major metals are recovered using electrowinning and then smelting to obtain the secondary usable raw materials. Precious metals being recovered at the anodic slimes in an electrochemical enhanced cell are predominantly recovered and rarely required further electrorefining (Alzate et al., 2017; Ashiq et al., 2018; Makuei and Senanayake, 2018). Table 6.3 lists out the major elements recovered from typical wastes with their purity and electrochemical conditions. Current efficiency needs to be studied further as the involvement of current density arising from the chemical reactions tends to make the system unstable to selectively refine the target elements (Lekka et al., 2015; Zhang et al., 2009a). One of the bigger pictures for sustainable usage of natural resources is to have the electronic equipment made from biodegradable materials so that they can be directly be converted to compost thereby, without the dependence of these expensive materials which still has a long way toward technological advancement in this electronic era.

References

Abdelbasir, S.M., Hassan, S.S.M., Kamel, A.H., El-Nasr, R.S., 2018. Status of electronic waste recycling techniques: a review. Environ. Sci. Pollut. Res. 25 (17), 16533−16547. Available from: https://doi.org/10.1007/s11356-018-2136-6.

Alzate, A., López, E., Serna, C., Gonzalez, O., 2017. Gold recovery from printed circuit boards by selective breaking of internal metallic bonds using activated persulfate solutions. J. Clean. Prod. 166, 1102−1112. Available from: https://doi.org/10.1016/j.jclepro.2017.08.124.

Ashiq, A., Gunarathne, V., Vithanage, M., 2018. Overview scheme for nickel removal and recovery from wastes. Nickel Soils Plants (March 2019), 319−340. Available from: https://doi.org/10.1201/9781315154664-14.

Ashiq, A., Kulkarni, J., Vithanage, M., 2019. Hydrometallurgical recovery of metals from e-waste. In: Prasad, M.N.V., Vithanage, M. (Eds.), Electronic Waste Management and Treatment Technology. Butterworth-Heinemann, pp. 225−246. https://doi.org/10.1016/B978-0-12-816190-6.00010-8.

Awasthi, A.K., Li, J., 2017. An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE. Resour. Conserv. Recycl. 126, 228–239. Available from: https://doi.org/10.1016/j.resconrec.2017.07.014.

Bagri, P., Luo, H., Popovs, I., Thapaliya, B.P., Dehaudt, J., Dai, S., 2018. Trimethyl phosphate based neutral ligand room temperature ionic liquids for electrodeposition of rare earth elements. https://doi.org/10.1016/j.elecom.2018.10.001.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-waste Monitor 2014: Quantities, Flows and Resources. The Global E-Waste Monitor—2014. https://doi.org/9789280845556.

Bisceglie, F., Civati, D., Bonati, B., Faraci, F.D., 2017. Reduction of potassium cyanide usage in a consolidated industrial process for gold recovery from wastes and scraps. J. Clean. Prod. 142, 1810–1818. Available from: https://doi.org/10.1016/j.jclepro.2016.11.103.

Boudesocque, S., Mohamadou, A., Conreux, A., Marin, B., Dupont, L., 2019. The recovery and selective extraction of gold and platinum by novel ionic liquids. Sep. Purif. Technol. 210, 824–834. Available from: https://doi.org/10.1016/j.seppur.2018.09.002.

Chang, T.-W., Lee, W.-H., Su, Y.-H., Hsiao, Y.-J., 2014. Effects of photo-assisted electrodeposited on CuInSe 2 thin films. Nanoscale Res. Lett. 9 (1), 660.

Chu, Y., Chen, M., Chen, S., Wang, B., Fu, K., Chen, H., 2015. Micro-copper powders recovered from waste printed circuit boards by electrolysis. https://doi.org/10.1016/j.hydromet.2015.06.006.

Coman, V., Robotin, B., Ilea, P., 2013. Nickel recovery/removal from industrial wastes: a review. Resour. Conserv. Recycl. 73, 229–238. Available from: https://doi.org/10.1016/j.resconrec.2013.01.019.

Conway, B.E., Liu, J., Qian, S.Y., 1992. Structure of interphases of low melting point salts and protonic hydrates with mercury and gold in relation to double-layer capacitance behaviour. J. Electroanal. Chem. 329 (1–2), 201–223.

Cortés López, C., Reyes Cruz, V.E., Veloz Rodríguez, M.A., Urbano Reyes, G., Cobos Murcia, J.A., Nava Montes de Oca, J.L., 2017. Electrochemical selective leaching and deposition of Ag, Au and Pt from electronic waste.. Int. J. Electrochem. Sci. 12 (9), 8198–8216. Available from: https://doi.org/10.20964/2017.09.45.

Cui, H., Anderson, C.G., 2016. Literature review of hydrometallurgical recycling of printed circuit boards (PCBs). J. Adv. Chem. Eng. 6 (1), 1–11. Available from: https://doi.org/10.4172/2090-4568.1000142.

Dergacheva, M.B., Urazov, K.A., Leont'eva, K.A., 2014. Photoelectrochemical deposition of thin tellurium films. Russ. J. Appl. Chem. 87 (6), 724–729.

Dermentzis, K., 2010. Removal of nickel from electroplating rinse waters using electrostatic shielding electrodialysis/electrodeionization. J. Hazard. Mater. 173 (1–3), 647–652. Available from: https://doi.org/10.1016/j.jhazmat.2009.08.133.

Dong, K., Zhang, S., 2012. Hydrogen bonds: a structural insight into ionic liquids. Chem.: Eur. J. 18 (10), 2748–2761.

Ehsani, A., Yazici, Y., Deveci, H., 2016. Influence of polyoxometallates as additive on electro-winning of copper. https://doi.org/10.1016/j.hydromet.2016.03.002.

EPA, 2007. Electronic Waste Management in the United States—Approach 1 (Draft Final). Washington, DC, 51.

Fan, Y., Jiang, L., Yang, J., Jiang, Y., Liu, F., 2016. The electrochemical behavior of tellurium on stainless steel substrate in alkaline solution and the illumination effects. J. Electroanal. Chem. 771, 17–22. Available from: https://doi.org/10.1016/j.jelechem.2016.03.043.

Fedorov, M.V., Kornyshev, A.A., 2014. Ionic liquids at electrified interfaces. Chem. Rev. 114 (5), 2978–3036.

Feng, D., Van Deventer, J.S.J., 2011. The role of amino acids in the thiosulphate leaching of gold. Miner. Eng. 24 (9), 1022–1024. Available from: https://doi.org/10.1016/j.mineng.2011.04.017.

Fogarasi, S., Imre-Lucaci, F., Egedy, A., Imre-Lucaci, Á., Ilea, P., 2015. Eco-friendly copper recovery process from waste printed circuit boards using Fe^{3+}/Fe^{2+} redox system. Waste Manage. 40, 136–143. Available from: https://doi.org/10.1016/j.wasman.2015.02.030.

Frazzoli, C., Orisakwe, O.E., Dragone, R., Mantovani, A., 2010. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environ. Impact Assess. Rev. 30 (6), 388–399. Available from: https://doi.org/10.1016/j.eiar.2009.12.004.

Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B.K., 2015. Criticality of metals and metalloids. Proc. Natl Acad. Sci. U.S.A. 112 (14), 4257–4262. Available from: https://doi.org/10.1073/pnas.1500415112.

Guimarães, Y.F., Santos, I.D., Dutra, A.J.B., 2014. Direct recovery of copper from printed circuit boards (PCBs) powder concentrate by a simultaneous electroleaching-electrodeposition process. Hydrometallurgy 149, 63–70. Available from: https://doi.org/10.1016/j.hydromet.2014.06.005.

Guo, X., Diao, P., Xu, D., Huang, S., Yang, Y., Jin, T., et al., 2014. CuO/Pd composite photocathodes for photoelectrochemical hydrogen evolution reaction. Int. J. Hydrogen Energy 39 (15), 7686–7696. Available from: https://doi.org/10.1016/j.ijhydene.2014.03.084.

Gutfleisch, O., Willard, M.A., Bruck, E., Chen, C.H., Sankar, S.G., Liu, J.P., 2011. Magnetic materials and devices for the 21st century.pdf. Adv. Mater. 23 (7), 821–842.

Haccuria, E., Ning, P., Cao, H., Venkatesan, P., Jin, W., Yang, Y., et al., 2017. Effective treatment for electronic waste—selective recovery of copper by combining electrochemical dissolution and deposition. J. Clean. Prod. 152, 150–156. Available from: https://doi.org/10.1016/j.jclepro.2017.03.112.

Halpert, G., Sredni, B., 2014. The effect of the novel tellurium compound AS101 on autoimmune diseases. Autoimmun. Rev. 13 (12), 1230–1235. Available from: https://doi.org/10.1016/j.autrev.2014.08.003.

Hor, Y.P., Mohamed, N., 2005. Removal and recovery of copper via a galvanic cementation system part II: batch-recycle reactor. J. Appl. Electrochem. 35. Available from: https://doi.org/10.1007/s10800-005-2322-3.

Hossain, S., Al-Hamadani, S.M.Z.F., Rahman, T., 2015. E-waste: a challenge for sustainable development. J. Health Pollut. 5 (9), 3–11. Available from: https://doi.org/10.5696/2156-9614-5-9.3.

Huang, J., Chen, M., Chen, H., Chen, S., Sun, Q., 2014. Leaching behavior of copper from waste printed circuit boards with Brønsted acidic ionic liquid. Waste Manage. (Oxford) 34 (2), 483–488. Available from: https://doi.org/10.1016/j.wasman.2013.10.027.

Işıldar, A., Rene, E.R., van Hullebusch, E.D., Lens, P.N.L., 2018. Electronic waste as a secondary source of critical metals: management and recovery technologies. Resour. Conserv. Recycl. 135, 296–312. Available from: https://doi.org/10.1016/j.resconrec.2017.07.031.

Ispas, A., Pölleth, M., Ba, K.H.T., Bund, A., Janek, J., 2011. Electrochemical deposition of silver from 1-ethyl-3-methylimidazolium trifluoromethanesulfonate. Electrochim. Acta 56 (28), 10332–10339. Available from: https://doi.org/10.1016/j.electacta.2011.04.060.

Jha, M.K., Choubey, P.K., Jha, A.K., Kumari, A., Lee, J.-chun, Kumar, V., et al., 2012. Leaching studies for tin recovery from waste e-scrap. Waste Manage. (Oxford) 32 (10), 1919–1925. Available from: https://doi.org/10.1016/j.wasman.2012.05.006.

Jin, W., Su, J., Chen, S., Li, P., Moats, M.S., Maduraiveeran, G., et al., 2018. Efficient electrochemical recovery of fine tellurium powder from hydrochloric acid media via mass transfer enhancement. Sep. Purif. Technol. 203, 117–123. Available from: https://doi.org/10.1016/j.seppur.2018.04.026.

Kasper, A.C., Berselli, G.B.T., Freitas, B.D., Tenório, J.A.S., Bernardes, A.M., Veit, H.M., 2011. Printed wiring boards for mobile phones: characterization and recycling of copper. Waste Manage. (Oxford) 31 (12), 2536–2545. Available from: https://doi.org/10.1016/j.wasman.2011.08.013.

Kasper, A.C., Veit, H.M., García-Gabaldón, M., Herranz, V.P., 2018. Electrochemical study of gold recovery from ammoniacal thiosulfate, simulating the PCBs leaching of mobile phones. Electrochim. Acta 259, 500–509. Available from: https://doi.org/10.1016/j.electacta.2017.10.161.

Kaya, M., 2016. Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. Waste Manage. 57, 64–90. Available from: https://doi.org/10.1016/j.wasman.2016.08.004.

Khaliq, A., Rhamdhani, M., Brooks, G., Masood, S., 2014. Metal extraction processes for electronic waste and existing industrial routes: a review and australian perspective. Resources 3 (1), 152–179. Available from: https://doi.org/10.3390/resources3010152.

Kim, E.Y., Kim, M.S., Lee, J.C., Pandey, B.D., 2011. Selective recovery of gold from waste mobile phone PCBs by hydrometallurgical process. J. Hazard. Mater. 198, 206–215. Available from: https://doi.org/10.1016/j.jhazmat.2011.10.034.

Lee, J., Kim, S., Shin, D., 2014. Electrodeposition of iron in HNO3 solution containing iron dissolved from copper slag. J. Electrochem. Soc. 161 (14), D719–D724.

Lekka, M., Masavetas, I., Benedetti, A.V., Moutsatsou, A., Fedrizzi, L., 2015. Gold recovery from waste electrical and electronic equipment by electrodeposition: a feasibility study. Hydrometallurgy 157, 97–106. Available from: https://doi.org/10.1016/j.hydromet.2015.07.017.

Li, J., Zeng, X., 2012. Recycling printed circuit boards. Waste Electrical and Electronic Equipment (WEEE) Handbook 287–311. Available from: https://doi.org/10.1533/9780857096333.3.287.

Li, L., Lu, J., Ren, Y., Zhang, X.X., Chen, R.J., Wu, F., et al., 2012. Ascorbic-acid-assisted recovery of cobalt and lithium from spent Li-ion batteries. J. Power Sources 218, 21–27. Available from: https://doi.org/10.1016/j.jpowsour.2012.06.068.

Li, F., Chen, M., Shu, J., Shirvani, M., Li, Y., Sun, Z., et al., 2019. Copper and gold recovery from CPU sockets by one-step slurry electrolysis. https://doi.org/10.1016/j.jclepro.2018.12.161.

Liu, W., Tang, M., Tang, C., He, J., Yang, S., Yang, J., 2010. Dissolution kinetics of low grade complex copper ore in ammonia-ammonium chloride solution. Trans. Nonfer. Metal. Soc. China 20 (5), 910–917. Available from: https://doi.org/10.1016/S1003-6326(09)60235-1.

Liu, F., Deng, Y., Han, X., Hu, W., Zhong, C., 2016. Electrodeposition of metals and alloys from ionic liquids. J. Alloys Compd. 654, 163–170. Available from: https://doi.org/10.1016/j.jallcom.2015.09.137.

Makuei, F.M., Senanayake, G., 2018. Extraction of tellurium from lead and copper bearing feed materials and interim metallurgical products: a short review. Miner. Eng. 115, 79–87. Available from: https://doi.org/10.1016/j.mineng.2017.10.013.

Mezine, Z., Kadri, A., Hamadou, L., Benbrahim, N., Chaouchi, A., 2018. Electrodeposition of copper oxides (Cu x O y) from acetate bath. J. Electroanal. Chem. 817, 36−47. Available from: https://doi.org/10.1016/j.jelechem.2018.03.055.

Molodkina, E.B., Ehrenburg, M.R., Broekmann, P., Rudnev, A.V., 2019. Initial stages of silver electrodeposition on single crystal electrodes from ionic liquids. Electrochim. Acta 299, 320−329. Available from: https://doi.org/10.1016/j.electacta.2019.01.018.

Oguchi, M., Sakanakura, H., Terazono, A., 2013. Toxic metals in WEEE: characterization and substance flow analysis in waste treatment processes. Sci. Total Environ. 463−464, 1124−1132. Available from: https://doi.org/10.1016/j.scitotenv.2012.07.078.

Ogunniyi, I., Vermaak, M.K., Groot, D., 2009. Chemical composition and liberation characterization of printed circuit board communition fines for beneficiation investigations. Waste Manag 29 (7), 2140−2146.

Oh, C.J., Lee, S.O., Yang, H.S., Ha, T.J., Kim, M.J., 2003. Selective leaching of valuable metals from waste printed circuit boards. J. Air Waste Manage. Assoc. 53 (7), 897−902. Available from: https://doi.org/10.1080/10473289.2003.10466230.

Oishi, T., Yaguchi, M., Koyama, K., Tanaka, M., Lee, J.C., 2008. Hydrometallurgical process for the recycling of copper using anodic oxidation of cuprous ammine complexes and flow-through electrolysis. Electrochim. Acta 53 (5), 2585−2592. Available from: https://doi.org/10.1016/j.electacta.2007.10.046.

Önal, M.A.R., Binnemans, K., 2019. Recovery of rare earths from waste cathode ray tube (CRT) phosphor powder by selective sulfation roasting and water leaching. Hydrometallurgy 183, 60−70. Available from: https://doi.org/10.1016/j.hydromet.2018.11.005.

Ozgur, C., Coskun, S., Akcil, A., Beyhan, M., Üncü, I.S., Civelekoglu, G., 2016. Combined oxidative leaching and electrowinning process for mercury recovery from spent fluorescent lamps. Waste Manage. 57, 215−219. Available from: https://doi.org/10.1016/j.wasman.2016.03.039.

Pinto, V., 2008. E-waste hazard: the impending challenge. Ind. J. Occup. Environ. Med. 12 (2), 65. Available from: https://doi.org/10.4103/0019-5278.43263.

Prakash, V., Sun, Z.H.I., Sietsma, J., Yang, Y., 2015. Simultaneous electrochemical recovery of rare earth elements and iron from magnet scrap: a theoretical analysis. Rare Earths Industry: Technological, Economic, and Environmental Implications. Elsevier Inc. Available from: https://doi.org/10.1016/B978-0-12-802328-0.00022-X.

Puente-Siller, D.M., Fuentes-Aceituno, J.C., Nava-Alonso, F., 2017. An analysis of the efficiency and sustainability of the thiosulfate-copper-ammonia-monoethanolamine system for the recovery of silver as an alternative to cyanidation. Hydrometallurgy 169, 16−25. Available from: https://doi.org/10.1016/j.hydromet.2016.12.003.

Quinet, P., Proost, J., Van Lierde, A., 2005. Recovery of precious metals from electronic scrap by hydrometallurgical processing routes. Miner. Metall. Process. 22, 17−22. Available from: https://doi.org/10.1007/BF03403191.

Rajagopal, R.R., Rajarao, R., Sahajwalla, V., 2016. High temperature transformations of waste printed circuit boards from computer monitor and CPU: characterisation of residues and kinetic studies. Waste Manage. 57, 91−101. Available from: https://doi.org/10.1016/j.wasman.2015.11.016.

Roslan, N.A., Suah, F.B.M., Mohamed, N., 2017. The use of an electrogenerative process as a greener method for recovery of gold(III) from the e-waste. Sep. Purif. Technol. 182, 1−8. Available from: https://doi.org/10.1016/j.seppur.2017.03.032.

Salhofer, S., Steuer, B., Ramusch, R., Beigl, P., 2016. WEEE management in Europe and China: a comparison. Waste Manage. 57, 27−35. Available from: https://doi.org/10.1016/j.wasman.2015.11.014.

Sebastián, P., Climent, V., Feliu, J.M., Gómez, E., 2018. Ionic liquids in the field of metal electrodeposition. Ref. Mod. Chem. Mol. Sci. Chem. Eng. 690−700. Available from: https://doi.org/10.1016/b978-0-12-409547-2.13379-7.

Seisko, S., Lampinen, M., Aromaa, J., Laari, A., Koiranen, T., Lundström, M., 2018. Kinetics and mechanisms of gold dissolution by ferric chloride leaching. Miner. Eng. 115 (October 2017), 131−141. Available from: https://doi.org/10.1016/j.mineng.2017.10.017.

Simka, W., Puszczyk, D., Nawrat, G., 2009. Electrodeposition of metals from non-aqueous solutions. Electrochim. Acta 54 (23), 5307−5319. Available from: https://doi.org/10.1016/j.electacta.2009.04.028.

Sobianowska-Turek, A., 2018. Hydrometallurgical recovery of metals: Ce, La, Co, Fe, Mn, Ni and Zn from the stream of used Ni-MH cells. https://doi.org/10.1016/j.wasman.2018.03.046.

Spitzer, M., Bertazzoli, R., 2004. Selective electrochemical recovery of gold and silver from cyanide aqueous effluents using titanium and vitreous carbon cathodes. Hydrometallurgy 74 (3), 233−242. Available from: https://doi.org/10.1016/j.hydromet.2004.05.001.

Su, Y., Fu, Y., Wei, Y., Yan, J., Mao, B., 2010. The electrode/ionic liquid interface: electric double layer and metal electrodeposition. ChemPhysChem 11 (13), 2764−2778.

Swain, B., Mishra, C., Hong, H.S., Cho, S.S., 2016. Beneficiation and recovery of indium from liquid-crystal-display glass by hydrometallurgy. Waste Manag. 57, 207−214. Available from: https://doi.org/10.1016/j.wasman.2016.02.019.

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25 (1), 28−37. Available from: https://doi.org/10.1016/j.mineng.2011.09.019.

Vander Hoogerstraete, T., Blanpain, B., Van Gerven, T., Binnemans, K., 2014. From NdFeB magnets towards the rare-earth oxides: a recycling process consuming only oxalic acid. RSC Adv. 4 (109), 64099−64111. Available from: https://doi.org/10.1039/c4ra13787f.

Vegliò, F., Quaresima, R., Fornari, P., Ubaldini, S., 2003. Recovery of valuable metals from electronic and galvanic industrial wastes by leaching and electrowinning. Waste Manag. 23 (3), 245−252. Available from: https://doi.org/10.1016/S0956-053X(02)00157-5.

Veit, H.M., Bernardes, A.M., Kasper, A.C., Juchneski, N.C., de, F., Calgaro, C.O., et al., 2015. In: Veit, H.M., Moura Bernardes, A. (Eds.), Electronic Waste. Springer International Publishing, Cham. Available from: https://doi.org/10.1007/978-3-319-15714-6.

Venkatesan, P., Vander Hoogerstraete, T., Hennebel, T., Binnemans, K., Sietsma, J., Yang, Y., 2018. Selective electrochemical extraction of REEs from NdFeB magnet waste at room temperature. Green Chem. 20 (5), 1065−1073. Available from: https://doi.org/10.1039/c7gc03296j.

Vidyadhar, A., 2016. A review of technology of metal recovery from electronic waste. E-Waste in Transition—From Pollution to Resource. Available from: https://doi.org/10.5772/61569.

Walker, R., 1979. The role of ultrasound in the electrowinning and electro-refining of metals. Hydrometallurgy 4 (3), 209−215. Available from: https://doi.org/10.1016/0304-386X(79)90012-4.

Wang, M., Wang, Z., Guo, Z., 2010. Preparation of electrolytic copper powders with high current efficiency enhanced by super gravity field and its mechanism. Trans. Nonfer. Metal. Soc. China 20 (6), 1154−1160. Available from: https://doi.org/10.1016/S1003-6326(09)60271-5.

Wang, H., Zhang, S., Li, B., Pan, D., Wu, Y., Zuo, T., 2017. Recovery of waste printed circuit boards through pyrometallurgical processing: a review. Resour. Conserv. Recycl. 126 (July), 209−218. Available from: https://doi.org/10.1016/j.resconrec.2017.08.001.

Wu, C.H., Kuo, C.Y., Lo, S.L., 2009. Recovery of heavy metals from industrial sludge using various acid extraction approaches. Water Sci. Technol. 59 (2), 289−293. Available from: https://doi.org/10.2166/wst.2009.859.

Yang, J.G., Wu, Y.T., Li, J., 2012. Recovery of ultrafine copper particles from metal components of waste printed circuit boards. Hydrometallurgy 121−124, 1−6. Available from: https://doi.org/10.1016/j.hydromet.2012.04.015.

Yang, J., Lai, Y., Fan, Y., Jiang, Y., Tang, D., Jiang, L., et al., 2015. Photoelectrochemically deposited Sb 2 Se 3 thin films: deposition mechanism and characterization. RSC Adv. 5 (104), 85592−85597.

Yap, C.Y., Mohamed, N., 2007. An electrogenerative process for the recovery of gold from cyanide solutions. Chemosphere 67 (8), 1502−1510. Available from: https://doi.org/10.1016/j.chemosphere.2006.12.017.

Yap, C.Y., Mohamed, N., 2008. Electrogenerative gold recovery from cyanide solutions using a flow-through cell with activated reticulated vitreous carbon. https://doi.org/10.1016/j.chemosphere.2008.07.014.

Yazici, E.Y., Deveci, H., 2013. Extraction of metals from waste printed circuit boards (WPCBs) in H2SO4−CuSO4−NaCl solutions. Hydrometallurgy 139, 30−38. Available from: https://doi.org/10.1016/j.hydromet.2013.06.018.

Yi, Q., Fan, R., Xie, F., Min, H., Zhang, Q., Luo, Z., 2016. Selective recovery of Au(III) and Pd(II) from waste PCBs using ethylenediamine modified persimmon tannin adsorbent. Proced. Environ. Sci. 31, 185−194. Available from: https://doi.org/10.1016/j.proenv.2016.02.025.

Yong, Y.S., An Lim, Y., Ilankoon, I., Selatan, L., Sunway, B., Darul Ehsan, S., 2019. An analysis of electronic waste management strategies and recycling operations in Malaysia: challenges and future prospects. https://doi.org/10.1016/j.jclepro.2019.03.205.

Zelinsky, A.G., 2015. Anode current on gold in mixed thiosulfate-sulfite electrolytes. Electrochim. Acta 154, 315−320. Available from: https://doi.org/10.1016/j.electacta.2014.12.097.

Zelinsky, A.G., Novgorodtseva, O.N., 2013. Effect of thiourea on the rate of anodic processes at gold and graphite electrodes in thiosulfate solutions. Electrochim. Acta 109, 482−488. Available from: https://doi.org/10.1016/j.electacta.2013.07.103.

Zeng, X., Yang, C., Chiang, J.F., Li, J., 2017. Innovating e-waste management: from macroscopic to microscopic scales. Sci. Total Environ. 575, 1−5. Available from: https://doi.org/10.1016/j.scitotenv.2016.09.078.

Zhang, L., Xu, Z., 2016. A review of current progress of recycling technologies for metals from waste electrical and electronic equipment. J. Clean. Prod. 127, 19−36. Available from: https://doi.org/10.1016/j.jclepro.2016.04.004.

Zhang, Q.B., Hua, Y.X., Wang, Y.T., Lu, H.J., Zhang, X.Y., 2009a. Effects of ionic liquid additive [BMIM]HSO 4 on copper electro-deposition from acidic sulfate electrolyte. https://doi.org/10.1016/j.hydromet.2009.05.017.

Zhang, Q.B., Hua, Y.X., Wang, Y.T., Lu, H.J., Zhang, X.Y., 2009b. Effects of ionic liquid additive [BMIM]HSO4 on copper electro-deposition from acidic sulfate electrolyte.

Hydrometallurgy 98 (3), 291–297. Available from: https://doi.org/10.1016/j.hydromet.2009.05.017.

Zhang, Qi. Bo, Hua, Y.X., Dong, T.G., Zhou, D.G., 2009c. Effects of temperature and current density on zinc electrodeposition from acidic sulfate electrolyte with [BMIM] HSO4 as additive. J. Appl. Electrochem. 39 (8), 1207.

Zhang, Y., Liu, S., Xie, H., Zeng, X., Li, J., 2012. Current satus on leaching precious metals from waste printed circuit boards. Proced. Environ. Sci. 16, 560–568. Available from: https://doi.org/10.1016/j.proenv.2012.10.077.

Zhang, Q., Zhang, S., Lu, X., Zhang, X., Wang, Q., 2015. Electrodeposition in ionic liquids. ChemPhysChem 17 (3), 335–351. Available from: https://doi.org/10.1002/cphc.201500713.

Zhang, Q., Wang, Q., Zhang, S., Lu, X., Zhang, X., 2016. Electrodeposition in ionic liquids. ChemPhysChem 17 (3), 335–351. Available from: https://doi.org/10.1002/cphc.201500713.

Zhang, S., Li, Y., Wang, R., Xu, Z., Wang, B., Chen, S., et al., 2017. Superfine copper powders recycled from concentrated metal scraps of waste printed circuit boards by slurry electrolysis. J. Clean. Prod. 152, 1–6. Available from: https://doi.org/10.1016/j.jclepro.2017.03.087.

Zhang, Y., Chen, M., Tan, Q., Wang, B., Chen, S., 2018a. Recovery of copper from WPCBs using slurry electrolysis with ionic liquid [BSO3HPy]•HSO 4. https://doi.org/10.1016/j.hydromet.2017.11.004.

Zhang, Y., Chen, M., Tan, Q., Wang, B., Chen, S., 2018b. Recovery of copper from WPCBs using slurry electrolysis with ionic liquid [BSO3HPy]•HSO4. Hydrometallurgy 175, 150–154. Available from: https://doi.org/10.1016/j.hydromet.2017.11.004.

Zhong, J., Wang, G., Fan, J., Li, Q., Kiani, M., Zhang, J., et al., 2018. Optimization of process on electrodeposition of 4N tellurium from alkaline leaching solutions. Hydrometallurgy 176, 17–25. Available from: https://doi.org/10.1016/j.hydromet.2017.11.011.

Zhu, P., Gu, G.B., 2002. Recovery of gold and copper from waste printed circuits. Chin. J. Rare Metals 26 (3), 214–216.

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Phytoremediation for E-waste contaminated sites

7

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7.1 Introduction

Electronic waste (E-waste) is defined as any electrical or electronic appliance discarded at the end of its life cycle that has become a solid waste of global concern during the last decade (Gaidajis et al., 2010; Ni and Zeng, 2009). Such waste can be categorized into a wide variety of classes including household appliances, IT and telecommunication equipment, consumer equipment, lightning equipment, tools, toys and sports equipment, medical devices, monitoring and control instruments, and automatic dispensers (Balde et al., 2017; Lundgren, 2012). The reported global E-waste generation in 2016 was approximately 45 million metric tons, which is expected to have an annual growth rate of 3%−4% (Balde et al., 2017). E-waste accumulation has become more significant in developed countries as compared to developing countries due to higher disposal rates (Lundgren, 2012; Ni and Zeng, 2009). In contrast, fewer rates of disposing of E-waste are observed in economically less developed or developing countries owing to prevailing trade, reuse, and resell of such appliances (Lundgren, 2012).

7.1.1 E-waste: types, composition, and hazardous components

A myriad of sources can contribute to the electronic and electrical rejects that make up highly complex waste streams. Inorganic and organic pollutants in E-waste amounting to more than a thousand have been reported in the scientific literature (Gaidajis et al., 2010). Inorganic pollutants can be attributed to toxic metals, such as mercury in switches and relays, lithium in batteries, beryllium in contact material, and several rare earth elements, such as antimony in flame retardants, gallium and indium in silicon chips, and LCD monitors (Kiddee et al., 2013; Li et al., 2011; Martin and Griswold, 2009; Tsydenova and Bengtsson, 2011). In addition, polyvinyl chlorides (PVCs) in fibers, polychlorinated biphenyls (PCBs) in transformers

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00005-X

and condensers, polycyclic aromatic hydrocarbons (PAHs) from computer casings and circuit boards, polychlorinated dibenzodioxins and dibenzofurans (PCDD/DFs) from dismantling E-waste, polybrominated diphenyl ethers (PBDEs) from flame retardants, and chlorofluorocarbons (CFCs) from dismantled refrigerators and air conditioners form the enumerate range of organic pollutants (Birnbaum et al., 2003; Gaidajis et al., 2010; Kim et al., 2013; Leung et al., 2006; Ni and Zeng, 2009; Robinson, 2009; Safe, 1993; Siddiqi et al., 2003; Wilkinson et al., 1999).

7.1.2 Major impacts on human health and environment

E-waste has been reported to cause severe impacts due to the inefficient waste management techniques used. Majority of solid wastes are disposed in landfills, and on most occasions, these landfills are either open dumps or poorly managed sites (Barba-Gutiérrez et al., 2008; Robinson, 2009). It has also been reported that many of the E-waste recycling site operations are primordial such as open burning, toner sweeping, circuit board recycling, acid stripping of chips, plastic fragmentation, and melting, which enable the easy escape of toxic substances to the environment (Ni and Zeng, 2009). The acts of dumping, dismantling, burning, and leaching yield in various toxic leachates, particulate matter, effluents, and fumes (Frenk et al., 2010). Moreover, the current legislation gap facilitates illegal transboundary movement of E-waste where a large quantity is exported to some Asian countries such as China, India, Pakistan, and in some African countries, such as Ghana and Nigeria, which are known as crude E-waste recycling hotspots (Chi et al., 2011; Lundgren, 2012).

In light of the aforementioned pollutants, the predicament created has presented many environmental and health-related complications. Bioaccumulation of toxic components in animal tissues and their presence in food chains have severely affected the normal functioning of natural ecosystems. Arable lands comprising livestock is found to have accumulated the undesired outputs of E-waste. Due to their slow metabolic rates inside the guts of animals, these chemicals continue to persist inside them (Lundgren, 2012). Humans exposed to these chemicals have shown undesirable side effects relating to the gastrointestinal tract, the respiratory system, and other organs (Nordbrand, 2009). Coughing, choking, breathing difficulties, eye irritations, skin diseases, convulsions, and even death are possible outcomes (Prakash et al., 2010; Yu et al., 2006). A detailed description of potential pollutants attributed to E-waste, their sources, and deleterious health effects are shown in Table 7.1.

Incorporation of apt remediation schemes for E-waste management has been understood to meet six major areas of the sustainable development goals (SDGs) out of the seventeen that exist. Controlling the release of hazardous chemicals from these waste into the environment ensures good health and wellbeing of the society. Achieving clean water and sanitation leads to the conservation of aquatic ecosystems, thereby attaining the goal of protection of life underwater. Sustainable cities and communities can be developed by entailing the 3 R (reduce, reuse, and recycle) procedures which fulfill the goal of responsible consumption and production alongside this. The goal of decent work and economic growth which is focused on the

Table 7.1 Sources and deleterious health effects of potential pollutants attributed to E-waste.

Compound	Applied in E-waste	Health effects	References
Antimony (Sb)	A melting agent in CRT glass, plastic computer housings, and a solder alloy in cabling	A carcinogen causes stomach pain, vomiting, diarrhea, and stomach ulcers through inhalation of high levels over a long time period	Kiddee et al. (2013) and Li et al. (2011)
Arsenic (As)	Gallium arsenide is used in light emitting diodes, semiconductors, and LEDs	Chronic effects that cause skin disease, lung liver, bladder cancers, and impaired nerve signaling	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)
Barium (Ba)	Sparkplugs, fluorescent lamps, CRT gutters in vacuum tubes, and an oxygen-removing agent	Causes brain swelling, muscle weakness, liver, heart, and spleen damage, and high blood pressure	Kiddee et al. (2013) and Martin and Griswold (2009)
Beryllium (Be)	Power supply boxes, motherboards, relays, finger clips, and silicon-controlled rectifiers	Exposure to beryllium, a carcinogen can lead to beryllicosis, lung cancer, and skin disease	Kiddee et al. (2013) and Li et al. (2011)
Cadmium (Cd)	Rechargeable Ni-Cd batteries, semiconductor chips, infrared detectors, metal coating, solder joints, UV stabilizers, and toners in photocopying	Causes kidney disease, lung damage, and fragile bones	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)
Chromium (Cr)	Plastic computer housing, cabling, hard disks, as a colorant in pigments, protective coatings on metal (electroplating), magnetic tapes, and floppy disks	Can cause DNA damage, permanent eye impairment, the lining of the nose, nose ulcers, runny nose, and breathing problems such as asthma, cough, wheezing, allergic reactions, liver and kidney damage as well as skin irritation	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)

(Continued)

Table 7.1 (Continued)

Compound	Applied in E-waste	Health effects	References
Lead (Pb)	Solder, lead-acid batteries, cathode ray tubes, cabling, printed circuit boards, fluorescent tubes, X-ray shielding devices, and stabilizers in PVC	Can damage the brain, nervous system, kidneys, reproductive system, and cause blood disorders. Has acute and chronic effects	Kiddee et al. (2013) and Martin and Griswold (2009)
Mercury (Hg)	Batteries, backlight bulbs or lamps, flat panel displays, switches, and thermostats	Can damage the brain, kidneys, and fetuses. Causes shyness, tremors, changes in vision or hearing, memory problems, lung damage, nausea, vomiting, diarrhea, increases in blood pressure or heart rate, skin rashes, and eye irritation	Kiddee et al. (2013); Li et al. (2011) and Martin and Griswold (2009)
Nickel (Ni)	Batteries, computer housing, cathode ray tubes, and printed circuit boards	Can cause an allergic reaction, bronchitis, reduced lung function, and lung cancers	Kiddee et al. (2013) and Li et al. (2011)
Selenium (Se)	Electronic semiconductors	High concentrations cause selenosis, neurological abnormalities, respiratory tract irritation, bronchitis, difficulty breathing, and stomach pains and coughing	Kiddee et al. (2013) and Martin and Griswold (2009)
Silver (Ag)	Electronic equipment, electrical contacts and conductors	Arygria, a blue-gray discoloration of the skin and other body tissues, breathing problems, lung and throat irritation, and stomach pains	Martin and Griswold (2009)
Polyvinyl chloride (PVC)	Monitors, keyboards, cabling, and plastic computer housing	Respiratory problems and an increased incidence of cancer	Kiddee et al. (2013) and Wilkinson et al. (1999)
Polychlorinated biphenyls (PCBs)	Condensers, transformers and heat transfer fluids, capacitor	Immunosuppression, liver damage, tumor promotion, neurotoxicity, damage to both male and female reproductive systems,	Kiddee et al. (2013) and Safe (1993)

	dielectrics, plasticizers, and printing inks	delayed cognitive development and behavioral problems elevated serum lipid levels, chloracne and related dermal lesions, possible hepatic damage, respiratory problems, cancer deaths, and lower birth weights	
Polycyclic aromatic hydrocarbons (PAHs)	Open burning of computer casings and circuit boards, rubber material of printer rollers	Has acute and chronic effects. Impaired lung function, asthmatic and thrombotic effects, increase risk of lung, skin, bladder, and gastrointestinal cancers	Kim et al. (2013) and Leung et al. (2006)
Polybrominated diphenyl ethers (PBDE)	Burnt plastic dump site and the printer roller	Impaired learning and memory functions, as well as interfering with the thyroid, disrupting normal estrogen pathways, live tumors, and gastrointestinal syndromes	Ni and Zeng (2009) and Siddiqi et al. (2003)
Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDs/Fs) and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDDs/Fs)	During the dismantling of E-waste	Lethality, wasting, thymic atrophy, tetratogenesis, reproductive effects, chloracne, immunotoxicity, enzyme induction, decrease in T4 and vitamin A, and increased hepatic porphyrins	Birnbaum et al. (2003) and Ni and Zeng (2009)

provision of a safe and reliable working environment where employees can innovate and conduct productive activities is also met (Balde et al., 2017).

As per the Global E-waste Monitor 2017, only 41 countries of the world were statistically updated about the problem posed by E-waste, and 20% of the total E-waste production was documented to be appropriately recycled. The remaining were either discarded into general waste streams or recycled under substandard conditions (Barba-Gutiérrez et al., 2008; Robinson, 2009). In the recent past, rapidly growing concerns about E-waste have gained much research interest worldwide to the extent that targets to minimize its volume by 50% by 2020 has been discussed at the International Telecommunication Union (ITU) (Balde et al., 2017). Therefore incorporation of proper management techniques for existing E-wastes and remediation practices for contaminated sites by E-wastes is vital.

7.2 Conventional management techniques for E-waste and associated release of pollutants

In order to manage the day to day generating E-waste loads, there are several management techniques in use. Recycling of E-wastes, thermal treatments methods, use of acid baths, and finally landfill disposal or disposal into dumpsites are main methods which are extensively utilized for E-waste management.

7.2.1 Recycling

Recycling involves dismantling and disassembly of different parts of obsolete electrical and electronic equipment together with their eventual reprocessing. Descriptively, recycling comprises with some subprocesses such as separation of the parts having hazardous substances (cathode ray tubes and printed circuit boards) and segregation of ferrous and nonferrous metals (Asante et al., 2012). With the use of an efficient E-waste recycler some precious metals including gold, copper, and lead can be recovered. Recycling can be undertaken either manually or mechanically where it facilitates to reutilize a wide range of electrical equipment such as mobile phones, laptops, keyboards, CPUs, monitors, cables, and connecting wires (Heacock et al., 2015).

However, vast quantities of E-wastes which are undergoing recycling processes leave significant environmental footprints on soil, water, and air worldwide (Table 7.2). Moreover, human health effects with often poisoning incidents are in greater consideration. Many local people who are engaged with the recycling activities are reported to be suffered from physical injuries, neurological disorders, reproductive problems, respiratory diseases, and cancers (Huang et al., 2011). The issues are extensively accounted in some regions such as Guiyu and Taizhou in China, Gauteng in South Africa, New Delhi in India, and Accra in Ghana, where large E-waste recycling sites are located (Tsydenova and Bengtsson, 2011).

Table 7.2 Pollutants released from the recycling of E-waste.

Pollution category	Country/region	Pollutants	Recycling process	References
Soil	Guiyu, China	POPs and trace metals (Pb, Cd, Ni, Cr, Hg and As) Organic pollutants PAHs, PCBs, brominated flame retardants (BFRs)	Crude thermal processes	Chen et al. (2009); Herat and Agamuthu (2012) and Wang et al. (2011)
	Guiyu and Taizhou, China	PBDEs, PAHs, PCDD/Fs and PCBs	Uncontrolled dismantling and acid treatment	Huang et al. (2011) and Tang et al. (2010)
	Bangalore, India	Ag, Bi, Cd, Cu, In, Hg, Pb, Sn and Zn	—	Ha et al. (2009) and Möller et al. (2012)
Air	Guiyu, China	Polybrominated dibenzo-p- dioxin/ furans (PBDD/Fs)	Production, weathering, and recycling of flame-retardant plastics	Ni et al. (2010) and Sepúlveda et al. (2010)
		Chlorinated and brominated compounds, PBDEs and trace metals (Cr, Zn and Cu)	—	
	Bangalore, India	Bi, Co, Cr, Cu, In, Mn, Pb, Sb, Sn, and Tl	—	Ha et al. (2009)
	Thailand	Dust containing compounds (e.g., BFRs, TPP, phthalates, and Cd).	Shredding	Muenhor et al. (2010)
		PPBDEs	E-waste storage facility	Muenhor et al. (2010)
Water	Liangjian and Nanya rivers, China	Dissolved metal, higher concentrations of Pb	—	Sepúlveda et al. (2010)

7.2.2 Dumps and landfills

Sanitary landfills are considered as the most common E-waste disposal technique which aims to reduce or mitigate the potential risks associated with the environment and human health. Landfills are typically positioned in areas where prevailing land features can perform as natural buffers between the environment and landfills. Trenches are made in excavated soil and impervious liners are formed prior to burying E-waste in order to prevent escaping the hazardous materials (Li et al., 2009).

Further, controlled dumps are used as an alternative method for sanitary landfills. They show some similarities to sanitary landfills where pollutants are dumped in mixtures. While having the well-planned capacity, these dumps do not associate with cell-planning. The pollution incidents may become complicated and diversified due to the mixed nature of pollutants and the absence of any gas management and proper covering (Kiddee et al., 2013).

However, due to the potential leaching of toxic substances into the soil and groundwater, landfills and dumps are not environmentally sound processes. It has been proved that E-waste receiving dumps and landfills are a major cause of groundwater contamination (Kasassi et al., 2008). The leachates which percolate from E-waste sites are reported to contain significantly higher concentrations of trace metals along with dissolved and suspended organic and inorganic substances (Spalvins et al., 2008). Those pollutants can be transferred along the food chains and may be accumulated in the living bodies finally affecting human health. Although the health and environmental risks are comparatively low in sanitary landfills, the initial cost is comparatively higher (Li et al., 2009).

7.2.3 Thermal treatment

Thermal treatment involves the application of heat to treat and decompose waste materials through different approaches (Sivaramanan, 2013). Open Burning is the primary method of thermal waste treatment but is considered as an environmentally invasive process. No pollution controlling devices are engaged in open burning, allowing pollutants to escape into the environment. This method is practiced in most of the countries since it provides a cheaper solution for solid waste treatment (Singh and Gautam, 2014).

Incineration is considered as one of the most common methods where E-waste undergoes combustion at high temperatures. Specifically designed incinerators are used for the controlled combustion in the presence of oxygen (Gramatyka et al., 2007). This is one of the most commonly used methods of E-waste management in China, Africa, Pakistan, and India. This process is demonstrated to be advantageous as the means of heat and energy recovery. Additionally, a significant reduction in waste volume can be achieved through the process. Nevertheless, incineration plants are considered as a source for a series of extremely toxic pollutants with neurotoxins and carcinogens (Vats and Singh, 2014).

Gasification and pyrolysis are more or less similar methods, where the waste materials are allowed to decompose under low oxygen levels and very high temperatures. Pyrolysis is undertaken in the absence of oxygen to convert the wastes into fumes, oils, and charcoal while gasification allows a considerably low amount of oxygen in the process. The emissions are low in comparison to the other thermal treatment methods (Sivaramanan, 2013).

Generally, thermal treatment generates substances which are more likely to be toxic in comparison to their ordinary forms. Noxious fumes are emitted during the processes including dioxins, furans, and harmful gases such as mercury and cadmium (Lukose, 2015). Erotic fumes are released with the heating of plastic or PVC circuit boards. The fumes may contain well-known carcinogens such as polychlorinated dibenzo-para-dioxins (PCDDs), polycyclic aromatics (PCAs), and polychlorinated dibenzofurans (PCDFs) along with other toxic gases such as carbon monoxide, sulfur dioxide, and nitrogen oxides (Zheng et al., 2008). Lower levels of trace metal residues also can be contained in these fumes.

7.2.4 Acid bath

Mostly in acid bath technique, electronic circuit boards are submerged in sulfuric, hydrochloric, or nitric acid solutions and soaked for a determined time period in order to extract some valuable metals (Sivaramanan, 2013). Copper, silver, and gold are some extractable metals which get dissolved in the concentrated acid solution during the soaking period and subsequently precipitated. Precipitated metals are recovered and utilized in manufacturing other products while acid wastes are discharged into the environment. These hazardous acid wastes and chemicals find their way to water sources as they end up with groundwater. For instance, Yamuna river banks in India are reported as a well-known site for acid baths. Moreover, this method can pose a health risk for humans due to exposure to acidic fumes, which are containing hazardous compounds (Sivakumaran et al., 2017).

All the methods discussed above have their own drawbacks and are involved in releasing contaminants into the environment. E-waste recycling sites bears significance since they release toxic metals and organic contaminants to the surrounding areas. The final product of thermal treatment techniques such as incineration generate bottom ash rich in toxic metals. Moreover, open dumping sites and poorly managed landfills cause to release contaminants rich landfill leachates which can pollute groundwater system and surrounding soils.

Hence, innovative, environment-friendly, and low-cost remediation techniques have to be investigated to remediate contaminated areas by E-waste. Fig. 7.1 listed widely used physicochemical and biological approaches for remediation of contaminants, which are resulted from E-waste. However, green approaches to mitigate environmental risk have become viable choices.

Bioremediation is an approach which utilizes natural biological activities to destroy or remove harmful contaminants from the environment. This approach relies on cost-effective and low-tech methods having high public acceptance to deliver on-site remediation of contaminants. Bioremediation uses a wide variety of

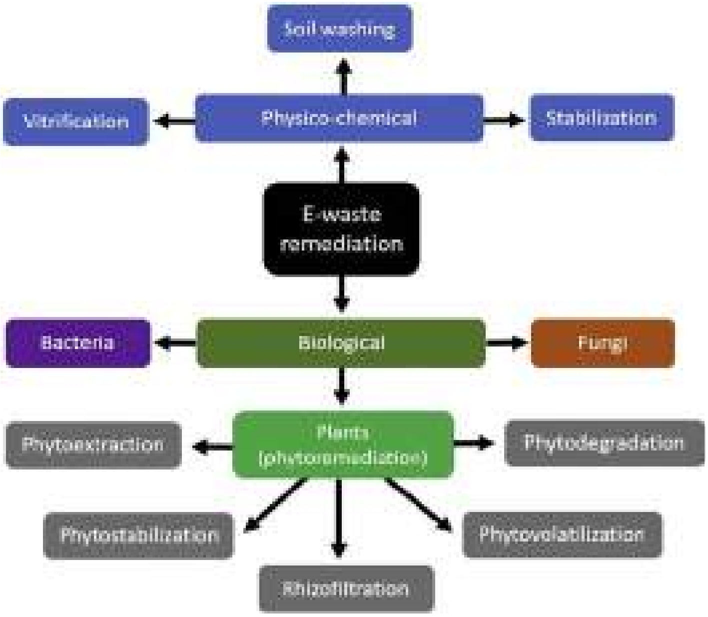

Figure 7.1 Available techniques to remediate contaminants from E-wastes.

bacteria, fungi, and plant species which are evolved to remove or destroy specific contaminant or range of contaminants through their specialized metabolic pathways. Many studies investigated the capacity of bioremediation for remediation of possible pollutants from E-wastes (Hiremath et al., 2015; Jiang et al., 2018; Kang et al., 2016). The term "phytoremediation" is particularly adopted for the situations which use plant species as a bioremediation agent.

7.3 Phytoremediation to mitigate contaminant from E-waste

The ability of plants, wild or genetically modified, to be used in the decontamination of the environment, termed phytoremediation, has been in progress ever since the 1990s. Research interest in this regard has led to consider phytoremediation as an appropriate means of E-waste remediation (Alkorta and Garbisu, 2001; Campos et al., 2008; Lukose, 2015).

A research gap is created because the knowledge on phytoremediation was scattered, and it has been the effort of the authors to amalgamate these details in order to fill this gap. Therefore hereafter this chapter focuses on the fundamentals of phytoremediation, phytoremediation approaches for inorganic, and organic contaminants in E-waste along with its associated advantages and limitations.

7.3.1 A brief history on the use phytoremediation

Phytoremediation is a plant-based bioremediation technology used to remediate trace metals, hazardous inorganic and organic contaminants from soils, sediments, surface and groundwater, wastewater, and the atmosphere (Luo et al., 2015; Susarla et al., 2002). The generic term of phytoremediation originates from the Greek prefix "phyto," which stands for "plant," and the Latin suffix "remedium," which means "able to cure" or "restore" (Laghlimi et al., 2015). This conception was introduced by Chaney (1983) to remediate metal-polluted sites using "hyperaccumulators," that is, the plants considered more efficient in the phytoremediation processes. Brooks et al. (1977) discovered hyperaccumulators as plants which could accumulate nickel in the shoot tissue at a concentration of 1000 mg/kg of the plant biomass which accounts >0.1%−1% of the dry weight of the plant. Around 500 species of plants under about 101 families have been discovered as hyperaccumulators, having the potential to thrive and accumulate high concentration of contaminants (Ghosh and Singh, 2005; Mahar et al., 2016; Prasad and De Oliveira Freitas, 2003; Sarma, 2011).

7.3.2 Mechanisms in phytoremediation

Plants utilized for phytoremediation possess specialized physiological characteristics compared with other plants. The number of mechanisms evolved in these plants, namely; phytoextraction, phytostabilisation, rhizofiltration, phytovolatilization, and phytodegradation/phytotransformation are mainly involved in the pollutant removal through phytoremediation. Fig. 7.2 explains the above-mentioned phytoremediation mechanisms in a simple manner.

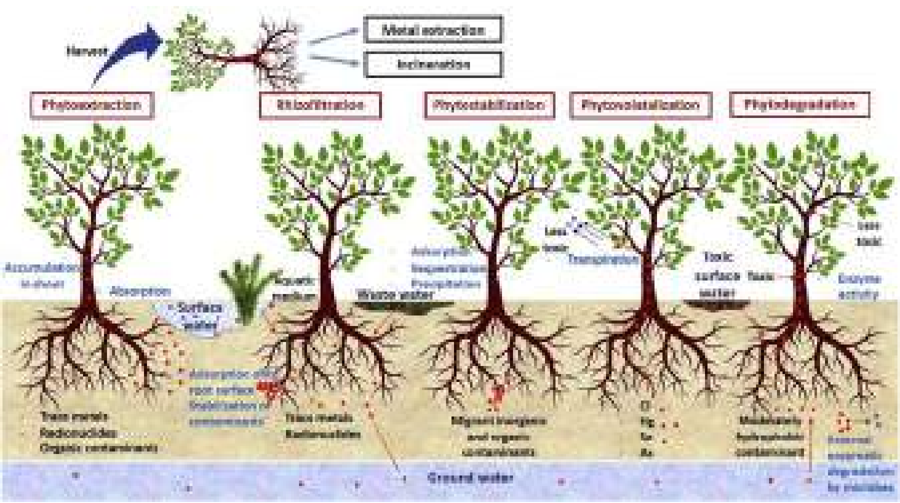

Figure 7.2 Mechanisms involved in contaminant mitigation by phytoremediation.

7.3.2.1 Phytoextraction

Phytoextraction is the removal of contaminants from soil, surface water, or groundwater through absorbing contaminants by plant roots and translocating them to above-ground tissues of the plant facilitating accumulation in the shoot biomass (Mahar et al., 2016; Susarla et al., 2002). This mechanism is adopted by hyperaccumulators to concentrate trace metals, radionuclides, and organic compounds in their biomass which is harvested later on and finally disposed through burning or recovered through metal extraction (Lee, 2013; Tangahu et al., 2011). Phytoextraction is possible for remediation of low to moderate levels of contaminations in the superficial layers of the soil as many hyperaccumulators cannot sustain in high contaminant loads (Prasad and De Oliveira Freitas, 2003).

7.3.2.2 Phytostabilization

This is the use of plants to stabilize or immobilize migrant inorganic and organic contaminants in the soil and water through roots or the rhizosphere thereby either reducing or preventing leaching of pollutants to groundwater and reducing the bioavailability of the pollutants in the environment (Cristaldi et al., 2017; Lee, 2013; Tangahu et al., 2011). Phytostabilization does not degrade nor necessarily remove contaminants from the soil but focuses mainly on stabilizing pollutants in the soil around the root system (Gerhardt et al., 2017). The mechanism may involve adsorption onto the root surface, sequestration within root tissues, and precipitation or complexation of metals with organic compounds in the root zone (Mahar et al., 2016).

7.3.2.3 Rhizofiltration

Rhizofilteration utilizes terrestrial or aquatic plants for the removal of organic and inorganic metal contaminants from surface water, groundwater, and wastewater by adsorption, precipitation pollutants onto the plant roots or accumulation pollutants in the root tissues in the surrounding solution of the root zone (Cristaldi et al., 2017; Ghosh and Singh, 2005; Lee, 2013). This method is usually practiced for the removal of trace metal and radio nuclei (U-Uranium) in aquatic environments and treatment of industrial discharges by means of a constructed wetland. Plants are grown hydroponically and then later on transplanted in the real aquatic environment of metal contaminations. This process is effective for remediation of low concentration of pollutants in large water bodies (Salt et al., 1995).

7.3.2.4 Phytovolatilization

Phytovolatilization requires the volatilization of contaminants taken up by the plants. Once contaminants are absorbed at the root level, they are being transported through the vascular tissues to the foliage where the contaminants are transformed into their less toxic gaseous forms as a result of metabolic processes and subsequently released to the atmosphere via transpiration (Cristaldi et al., 2017; Laghlimi et al., 2015;

Sharma and Pandey, 2014). Phytovolatilization is utilized for the removal of chlorinated organic compounds such as tetrachloroethane and trichloromethane, volatile trace metals like Hg, Se, and As from the soil and water (Lee, 2013; Susarla et al., 2002). Mostly this technique is used to treat Hg to form less toxic mercuric compounds that eventually end up into the air. The major drawback of phytovolatilization is that the contaminants are not entirely fixed instead they can recycle by resettling on the land and water through precipitation (Mahar et al., 2016; Sharma and Pandey, 2014).

7.3.2.5 Phytodegradation/phytotransformation

Phytodegradation is either the external enzymatic degradation of contaminants in the rhizosphere or the breakdown/transformation of contaminants taken up by the plants to less toxic compounds through metabolic modification within the plant (Pandey and Bajpai, 2019; Tangahu et al., 2011). Plants produce a wide range of enzymes: dehalogenases, peroxidases, reductases, and oxygenases which capable of transforming contaminants to nontoxic products inside the plant as well as in the rhizosphere with the aid of the microbial community (Ghosh and Singh, 2005). Phytodegradation applies for moderately hydrophobic organic chemicals including herbicides, insecticides, pesticides, chlorinated solvents, and inorganic contaminants for the recovery of contaminated surface and groundwater and even soil at low concentrations (Ghosh and Singh, 2005; Lee, 2013).

7.3.3 Phytoremediation approaches for different contaminants from E-wastes

Out of various remediation techniques utilized so far to remediate E-waste contaminants, phytoremediation has been identified as a promising tool in terms of eco-conservation and cost-benefit analysis. Ever since government organizations and academic institutions have been working on the removal of these contaminants in the laboratory and field trial scale, developing them further into effective full-scale field application.

Recently, most of the phytoremediation approaches have been applied to the E-waste contaminated sites in the Chinese region. Globally, the highest amount of E-waste generated in China about 7.2 million tons, which is expected to grow up to 27 million tons by the year 2030 (Balde et al., 2017). The city of Guiyu in Guangdong Province of China is known to be the largest electronic waste recycling site in the world while Taizhou region of the Zhejiang province is also a well-known E-waste processing center (Meagher, 2000; Robinson, 2009). The soil in these areas are vastly contaminated with trace metals, including lead, cadmium, copper, and organic pollutants, such as PCBs, PBDEs, and phthalic acid esters (PAEs) leached out from the electronic waste (Chen et al., 2010; Huang et al., 2011; Luo et al., 2017; Shen et al., 2009).

Although phytoremediation is a favorable technique for contaminant eradication, the conventional methods are however, time-consuming and less effective to be applied in the real-life scenario. In addition, due to the binding tendency of hydrophobic organic contaminants to soil organic matter, the bioavailability of contaminants in the soil becomes very low, restricting the extraction, removal, and degradation by plants themselves (Tu et al., 2011). Incorporation of various cutting-edge techniques including, gene modification (Da Conceição Gomes et al., 2016), chelator application (De Araújo and Do Nascimento, 2010; Luo et al., 2016), surfactant application (Chen et al., 2010), electrokinetic assistance (Cang et al., 2012; Lim et al., 2012), soil microbial enhancement (Teng et al., 2010), and microbial enzyme stimulation (Tu et al., 2011) could enhance the overall removal efficiency and the bioavailability during phytoremediation.

The studies of Shen et al. (2009) and Chen et al. (2010) have employed randomly methylated and nonmethylated β-cyclodextrin, a surfactant, to demonstrate the potential removal of PCBs with several plant species in the presence and absence of rhizosphere. The higher levels of PCB removal related to the amendment with surfactant and soil microbial activity as surfactants are capable of increasing the water solubility of the organic contaminants making them available for the plant extraction (Liu et al., 2013). The effect of chelating agents such as citric acid, nitrilotriacetic acid, and EDTA was examined by De Araújo and Do Nascimento (2010) for phytoremediation of lead. A multitechnique phytoremediation study was done by Luo et al. (2017) to test the effect of AC and DC electric fields ranging from 2 to 10 V simultaneously with foliar cytokinin and EDTA treatment to remediate cadmium, copper, and lead through *Eucalyptus globulus*. This combined approach was proved to be efficient than individual methods suggesting the fact that the integration of other techniques with phytoremediation can be successfully applied to eliminate contaminants from E-waste sites. Table 7.3 indicates the detailed information about plant species which were used for removal of different kind of contaminants from E-wastes and percentage contaminant removal or bioaccumulation resulted through phytoremediation process.

7.3.4 Advancement of phytoremediation for remediation of E-waste contaminated sites

Despite the use of traditional plant varieties for phytoremediation, there are several other methods that have been evolved as an effective strategy of remediation. Incorporation of mycorrhizal fungi and/or other soil organisms, use of invasive plants and transgenic plants might be the promising advances of phytoremediation for E-waste contaminated sites.

7.3.4.1 Use of mycorrhizal fungi and other soil organisms

Mycorrhizal fungi show extensively evolved, mutualistic relationship with plant roots of widespread plant families. These fungal interactions provide numbers of benefits for plants, including the supply of mineral nutrients, which ultimately involve for better survival and high biomass production of plants (Mafaziya and Madawala, 2015). Not only these interactions enable plant species to live in

Table 7.3 Phytoremediation approaches for E-waste contaminated sites in different places in the world.

Contaminated site or source	Plant species	Amendment	Contaminant	Contaminant removal or bioaccumulation (% or μg/g)	References
Taizhou city, China		Randomly methylated-β-cyclodextrins (RAMEB) (3.0%)	Polychlorinated biphenyls (PCBs)	Nonamended amended soil[a] soil[a]	Shen et al. (2009)
	Rice (*Oryza sativa*)			26.9% | 34.4%	
	Alfalfa (*Medicago sativa L.*)			26.6% | 34.6%	
	Ryegrass (*Lolium perenne L.*)			28.5 % | 31.4%	
	Tall fescue (*Festuca arundinacea*)			25.6 % | 48.1%	
Taizhou city, China		β-cyclodextrin (3.0%)	PCB	Nonamended amended soil[a] soil[a]	Chen et al. (2010)
	Rice (*Oryza sativa*)			26.9% | 23.8%	
	Alfalfa (*Medicago sativa L.*)			26.6% | 18.3%	
	Ryegrass (*Lolium perenne L*)			28.5% | 31.7%	
	Tall fescue (*Festuca arundinacea*)			25.6% | 27.3%	

(*Continued*)

Table 7.3 (Continued)

Contaminated site or source	Plant species	Amendment	Contaminant	Contaminant removal or bioaccumulation (% or μg/g)		References
Taizhou, Zhejiang Province, China	Alfalfa *(Medicago sativa L.)*	–	PCB	Soil[a] 31.4 % (first year) 78.4 % (second year)		Tu et al. (2011)
Yaocuowei, Guangdong Province, China	Italian ryegrass (*Lolium multiflorum L.*) Pumpkin *(Cucurbita pepo spp.)* Maize *(Zea mays L.)*	–	Polybrominated diphenyl ethers (PBDEs)	Soil[a] 13.3%–21.7%		Huang et al. (2011)
Taizhou, Zhejiang Province, China	Alfalfa *(Medicago sativa L.)*			Root[b]	Shoot[b]	Teng et al. (2010)
		Uninoculated alfalfa	PCB	27.4	230.8	
		Alfalfa + *G. caledonium*		36.6	324.5	
		Alfalfa + *R. meliloti*		42.1	326.1	
		Alfalfa + *G. caledonium* + *R. meliloti*		46.9	267.8	
Automobile-battery recycling facility, Brazil	*Maize (Zea mays)*		Pb	Root[b]	Shoot[b]	De Araújo and Do Nascimento (2010)
		Citric acid (30 mM)		15,604	1545	
		Nitrilotriacetic acid (10 mM)		6892	836	
		EDTA (10 mM)		52,151	5787	

Taizhou, Zhejiang Province, China	Alfalfa *(Medicago sativa L.)*	Intercropping	Phthalic acid esters (PAEs)	Shoot[b]		Ma et al. (2013)
				3.36		
	Ryegrass *(Lolium perenne L.)*			3.10		
	Tall fescue (*Festuca arundinacea*)			3.05		
Landfill leachate, Kenya	Water hyacinth (*Eichhornia crassipes*)	—	PCBs	Roots[b]		Omondi et al. (2015)
				0.179		
Guiyu, Guangdong Province, China	*Eucalyptus globulus*			Root[b]	Shoot[b]	Luo et al. (2017)
		Nonamended	Cd	0.81	0.23	
			Pb	40.2	7.92	
			Cu	50.13	28.31	
		EDTA (0.5 mM)	Cd	3.16	2.68	
			Pb	128.5	56.6	
			Cu	89.2	56.8	
		Electric field (2 V DC)	Cd	1.32	0.42	
			Pb	47.2	9.67	
			Cu	56.8	32.9	
			Cd	1.89	0.58	
		Electric field (4 V DC)	Pb	62.8	11.96	
			Cu	62.5	38.7	
		Electric field (10 V DC)	Cd	2.05	0.62	
			Pb	63.8	10.62	
			Cu	68.2	39.1	
		Cytokinin (20 mg kg^{-1})	Cd	1.55	2.93	
			Pb	46.3	23.1	
			Cu	59.8	35.3	

(*Continued*)

Table 7.3 (Continued)

Contaminated site or source	Plant species	Amendment	Contaminant	Contaminant removal or bioaccumulation (% or μg/g)		References
				Root[b]	Shoot[b]	
Guiyu, Guangdong Province, China	*Eucalyptus globulus*	Nonamended	Cd	0.63	0.23	Luo et al. (2018)
			Pb	32.80	5.80	
			Cu	60.2	33.3	
		Electric field (2 V DC)	Cd	0.89	0.29	
			Pb	40.3	8.6	
			Cu	69.8	35.9	
		Electric field (4 V DC)	Cd	1.07	0.35	
			Pb	55.2	9.3	
			Cu	73.5	38.2	
		Electric field (10 V DC)	Cd	1.31	0.41	
			Pb	62.8	12.5	
			Cu	75.1	41.6	
		Electric field (2 V AC)	Cd	0.72	0.52	
			Pb	35.1	20.6	
			Cu	64.2	59.8	
		Electric field (4 V AC)	Cd	0.93	0.68	
			Pb	42.9	29.8	
			Cu	68.1	63.7	
		Electric field (10 V AC)	Cu	1.12	1.03	
			Pb	55.6	32.5	
			Cu	70.3	71.2	

[a]Contaminant removal %.
[b]Bioaccumulation in the plant shoot/root.

nutrient-poor and contaminated soils but also assist them to uptake and detoxification of a range of pollutants, making them possible agents for effective phytoremediation (Bahraminia et al., 2016).

Bahraminia et al. (2016) examined the effect of two mycorrhizal fungal species with Vetiver grass (*Vetiveria zizanoides*) on phytoremediation of lead-contaminated soils. Inoculation of two mycorrhizal species, *Glomus versiforme*, and *Rhizophagus intraradices* has been involved for the significant increase in uptake efficiencies, phytoextraction, and translocation factor of lead, which is one of the major contaminants in E-waste. The study of Abu-Muriefah (2016) highlighted the use of *Glomus deserticola* to enhance phytoremediation capabilities of *Eucalyptus rostrata* toward the rehabilitation of trace metal contaminated sites. Moreover, Schneider et al. (2016) revealed the positive correlation exhibited on plant distribution with arbuscular mycorrhizal root colonization in lead-contaminated sites. This study explains the effect of the mycorrhizal associations on the survival of plant communities in harsh environmental conditions, which further influence phytoremediation mechanisms such as phytostabilization. Furthermore, the study of Ren et al. (2017) examined the effect of triple symbiosis among legume species (*Sesbania cannabina*), arbuscular mycorrhizal fungi (*Glomus mosseae*) and rhizobia (*Ensifer* sp.) for phytoremediation of PAHs, one of the possible contaminant classes resulting from E-wastes. The interaction of plant, arbuscular mycorrhizal fungi, and rhizobial bacteria resulted the highest reduction of PAHs, phenanthrene and pyrene by $>97\%$ and $85\%-87\%$, respectively. This study suggests the synergistic effect evolves from arbuscular mycorrhizal and rhizobium bacteria which improve phytoremediation capabilities of plants by increasing the biomass production and PAHs accumulation inside the plant tissues.

Other than mycorrhizal associations, actions of soil biota also have a major influence on the increase or decrease of phytoremediation efficiency. Luo et al. (2016) studied about the involvement of nitrogen fixers such as chickpeas (*Cicer arietinum*) and earthworms for the biomass production and phytoremediation efficiency of *Eucalyptus globulus* for Cd, a major contaminant released from E-wastes. That study indicated that the *Eucalyptus globulus* with earthworm required 30% less time for complete removal of Cd from the system than the second most successful system. On the other hand, soil borne pathogens and denitrifying bacteria involved in causing plant diseases and limiting soil nutrients could have negative impacts on phytoremediation.

Therefore the proper understanding of mycorrhizal associations of plants which are used in phytoremediation is an urgent need to increase the efficiency and effectiveness of contaminant removal from the lands contaminated with E-wastes. Further, the knowledge about other kinds of symbiotic relationships such as rhizobial bacteria and the contribution of other soil macroorganisms which increase the survival, growth rate, and biomass production of phytoremediation agents is essential to harvest maximum advantage of phytoremediation.

7.3.4.2 The capacity of invasive plants for phytoremediation

Invasive plants have a unique set of characteristics including high growth rates, tolerance to harsh environmental conditions, high reproductive rate, and adaptive abilities for a vast range of environmental conditions. These characters could be useful when the use of them as agents for phytoremediation of E-wastes contaminated sites. Several studies investigated the potential of invasive or potentially invasive plants on the phytoremediation process.

The study of Chinmayee et al. (2012) identified *Amaranthus spinosus*, a potentially invasive species as a potential phytoremediation agent for trace metal contaminated sites. This study emphasized the ability of examined plant species for effective bioaccumulation and translocation of cadmium, copper, and zinc. Similarly, Wei et al. (2018) studied about phytoremediation abilities of three invasive species in China, namely, *Chromolaena odorata*, *Bidens pilosa*, and *Praxelis clematidea*, for removal of cadmium. The results of this study revealed that all the three tested plant species had the tolerance to grow in cadmium contaminated soils, and *Chromolaena odorata* expressed high bioaccumulation capacity for cadmium than others. Also, Pandey (2012) recognized *Ipomoea carnea* as an agent for phytoremediation as it possesses favorable characteristics including easy propagation through vegetative methods, high level of tolerance to, flooding, desiccation, salinity, pH, and toxic metals.

Moreover, its capacity to grow in nutrient poor conditions, high growth rate, and unpalatable nature correspondingly make it an effective phytoremediation agent.

Furthermore, Ekperusi et al. (2019) described the phytoremediation application of aquatic macrophyte, Duckweed (*Lemna minor*). Duckweed has extensive phytoremediation capabilities for a wide range of contaminants, including trace metals, organic pollutants, dyes, and radioactive wastes. Therefore it has high potential to apply for wastewater systems contaminated with multiple components of E-wastes.

However, the use of invasive plants as phytoremediation agents might induce ecological and human health-related consequences, if they manage to escape into natural habitats. Invasive plant species have abilities to adapt to a wide range of environmental conditions, and their high reproduction rates allow them to spread in the natural environment over the native plant species. Therefore utilizing them for phytoremediation purposes should be done under extreme caution with regular monitoring.

7.3.4.3 Transgenic plant technology as phytoremediation approach

A limited number of plant species had been identified as hyperaccumulators, and developing of new plant varieties for remediation of emerging contaminants by conventional breeding techniques is a challenge (Gunarathne et al., 2019). Survival of plant species is highly dependent on the edaphic conditions and environmental factors which vary among different regions of the world. Moreover, intrinsic factors such as less biomass production, slow growth rate, and less adaptability that might be associated with hyperaccumulators limit their usability as “real life” phytoremediation agents in field conditions. In this regard, transgenic plants with enhanced remediation capabilities have been introduced to overcome the limitations and drawbacks that are associated with traditional plant varieties used for phytoremediation (Ellis et al., 2004).

Transgenic plants are the plants which have been genetically modified utilizing recombinant DNA technology to express exogenous genes or modify endogenous genes (Key et al., 2008). Exogenous genes, including peroxidases and monooxygenases introduced into the plant genome have a great capacity for detoxification and remediation of contaminants (Wang et al., 2015). The first major attempts in transgenic plant technology for phytoremediation have been made to produce trace metal tolerance plants (Van Aken, 2008). However, several studies were conducted during the past few decades to produce viable transgenes for effective remediation of a wide range of contaminants. Details of some of the recent studies are stated below.

The study of Zhang and Liu (2011) involved to produce transgenic alfalfa, *Medicago sativa* by incorporating of human P450 2E1 (CYP2E1) and glutathione S-transferase (GST) genes through *Agrobacterium tumefaciens* mediated gene transfer method for remediation of mercury and trichloroethylene (TCE). Coexpressing of these two genes caused by synergistically improved tolerance and accumulation of heavy metals and organic complex contaminants. The transgene expressed a high tolerance for cadmium-TCE complexes than nontransgenes. A similar study has been conducted by Zhang et al. (2013) using the same transgenic alfalfa for removal of mercury-TCE complexes. Experimental results revealed that the improved plants which express these two genes are extensively tolerable for mercury-TCE complex pollutants. Further, those modified plants were able to accumulate many folds of mercury-TCE than nonmodified plants. Therefore modified alfalfa by human CYP2E1 and GST has high phytoremediation potential on soils contaminated with trace metals-organic complexes. Shim et al. (2013) also sued *Agrobacterium tumefaciens* mediated technique to establish yeast cadmium factor 1 (*ScYCF1*) gene in poplar (*Populus alba* X P. *tremula var. glandulosa*, BH1). The transgenes expressing *ScYCF1* were able to bioaccumulate higher amounts of trace metals, Cd, Zn, and Pb in root tissues. Further, these transgenic poplars showed extensive growth rates, less toxicity symptoms, and high content of Cd accumulation in shoots than nontransgenes. Moreover, Nahar et al. (2017) investigated the ability of tobacco (*Nicotiana tabacum*, var. Sumsun) incorporated with arsenic reductase 2 (*AtACR2*) gene from *Arabidopsis thaliana* for arsenic removal. The transgenic tobacco plants observed to be more resistant for arsenic and accumulated significantly higher arsenic concentrations in root systems than the nontransgenic wild variety. Therefore transgenic plant technology seems to be the most viable approach to develop new plants varieties for phytoremediation of E-waste contaminated sites.

However, the possible risks associated with these modified plants on environmental aspects is still a doubt. The transgenic technology involved to develop transgenes that have extreme capabilities to establish and thrive under harsh environmental conditions which present in polluted sites in order to facilitate phytoremediation in a more effective manner (Gunarathne et al., 2019). Therefore these transgenes bear the high potential to act like invasive species in the natural environment and can induce threats for the survival of native plant species (Ellstrand and

Schierenbeck, 2006). Moreover, the hybridization of native plant varieties with pollen from transgenic plants might lead for the extinction of native plant varieties by expression of deleterious genes such as gene which induce male sterility (Ellstrand and Schierenbeck, 2006). Therefore the development of new plant varieties for phytoremediation applications through transgenic plant technology should be done under extensive caution.

7.3.5 Advantages and limitations associated with phytoremediation for E-waste contaminated sites

Traditional soil remediation techniques are associated with several negative impacts on the environment including changes in edaphic conditions, generation of toxic byproducts, accelerated soil erosion, and economic nonviability (Luo et al., 2016). On the other hand, phytoremediation has been accepted by the public community as an environment-friendly approach for decontamination of polluted sites. Moreover, the use of phytoremediation saves about 60%−80% of the cost associated with traditional physicochemical remediation methods (Mwegoha, 2008). Phytoremediation is capable of mitigating most of the contaminants generated from E-wastes without interfering the natural soil functions. This technique not only removes the pollutants from contaminated sites but also reduces the leaching of trace elements, decreasing water percolation through the soil profile (Kidd et al., 2009). Further, the phytoremediation delivers added benefits such as carbon sequestration, soil erosion control, fuelwood production, biodiversity protection, and aesthetic value addition to the landscape, in addition to the contaminant mitigation (Hu et al., 2012; Pandey et al., 2015). Moreover, it is well suited over traditional methods for remediation of lands having a large area and a moderate amount of contamination.

Although phytoremediation has many advantages on contaminant mitigation, several associated disadvantages and drawbacks cannot be neglected. Even though that technique removes contaminants from the soil system, risk to transport them through food chains and bioaccumulate in tissues of organisms bears great significance from an environmental health perspective. (Rathod et al., 2014). The soil in E-waste contaminated sites generally comprise high concentrations of trace metals, so the risk to bioaccumulate them through food chains is high. Especially in cases which use plant species having edible fruits might create threats for human health. In particular, trace metals cannot be destroyed by biological pathways, but transformation between different oxidation status or complexation happen inside the plant body (Garbisu and Alkorta, 2001). Therefore the main drawback of this technique is to find proper disposal method for “pollutant-rich plants” that are used for uptake and storage of pollutants from contaminated sites (Pandey et al., 2015).

7.4 Remarks

Phytoremediation is not a new technique which is utilized for contaminant mitigation from the affected sites. However, it has been proven its effectiveness against remediation of emerging contaminants resulting from E-wastes. Due to the complex pattern of electronic product consumption by a modern human, generating E-waste load and the extent of the affected area are drastically increasing throughout the world. Therefore as an environment-friendly and cost-effective approach, phytoremediation is still receiving the attention of the scientific community for remediation of E-waste contaminated sites. This technique provides not only remediation but also offers added benefits, including erosion control, protection of biodiversity by providing habitats for animals and birds, and an increase in the scenic beauty of the environment. On the other hand, the public community also has positive attitudes toward phytoremediation.

Therefore new researches are emerging in the field of phytoremediation in order to increase the removal efficacy of contaminants, including emerging contaminants, and extend the number of cobenefits to be harnessed. If the invasive plant species can act as hyperaccumulators for particular contaminants, they are known to be useful for phytoremediation. They possess some desirable characteristics to act as effective phytoremediation agent, including high growth rates and ability to adapt for new environments. However, the threat that generates by them for the natural environment must be evaluated carefully, before their use as phytoremediation agents. Therefore the use of native plant species for phytoremediation has been evaluated by a few researchers (Pandey et al., 2015; Pandey and Singh, 2011). Native plants will not pose a negative impact on the particular environment but involve to increase the biodiversity. Moreover, native plant species might provide socio-economic benefits for local communities. However, the most recent approach for phytoremediation is the use of transgenic plants. Plants incorporated with new genes which express desirable features for pollutants uptake, metabolism, and/or accumulation inside plant tissues usually have certain advantages over the traditional plant species used. Besides, different countries made their own policies toward the use of genetically manipulated crops for the food industry, use of this kind of plants for phytoremediation is still questionable.

For assessing the effectiveness of plants as agents of bioremediation, the status of edaphic factors and soil macro- and micro-organism communities cannot be neglected. In order to produce high biomass for the success of phytoremediation, sufficient supply of essential plant nutrients is vital. Additionally, the majority of plant species rely on symbiotic organisms, such as mycorrhiza and plant growth, promoting bacteria. Primarily, these interactions are beneficial for the survival of plant species as well as for the high biomass production, which are essential for effective phytoremediation. Therefore future research works should address the above issues in order to fill knowledge gaps to increase the efficiency of phytoremediation for contaminants removal from E-waste contaminated sites.

References

Abu-Muriefah, S.S., 2016. The use of Acacia saligna inoculated with mycorrhizae in phytoremediation of lead-contaminated soils in the Kingdom of Saudi Arabia. Global J. Agr. Res. 4, 58−70.

Alkorta, I., Garbisu, C., 2001. Phytoremediation of organic contaminants in soils. Bioresour. Technol. 79, 273−276. Available from: https://doi.org/10.1016/S0960-8524(01)00016-5.

Asante, K.A., Agusa, T., Biney, C.A., Agyekum, W.A., Bello, M., Otsuka, M., et al., 2012. Multi-trace element levels and arsenic speciation in urine of e-waste recycling workers from Agbogbloshie, Accra in Ghana. Sci. Total Environ. 424, 63−73. Available from: https://doi.org/10.1016/j.scitotenv.2012.02.072.

Bahraminia, M., Zarei, M., Ronaghi, A., Ghasemi-Fasaei, R., 2016. Effectiveness of arbuscular mycorrhizal fungi in phytoremediation of lead-contaminated soil by vetiver grass. Int. J. Phytoremed. 18, 730−737. Available from: https://doi.org/10.1080/15226514.2015.1131242.

Balde, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-Waste Monitor 2017: Quantities, Flows and Resources. United Nations University, International Telecommunication Union, and International Solid Waste Association.

Barba-Gutiérrez, Y., Adenso-Diaz, B., Hopp, M., 2008. An analysis of some environmental consequences of European electrical and electronic waste regulation. Resour. Conserv. Recycl. 52, 481−495. Available from: https://doi.org/10.1016/j.resconrec.2007.06.002.

Birnbaum, L.S., Staskal, D.F., Diliberto, J.J., 2003. Health effects of polybrominated dibenzo-p-dioxins (PBDDs) and dibenzofurans (PBDFs). Environ. Int. 29, 855−860. Available from: https://doi.org/10.1016/S0160-4120(03)00106-5.

Brooks, R.R., Lee, J., Reeves, R.D., Jaffré, T., 1977. Detection of nickeliferous rocks by analysis of herbarium specimens of indicator plants. J. Geochem. Explor. 7, 49−57. Available from: https://doi.org/10.1016/0375-6742(77)90074-7.

Campos, V., Merino, I., Casado, R., Pacios, L., Gómez, L., 2008. Phytoremediation of organic pollutants. Spanish J. Agr. Res. 38−47.

Cang, L., Zhou, D.-M., Wang, Q.-Y., Fan, G.-P., 2012. Impact of electrokinetic-assisted phytoremediation of heavy metal contaminated soil on its physicochemical properties, enzymatic and microbial activities. Electrochim. Acta 86, 41−48. Available from: https://doi.org/10.1016/j.electacta.2012.04.112.

Chaney, R., 1983. Plant uptake of inorganic waste constituents. In: Parr, P., Kia, J. (Eds.), Land Treatment of Hazardous Wastes. Noyes Data Corporation, Park Ridge, NJ.

Chen, D., Bi, X., Zhao, J., Chen, L., Tan, J., Mai, B., et al., 2009. Pollution characterization and diurnal variation of PBDEs in the atmosphere of an E-waste dismantling region. Environ. Pollut. 157, 1051−1057. Available from: https://doi.org/10.1016/j.envpol.2008.06.005.

Chen, Y., Tang, X., Cheema, S.A., Liu, W., Shen, C., 2010. β-cyclodextrin enhanced phytoremediation of aged PCBs-contaminated soil from e-waste recycling area. J. Environ. Monitor. 12, 1482−1489. Available from: https://doi.org/10.1039/C0EM00029A.

Chi, X., Streicher-Porte, M., Wang, M.Y., Reuter, M.A., 2011. Informal electronic waste recycling: a sector review with special focus on China. Waste Manag. 31, 731−742. Available from: https://doi.org/10.1016/j.wasman.2010.11.006.

Chinmayee, M.D., Mahesh, B., Pradesh, S., Mini, I., Swapna, T., 2012. The assessment of phytoremediation potential of invasive weed Amaranthus spinosus L. Appl. Biochem. Biotechnol. 167, 1550−1559. Available from: https://doi.org/10.1007/s12010-012-9657-0.

Cristaldi, A., Conti, G.O., Jho, E.H., Zuccarello, P., Grasso, A., Copat, C., et al., 2017. Phytoremediation of contaminated soils by heavy metals and PAHs: a brief review. Environ. Technol. Innov. 8, 309−326. Available from: https://doi.org/10.1016/j.eti.2017.08.002.

Da Conceição Gomes, M.A., Hauser-Davis, R.A., De Souza, A.N., Vitória, A.P., 2016. Metal phytoremediation: general strategies, genetically modified plants and applications in metal nanoparticle contamination. Ecotoxicol. Environ. Saf. 134, 133−147. Available from: https://doi.org/10.1016/j.ecoenv.2016.08.024.

De Araújo, J.D.C.T., Do Nascimento, C.W.A., 2010. Phytoextraction of lead from soil from a battery recycling site: the use of citric acid and NTA. Water Air Soil Pollut. 211, 113−120. Available from: https://doi.org/10.1007/s11270-009-0285-4.

Ekperusi, A.O., Sikoki, F.D., Nwachukwu, E.O., 2019. Application of common duckweed (lemna minor) in phytoremediation of chemicals in the environment: state and future perspective. Chemosphere 223, 285−309. Available from: https://doi.org/10.1016/j.chemosphere.2019.02.025.

Ellis, D.R., Sors, T.G., Brunk, D.G., Albrecht, C., Orser, C., Lahner, B., et al., 2004. Production of Se-methylselenocysteine in transgenic plants expressing selenocysteine methyltransferase. BMC Plant Biol. 4, 1. Available from: https://doi.org/10.1186/1471-2229-4-1.

Ellstrand, N.C., Schierenbeck, K.A., 2006. Hybridization as a stimulus for the evolution of invasiveness in plants? Euphytica 148, 35−46. Available from: https://doi.org/10.1007/s10681-006-5939-3.

Frenk, J., Chen, L., Bhutta, Z.A., Cohen, J., Crisp, N., Evans, T., et al., 2010. Health professionals for a new century: transforming education to strengthen health systems in an interdependent world. Lancet 376, 1923−1958. Available from: https://doi.org/10.1016/S0140-6736(10)61854-5.

Gaidajis, G., Angelakoglou, K., Aktsoglou, D., 2010. E-waste: environmental problems and current management. J. Eng. Sci. Technol. Rev. 3, 193−199.

Garbisu, C., Alkorta, I., 2001. Phytoextraction: a cost-effective plant-based technology for the removal of metals from the environment. Bioresour. Technol. 77, 229−236. Available from: https://doi.org/10.1016/S0960-8524(00)00108-5.

Gerhardt, K.E., Gerwing, P.D., Greenberg, B.M., 2017. Opinion: taking phytoremediation from proven technology to accepted practice. Plant Sci. 256, 170−185. Available from: https://doi.org/10.1016/j.plantsci.2016.11.016.

Ghosh, M., Singh, S., 2005. A review on phytoremediation of heavy metals and utilization of it's by products. Asian J. Energy Environ. 6, 18.

Gramatyka, P., Nowosielski, R., Sakiewicz, P., 2007. Recycling of waste electrical and electronic equipment. J. Achiev. Mater. Manuf. Eng. 20, 535−538.

Gunarathne, V., Mayakaduwa, S., Ashiq, A., Weerakoon, S.R., Biswas, J.K., Vithanage, M., 2019. Transgenic plants: benefits, applications, and potential risks in phytoremediation. Transgenic Plant Technology for Remediation of Toxic Metals and Metalloids. Elsevier. Available from: https://doi.org/10.1016/B978-0-12-814389-6.00005-5.

Ha, N.N., Agusa, T., Ramu, K., Tu, N.P.C., Murata, S., Bulbule, K.A., et al., 2009. Contamination by trace elements at e-waste recycling sites in Bangalore, India. Chemosphere 76, 9−15. Available from: https://doi.org/10.1016/j.chemosphere.2009.02.056.

Heacock, M., Kelly, C.B., Asante, K.A., Birnbaum, L.S., Bergman, Å.L., Bruné, M.-N., et al., 2015. E-waste and harm to vulnerable populations: a growing global problem.

Environ. Health Perspect. 124, 550–555. Available from: https://doi.org/10.1289/ehp.1509699.
Herat, S., Agamuthu, P., 2012. E-waste: a problem or an opportunity? Review of issues, challenges and solutions in Asian countries. Waste Manag. Res. 30, 1113–1129. Available from: https://doi.org/10.1177/0734242X12453378.
Hiremath, L., Kumar, V., Sathyanarayana, B., 2015. Exploitation of live fungus (Aspergillus niger RV-11) for bioremediation of heavy metals from e-waste. Int. J. 6.
Hu, C., Ou, Y., Zhang, D., Zhang, H., Yan, C., Zhao, Y., et al., 2012. Phytoremediation of the polluted Waigang River and general survey on variation of phytoplankton population. Environ. Sci. Pollut. Res. 19, 4168–4175. Available from: https://doi.org/10.1007/s11356-012-0931-z.
Huang, H., Zhang, S., Christie, P., 2011. Plant uptake and dissipation of PBDEs in the soils of electronic waste recycling sites. Environ. Pollut. 159, 238–243. Available from: https://doi.org/10.1016/j.envpol.2010.08.034.
Jiang, L., Luo, C., Zhang, D., Song, M., Sun, Y., Zhang, G., 2018. Biphenyl-metabolizing microbial community and a functional operon revealed in e-waste-contaminated soil. Environ. Sci. Technol. 52, 8558–8567. Available from: https://doi.org/10.1021/acs.est.7b06647.
Kang, C.-H., Kwon, Y.-J., So, J.-S., 2016. Bioremediation of heavy metals by using bacterial mixtures. Ecol. Eng. 89, 64–69. Available from: https://doi.org/10.1016/j.ecoleng.2016.01.023.
Kasassi, A., Rakimbei, P., Karagiannidis, A., Zabaniotou, A., Tsiouvaras, K., Nastis, A., et al., 2008. Soil contamination by heavy metals: measurements from a closed unlined landfill. Bioresour. Technol. 99, 8578–8584. Available from: https://doi.org/10.1016/j.biortech.2008.04.010.
Key, S., Ma, J.K., Drake, P.M., 2008. Genetically modified plants and human health. J. R. Soc. Med. 101, 290–298. Available from: https://doi.org/10.1258/jrsm.2008.070372.
Kidd, P., Barceló, J., Bernal, M.P., Navari-Izzo, F., Poschenrieder, C., Shilev, S., et al., 2009. Trace element behaviour at the root–soil interface: implications in phytoremediation. Environ. Exp. Bot. 67, 243–259. Available from: https://doi.org/10.1016/j.envexpbot.2009.06.013.
Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33, 1237–1250. Available from: https://doi.org/10.1016/j.wasman.2013.01.006.
Kim, K.-H., Jahan, S.A., Kabir, E., Brown, R.J., 2013. A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. Environ. Int. 60, 71–80. Available from: https://doi.org/10.1016/j.envint.2013.07.019.
Laghlimi, M., Baghdad, B., El Hadi, H., Bouabdli, A., 2015. Phytoremediation mechanisms of heavy metal contaminated soils: a review. Open J. Ecol. 5, 375. Available from: https://doi.org/10.4236/oje.2015.58031.
Lee, J.H., 2013. An overview of phytoremediation as a potentially promising technology for environmental pollution control. Biotechnol. Bioproc. Eng. 18, 431–439. Available from: https://doi.org/10.1007/s12257-013-0193-8.
Leung, A., Cai, Z.W., Wong, M.H., 2006. Environmental contamination from electronic waste recycling at Guiyu, southeast China. J. Mater. Cycles Waste Manag. 8, 21–33. Available from: https://doi.org/10.1007/s10163-005-0141-6.
Li, Y., Richardson, J.B., Bricka, R.M., Niu, X., Yang, H., Li, L., et al., 2009. Leaching of heavy metals from E-waste in simulated landfill columns. Waste Manag. 29, 2147–2150. Available from: https://doi.org/10.1016/j.wasman.2009.02.005.

Li, J., Duan, H., Shi, P., 2011. Heavy metal contamination of surface soil in electronic waste dismantling area: site investigation and source-apportionment analysis. Waste Manag. Res. 29, 727–738. Available from: https://doi.org/10.1177/0734242X10397580.

Lim, J.-M., Jin, B., Butcher, D.J., 2012. A comparison of electrical stimulation for electrodic and EDTA-enhanced phytoremediation of lead using Indian mustard (Brassica juncea). Bulletin of the Korean Chemical Society 33, 2737–2740. Available from: https://doi.org/10.5012/bkcs.2012.33.8.2737.

Liu, F., Wang, C., Liu, X., Liang, X., Wang, Q., 2013. Effects of alkyl polyglucoside (APG) on phytoremediation of PAH-contaminated soil by an aquatic plant in the Yangtze estuarine wetland. Water Air Soil Pollut. 224, 1633. Available from: https://doi.org/10.1007/s11270-013-1633-y.

Lukose, N., 2015. A review on e-waste management and recycling challenges in India. Int. J. Sci. Eng. Res. 6, 18–29.

Lundgren, K., 2012. The Global Impact of E-Waste: Addressing the Callenge. International Labour Organization.

Luo, C., Wang, S., Wang, Y., Yang, R., Zhang, G., Shen, Z., 2015. Effects of EDDS and plant-growth-promoting bacteria on plant uptake of trace metals and PCBs from e-waste–contaminated soil. J. Hazard. Mater. 286, 379–385. Available from: https://doi.org/10.1016/j.jhazmat.2015.01.010.

Luo, J., Qi, S., Gu, X.S., Wang, J., Xie, X., 2016. Evaluation of the phytoremediation effect and environmental risk in remediation processes under different cultivation systems. J. Clean. Prod. 119, 25–31. Available from: https://doi.org/10.1016/j.jclepro.2016.01.043.

Luo, J., Cai, L., Qi, S., Wu, J., Gu, X.S., 2017. A multi-technique phytoremediation approach to purify metals contaminated soil from e-waste recycling site. J. Environ. Manag. 204, 17–22. Available from: https://doi.org/10.1016/j.jenvman.2017.08.029.

Luo, J., Wu, J., Huo, S., Qi, S., Gu, X.S., 2018. A real scale phytoremediation of multi-metal contaminated e-waste recycling site with Eucalyptus globulus assisted by electrical fields. Chemosphere 201, 262–268. Available from: https://doi.org/10.1016/j.chemosphere.2018.03.018.

Ma, T.T., Teng, Y., Luo, Y.M., Christie, P., 2013. Legume-grass intercropping phytoremediation of phthalic acid esters in soil near an electronic waste recycling site: a field study. Int. J. Phytoremed. 15, 154–167. Available from: https://doi.org/10.1080/15226514.2012.687016.

Mafaziya, F., Madawala, S., 2015. Abundance, richness and root colonization of arbuscular mycorrhizal fungi in natural and semi-natural land use types at upper Hantana. Ceylon J. Sci. (Biol. Sci.) 44, 25–34.

Mahar, A., Wang, P., Ali, A., Awasthi, M.K., Lahori, A.H., Wang, Q., et al., 2016. Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: a review. Ecotoxicol. Environ. Saf. 126, 111–121. Available from: https://doi.org/10.1016/j.ecoenv.2015.12.023.

Martin, S., Griswold, W., 2009. Human health effects of heavy metals. Environ. Sci. Technol. Briefs Citizens 15, 1–6.

Meagher, R.B., 2000. Phytoremediation of toxic elemental and organic pollutants. Curr. Opin. Plant Biol. 3, 153–162. Available from: https://doi.org/10.1016/S1369-5266(99)00054-0.

Möller, A., Sturm, R., Xie, Z., Cai, M., He, J., Ebinghaus, R., 2012. Organophosphorus flame retardants and plasticizers in airborne particles over the Northern Pacific and Indian Ocean toward the polar regions: evidence for global occurrence. Environ. Sci. Technol. 46, 3127–3134. Available from: https://doi.org/10.1021/es204272v.

Muenhor, D., Harrad, S., Ali, N., Covaci, A., 2010. Brominated flame retardants (BFRs) in air and dust from electronic waste storage facilities in Thailand. Environ. Int. 36, 690–698. Available from: https://doi.org/10.1016/j.envint.2010.05.002.

Mwegoha, W.J., 2008. The use of phytoremediation technology for abatement soil and groundwater pollution in Tanzania: opportunities and challenges. J. Sustain. Devel. Africa 10, 140–156.

Nahar, N., Rahman, A., Nawani, N.N., Ghosh, S., Mandal, A., 2017. Phytoremediation of arsenic from the contaminated soil using transgenic tobacco plants expressing ACR2 gene of Arabidopsis thaliana. J. Plant Physiol. 218, 121–126. Available from: https://doi.org/10.1016/j.jplph.2017.08.001.

Ni, H.G., Zeng, E.Y., 2009. Law Enforcement and Global Collaboration Are the Keys to Containing E-Waste Tsunami in China. ACS Publications. Available from: https://doi.org/10.1021/es802725m.

Ni, H.G., Zeng, H., Tao, S., Zeng, E.Y., 2010. Environmental and human exposure to persistent halogenated compounds derived from e-waste in China. Environ. Toxicol. Chem. 29, 1237–1247. Available from: https://doi.org/10.1002/etc.160.

Nordbrand, S., 2009. Out of Control: E-Waste Trade Flows From the EU to Developing Countries. SwedWatch, Stockholm, p. 46.

Omondi, E., Ndiba, P., Njuru, P., 2015. Phytoremediation of polychlorobiphenyls (PCB's) in landfill e-waste leachate with water hyacinth (E. crassipes). Int. J. Sci. Technol. Res 4, 147–156.

Pandey, V.C., 2012. Invasive species based efficient green technology for phytoremediation of fly ash deposits. J. Geochem. Explor. 123, 13–18. Available from: https://doi.org/10.1016/j.gexplo.2012.05.008.

Pandey, V.C., Bajpai, O., 2019. Phytoremediation: from theory toward practice. Phytomanagement of Polluted Sites. Elsevier. Available from: https://doi.org/10.1016/B978-0-12-813912-7.00001-6.

Pandey, V.C., Singh, K., 2011. Is Vigna radiata suitable for the revegetation of fly ash landfills? Ecol. Eng. 37, 2105–2106. Available from: https://doi.org/10.1016/j.ecoleng.2011.07.003.

Pandey, V.C., Pandey, D.N., Singh, N., 2015. Sustainable phytoremediation based on naturally colonizing and economically valuable plants. J. Clean. Prod. 86, 37–39. Available from: https://doi.org/10.1016/j.jclepro.2014.08.030.

Prakash, S., Manhart, A., Amoyaw-Osei, Y., Agyekum, O.O., 2010. Socio-Economic Assessment and Feasibility Study on Sustainable E-Waste Management in Ghana. Öko-Institut eV in cooperation with Ghana Environmental Protection Agency (EPA) & Green Advocacy Ghana, Ministry of Housing, Spatial Planning and the Environment, VROM-Inspectorate.

Prasad, M., De Oliveira Freitas, H., 2003. Metal hyperaccumulation in plants-Biodiversity prospecting forphytoremediation technology. Electron. J. Biotechnol. 6, 110–146.

Rathod, M., Mody, K., Basha, S., 2014. Efficient removal of phosphate from aqueous solutions by red seaweed, Kappaphycus alverezii. J. Clean. Prod. 84, 484–493. Available from: https://doi.org/10.1016/j.jclepro.2014.03.064.

Ren, C.-G., Kong, C.-C., Bian, B., Liu, W., Li, Y., Luo, Y.-M., et al., 2017. Enhanced phytoremediation of soils contaminated with PAHs by arbuscular mycorrhiza and rhizobium. Int. J. Phytoremed. 19, 789–797. Available from: https://doi.org/10.1080/15226514.2017.1284755.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–191. Available from: https://doi.org/10.1016/j.scitotenv.2009.09.044.

Safe, S., 1993. Toxicology, structure-function relationship, and human and environmental health impacts of polychlorinated biphenyls: progress and problems. Environ. Health Perspect. 100, 259–268. Available from: https://doi.org/10.1289/ehp.93100259.

Salt, D.E., Blaylock, M., Kumar, N.P., Dushenkov, V., Ensley, B.D., Chet, I., et al., 1995. Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. Biotechnology 13, 468. Available from: https://doi.org/10.1038/nbt0595-468.

Sarma, H., 2011. Metal hyperaccumulation in plants: a review focusing on phytoremediation technology. J. Environ. Sci. Technol. 4, 118–138. Available from: https://doi.org/10.3923/jest.2011.118.138.

Schneider, J., Bundschuh, J., Do Nascimento, C.W.A., 2016. Arbuscular mycorrhizal fungi-assisted phytoremediation of a lead-contaminated site. Science of The Total Environment 572, 86–97. Available from: https://doi.org/10.1016/j.scitotenv.2016.07.185.

Sepúlveda, A., Schluep, M., Renaud, F.G., Streicher, M., Kuehr, R., Hagelüken, C., et al., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environ. Impact Assess. Rev. 30, 28–41. Available from: https://doi.org/10.1016/j.eiar.2009.04.001.

Sharma, P., Pandey, S., 2014. Status of phytoremediation in world scenario. Int. J. Environ. Bioremed. Biodeg. 2, 178–191.

Shen, C., Tang, X., Cheema, S.A., Zhang, C., Khan, M.I., Liang, F., et al., 2009. Enhanced phytoremediation potential of polychlorinated biphenyl contaminated soil from e-waste recycling area in the presence of randomly methylated-β-cyclodextrins. J. Hazard. Mater. 172, 1671–1676. Available from: https://doi.org/10.1016/j.jhazmat.2009.08.064.

Shim, D., Kim, S., Choi, Y.-I., Song, W.-Y., Park, J., Youk, E.S., et al., 2013. Transgenic poplar trees expressing yeast cadmium factor 1 exhibit the characteristics necessary for the phytoremediation of mine tailing soil. Chemosphere 90, 1478–1486. Available from: https://doi.org/10.1016/j.chemosphere.2012.09.044.

Siddiqi, M.A., Laessig, R.H., Reed, K.D., 2003. Polybrominated diphenyl ethers (PBDEs): new pollutants–old diseases. Clin. Med. Res. 1, 281–290. Available from: https://doi.org/10.3121/cmr.1.4.281.

Singh, A., Gautam, A., 2014. Study and comparison of e-waste disposal solutions. Int. J. Emerg. Technol. Adv. Eng. 4, 474–477.

Sivakumaran, R., Anandkumar, K., Shanmugasundaram, G., 2017. Management of electronic waste disposal in India. Adv. Nat. Appl. Sci. 11, 522–530.

Sivaramanan, S., 2013. E-waste management, disposal and its impacts on the environment. Univ. J. Environ. Res. Technol. 3, 531–537.

Spalvins, E., Dubey, B., Townsend, T., 2008. Impact of electronic waste disposal on lead concentrations in landfill leachate. Environ. Sci. Technol. 42, 7452–7458. Available from: https://doi.org/10.1021/es8009277.

Susarla, S., Medina, V.F., Mccutcheon, S.C., 2002. Phytoremediation: an ecological solution to organic chemical contamination. Ecol. Eng. 18, 647–658. Available from: https://doi.org/10.1016/S0925-8574(02)00026-5.

Tang, X., Shen, C., Shi, D., Cheema, S.A., Khan, M.I., Zhang, C., et al., 2010. Heavy metal and persistent organic compound contamination in soil from Wenling: an emerging e-waste recycling city in Taizhou area, China. J. Hazard. Mater. 173, 653–660. Available from: https://doi.org/10.1016/j.jhazmat.2009.08.134.

Tangahu, B.V., Abdullah, S., Rozaimah, S., Basri, H., Idris, M., Anuar, N., et al., 2011. A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. Int. J. Chem. Eng. 2011. Available from: https://doi.org/10.1155/2011/939161.

Teng, Y., Luo, Y., Sun, X., Tu, C., Xu, L., Liu, W., et al., 2010. Influence of arbuscular mycorrhiza and rhizobium on phytoremediation by alfalfa of an agricultural soil contaminated with weathered PCBs: a field study. Int. J. Phytoremed. 12, 516−533. Available from: https://doi.org/10.1080/15226510903353120.

Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31, 45−58. Available from: https://doi.org/10.1016/j.wasman.2010.08.014.

Tu, C., Teng, Y., Luo, Y., Sun, X., Deng, S., Li, Z., et al., 2011. PCB removal, soil enzyme activities, and microbial community structures during the phytoremediation by alfalfa in field soils. J. Soils Sedim. 11, 649−656. Available from: https://doi.org/10.1007/s11368-011-0344-5.

Van Aken, B., 2008. Transgenic plants for phytoremediation: helping nature to clean up environmental pollution. Trends Biotechnol. 26, 225−227. Available from: https://doi.org/10.1016/j.tibtech.2008.02.001.

Vats, M., Singh, S., 2014. E-Waste characteristic and its disposal. Int. J. Ecol. Sci. Environ. Eng. 1, 49−61.

Wang, Y., Luo, C., Li, J., Yin, H., Li, X., Zhang, G., 2011. Characterization of PBDEs in soils and vegetations near an e-waste recycling site in South China. Environ. Pollut. 159, 2443−2448. Available from: https://doi.org/10.1016/j.envpol.2011.06.030.

Wang, Y., Ren, H., Pan, H., Liu, J., Zhang, L., 2015. Enhanced tolerance and remediation to mixed contaminates of PCBs and 2, 4-DCP by transgenic alfalfa plants expressing the 2, 3-dihydroxybiphenyl-1, 2-dioxygenase. J. Hazard. Mater. 286, 269−275. Available from: https://doi.org/10.1016/j.jhazmat.2014.12.049.

Wei, H., Huang, M., Quan, G., Zhang, J., Liu, Z., Ma, R., 2018. Turn bane into a boon: application of invasive plant species to remedy soil cadmium contamination. Chemosphere 210, 1013−1020. Available from: https://doi.org/10.1016/j.chemosphere.2018.07.129.

Wilkinson, C.F., Lamb, I.V., James, C., 1999. The potential health effects of phthalate esters in children's toys: a review and risk assessment. Regul. Toxicol. Pharmacol. 30, 140−155. Available from: https://doi.org/10.1006/rtph.1999.1338.

Yu, J., Welford, R., Hills, P., 2006. Industry responses to EU WEEE and ROHS directives: perspectives from China. Corp. Soc. Respons. Environ. Manag. 13, 286−299. Available from: https://doi.org/10.1002/csr.131.

Zhang, Y., Liu, J., 2011. Transgenic alfalfa plants co-expressing glutathione S-transferase (GST) and human CYP2E1 show enhanced resistance to mixed contaminates of heavy metals and organic pollutants. J. Hazard. Mater. 189, 357−362. Available from: https://doi.org/10.1016/j.jhazmat.2011.02.042.

Zhang, Y., Liu, J., Zhou, Y., Gong, T., Wang, J., Ge, Y., 2013. Enhanced phytoremediation of mixed heavy metal (mercury)−organic pollutants (trichloroethylene) with transgenic alfalfa co-expressing glutathione S-transferase and human P450 2E1. J. Hazard. Mater. 260, 1100−1107. Available from: https://doi.org/10.1016/j.jhazmat.2013.06.065.

Zheng, G.J., Leung, A.O., Jiao, L.P., Wong, M.H., 2008. Polychlorinated dibenzo-p-dioxins and dibenzofurans pollution in China: sources, environmental levels and potential human health impacts. Environ. Int. 34, 1050−1061. Available from: https://doi.org/10.1016/j.envint.2008.02.011.

Organic pollutants from E-waste and their electrokinetic remediation

8

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8.1 Organic pollutant types from E-waste

As described in the previous chapters E-waste is quite copious in the environment with a significant contribution from computers, mobile phones, and entertainment electronics, as their life spans are not that long. In today's throwaway society the desire for the novel state-of-the art devices explains the rising volumes of the E-waste. E-waste typically describes waste electronic goods such as the above-mentioned computers, mobile phones, and televisions. In addition, the term, waste electrical and electronic equipment (WEEE) comprises traditionally nonelectronic goods such as refrigerators, washing machines, and ovens. However, the distinction between E-waste and WEEE is becoming less sharp as the equipment such as modern refrigerators consist of programmable microprocessors. Therefore a discussion on E-waste should carry all these common sources.

Human exposure to E-waste is an emerging threat in the current century with the high volumes of E-waste. The chemical composition of E-wastes depends on the type of the electronic device discarded. It is usually consisted of metals such as Cu, Al, Au, and Fe (Köhler and Erdmann, 2004). Also, several plastic types and/or ceramics are predominantly found in E-waste. Heavy WEEE items such as refrigerators and washing machines are mostly consisted of steel and may contain fewer environmental contaminants. However, lighter items such as mobile phones and laptops may contain high concentrations of flame retardants and heavy metals. When it comes to waste materials like flame retardants, they are having a significant contribution on organic pollutants originates from electronic devices. Such organic pollutants can be considered under persistent organic pollutants (POPs), as they are resistant to environmental degradation through chemical, biological, and photolytic processes. Several classes of POPs can be found such as polycyclic aromatic hydrocarbons (PAHs), polyhalogenated aromatic hydrocarbons (PHAHs), polychlorinated biphenyls (PCBs), polybrominated biphenyls (PBBs), and polybrominated diphenyl ethers (PBDEs) (Hites, 2004).

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00006-1

8.1.1 Polycyclic aromatic hydrocarbons/polynuclear aromatic hydrocarbons

Two or more fused benzene rings arranged in different configurations make the large group of organic compounds, PAHs. The PAHs available in the atmosphere is a burning issue because of their carcinogenicity, teratogenicity, and mutagenicity (Boström et al., 2002). The ubiquitous nature of these organic pollutants makes the scenario even worse. Among natural and all the other anthropogenic sources of PAHs, the generation through electronic waste disposal processes plays a significant role. PAHs can be categorized into two groups: low molecular weight compounds with less than four rings and high molecular weight compounds with four or more rings. Compounds such as benzo[a]anthracene, benzo[a]pyrene, and dibenz[ah]anthracene have been recognized as most potent PAH carcinogens (Armstrong et al., 2004). Some of the dominant PAHs from E-waste recycling sites are naphthalene, phenanthrene, and fluoranthene which are mainly derived from incomplete combustion of wire insulations and PVC materials (Fig. 8.1).

8.1.1.1 Physicochemical properties of polycyclic aromatic hydrocarbons

Pure PAHs are colored crystalline solid material at ambient temperatures. The physical properties depend on their molecular weight and on the structure. As expected, the vapor pressure decreases with the increasing molecular weight. The water solubility also decreases with increasing number of ring moieties (Masih et al., 2012). PAHs are lipophilic making them soluble in organic solvents. The hydrophobicity and poor solubility of these PAHs make them bioaccumulate in the environment through the food chain without easy biodegradations.

PAHs show other features such as light sensitivity, heat resistance, conductivity, corrosion resistance, and physiological action (Masih et al., 2012).

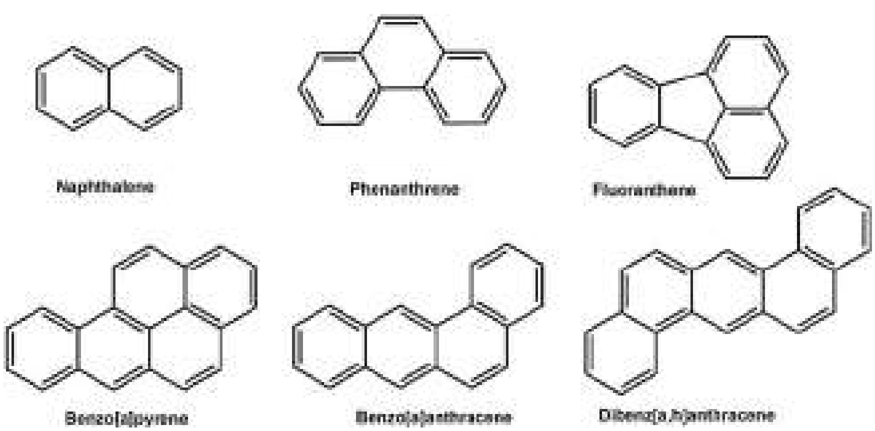

Figure 8.1 Structures of some of the PAHs generating through E-waste.

Furthermore, they display characteristic UV absorption spectra and each structure has a unique UV spectrum. This feature can be utilized as an identification tool for PAHs. Not limited to characteristic UV absorptions, most of these compounds exhibit fluorescence properties upon excitations.

8.1.1.2 Fate and transformations of polycyclic aromatic hydrocarbons

The PAHs are readily available in the atmosphere either as a vapor or adsorbed into atmospheric particulate matter. This adsorption process depends on the nature of the compounds and on the atmospheric conditions such as relative humidity and the ambient temperature (Ravindra et al., 2008). For an instance, low molecular weight compounds are relatively higher in volatility and mostly be in the vapor phase. The fate of PAHs depends on several factors such as the interactions of each compound with other contaminants, dry and wet depositions, photodegradations, or photochemical reactions (Zhang and Tao, 2009). Such examples can be seen, when certain PAHs react with other pollutants namely ozone, nitrogen oxides, and sulfur dioxide to generate diones, nitro and dinitro-PAHs, and sulfuric acids respectively. These interactions with other pollutants can result more toxic species which ultimately leads to severe environmental issues (Park et al., 2001). These derivatized PAHs typically have lower vapor pressures than the parent compounds and likely to be deposited on airborne particles.

PAHs are toxic to humans and acting as mutagens, carcinogens, and potentially as reproductive toxicants. They can be lethal even at few ppm concentrations and may cause chronic effects even at ppb level. These PAHs tend to bioaccumulate in soft tissues. Yet, they may not be directly carcinogenic but act as precursors. Their carcinogenicity originates as a result of their ability to bind to DNA causing a series of disruptive effects which lead to tumor initiation.

Specifically evaluating the behavior of Benzo[a]pyrene (Trushin et al., 2012), its' genotoxicity effect appears only after the biotransformation to reactive electrophilic metabolites that covalently binds to cellular elements such as DNA. The ultimate carcinogenic product is formed via a three-step process. First, the formation of (7R,8S)-epoxy-7,8-dihydrobenzo(a)pyrene [B(a)P-7,8-oxide] is catalyzed by cytochrome 450 enzymes. Next the conversion of B(a)P-7,8-oxide to (7R,8R)-dihydroxy-7,8 dihydrobenzo(a)pyrene [B(a)P-7,8-diol] is catalyzed by epoxide hydrolase. Finally, cytochrome P450 enzyme catalyzes the process to generate four possible isomers of 7,8-diol-9,10-epoxide. Out of the isomers (7R,8S)-dihydroxy-(9S,10R)-epoxy-7,8,9,10-tetrahydrobenzo(a)pyrene (BPDE) plays a key role as it can be bound to DNA at guanine residues creating mutations (Fig. 8.2).

As in the case of Benzo[a]pyrene, many other PAHs are prone to undergo transformations due to the influence of biological, chemical, or photochemical effects (Park et al., 2001).

Simple aromatic alcohol, phenol (Cook et al., 2015), and its derivatives can also be found in E-waste dismantling sites. As shown in Fig. 8.3, even the simplest form of aromatic alcohols, phenol induces the breaking of the O−H bond to generate a

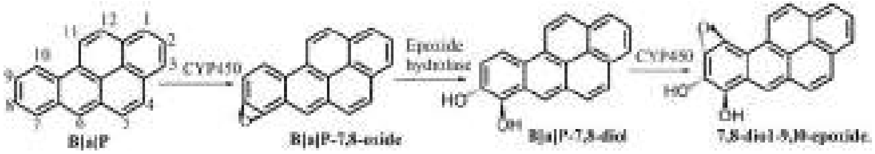

Figure 8.2 Metabolic activation Benzo[a]pyrene, B[a]P: the activated benzo(a)pyrene diol epoxide congener can bind with DNA.

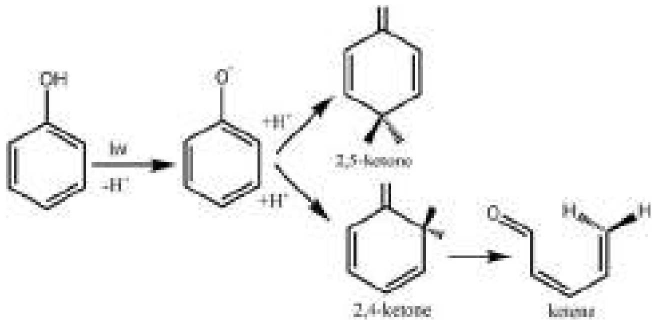

Figure 8.3 The decomposition of phenol upon UV photolysis.
Source: Adapted from Cook, A., Ricca, A., Mattioda, A., Bouwman, J., Roser, J., Linnartz, H., et al., 2015. Photochemistry of polycyclic aromatic hydrocarbons in cosmic water ice: the role of PAH ionization and concentration. Astrophys. J. 799, 14.

phenoxyl radical. In the presence of H^+ this phenoxyl radical leads to the formation of two isomers of a ketone namely 2,4- or 2,5-cyclohexadienone.

Further decomposition occurs via 2,4-cyclohexadienone, as it is the photochemically unstable version of the ketone (Cook et al., 2015). This instability of the ketone results a ring opening to generate a ketene. Ketenes are respiratory poisons and create a severe situation with respect to its initial counterpart (Fig. 8.3).

8.1.2 Polychlorinated biphenyls, polybrominated biphenyls, and polybrominated diphenyl ethers

PBBs and PBDEs are classes of POPs which are commonly found in the environment. Both PBBs and PBDEs are used as flame retardants and they represent the larger class of PHAHs. PBDEs are used in plastics, epoxy resins. and rubber, hence may find in E-waste products such as printed circuit boards, cables, and television sets (Fig. 8.4).

PCBs are widely used as coolants and insulators in electrical capacitors and transformers and as plasticizers (Safe, 1994). Zhao et al. (2006) suggested that obsolete transformers and electrical waste are key sources of PCB emissions into the environment. About 209 different compounds can be found as PCBs and their toxicity can be varied based on the structure of each PCB. Furthermore, as all these

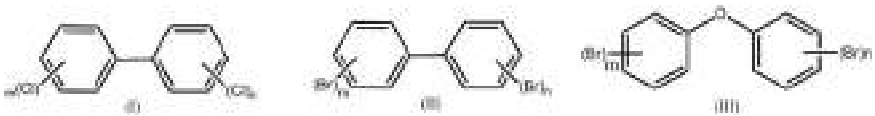

Figure 8.4 The structures of (I) polychlorinated biphenyls (PCBs), (II) polybrominated biphenyls (PBBs), and (III) polybrominated diphenyl ethers (PBDEs).

three categories are highly lipophilic and persistent in the environment, they are notably toxic and bio accumulative. These PHAHs are also known for possible transformations resulting, compounds with higher degrees of toxicity.

Zhao et al. carried out a study to investigate the exposure of Chinese residents to PBBs, PBDEs and PCBs in E-waste disassembly sites (Zhao et al., 2008). There, the pollutants from E-waste were detected using GC-MS and, all the congeners of the expected PHAHs were present at higher levels than regular sites with no E-waste disassembly sites nearby. Among the PHAHs PCBs was the major pollutant. The study was carried out using hair samples of individuals and the amounts of PHAHs found in hair samples were pretty much similar to the amounts found in the soil samples in the vicinity. Therefore the authors have concluded that hair sampling can be considered as a valid screening method for assessing PHAHs exposure in and around E-waste disassembly sites. Yang et al. reported higher amounts of organohalogen pollutants in human serum samples of individuals from another E-waste dismantling site in China. They have also used GC-MS for their analysis and found out higher concentrations of hexa through nona PBDEs, PCBs, and PBBs than regular sites. Furthermore, they have claimed even higher amounts of PHAHs in body serums of workers at these disassembly sites (Yang et al., 2013). In another study, Yu et al. (2006) studied the concentration profiles of PAHs in soil of an E-waste disassembling site. The concentrations of 16 PAHs were studied and they were in the descending order of E-waste open burning site > areas near burning site > rice fields > reservoir areas, concluding an obvious behavior of higher concentrations at the site itself. Also, they have reported naphthalene, phenanthrene, and fluoranthene as the dominant PAHs derived from incomplete combustion of E-waste.

8.2 Electrokinetic remediation

Electrokinetic remediation (EKR) is a promising environmental technique developed to fulfill the challenging demand of an in situ and cost-effective remediation technology for waste management (Virkutyte et al., 2002). As this process can be performed in situ, there is no need of soil excavation for the purpose of decontamination (De battisti and Ferro, 2007). This technique is productive for the removal of inorganic, organic, and mixed contaminants in soil, sediments and sludge, although it can be applied to any solid porous material (Yeung and Gu, 2011; Cameselle and Reddy, 2009). This technique variably termed as EKR, electroreclamation, electrokinetic soil processing, and electrochemical decontamination (Acar and Alshawabkeh, 1993). Conduction phenomena under electrical currents is the primary principle in EKR whereas low-level DC electrical field (generally 1DCV/cm) is applied (Acar et al., 1993). As a DC electric field force is much more effective than a hydraulic gradient in driving fluid through fine-grained soils, EKR is particularly applicable to soils of low hydraulic conductivity and large specific area (Yeung and Gu, 2011) (Fig. 8.5).

Fig. 8.5 shows the basic set up of an EKR system. There should be a minimum of two electrodes (anode and cathode) which are typically inside a chamber. Those electrodes are inserted in the soil which is contaminated. The effect of the electric field induces the mobilization and transportation of contaminants through the porous matrix toward the electrodes. The anode is positively charged, and it attracts the negatively charged contaminants and the cathode is negatively charged and it attracts the positively charged contaminants when the current is passed (Sharma and Reddy, 2004). The ground water generally suffices as a conductive medium for the passage of current but in a situation where the groundwater proves to be insufficient, external processing fluid is used as conductive medium (Acar and Alshawabkeh, 1993). The contaminated water from the electrode casings is pumped out and treated. The electrode arrangement depends on the extent of contamination. Arrays of cathode and anode electrodes can be installed in areas of extensive contamination of soil.

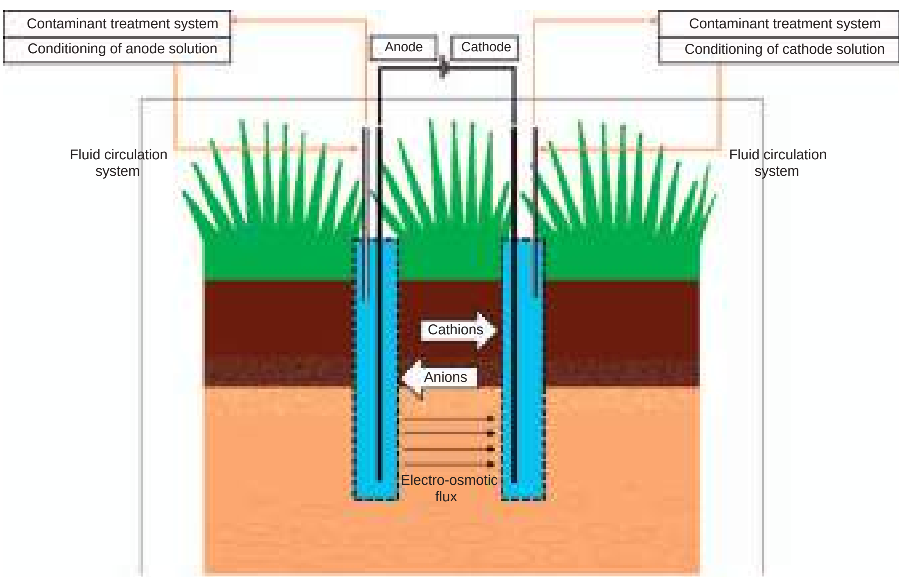

Figure 8.5 Electrokinetic remediation system.
Source: Adapted from Cameselle, C., Gouveia, S., Akretche, D.E., Belhadj, B., 2013. Advances in electrokinetic remediation for the removal of organic contaminants in soils. Organic Pollutants: Monitoring, Risk and Treatment. In Tech 209–229.

Electrodes that are inert to anodic dissolution should be used during the remediation process. The most suitable electrodes used for research purposes include graphite, platinum, gold, and silver. However, for pilot studies, it is more appropriate to use much cheaper, although reliable, titanium, stainless steel, or even plastic electrodes (Virkutyte et al., 2002).

According to the experiments and pilot-scale studies conducted, metals such as lead, chromium, cadmium, copper, uranium, mercury, and zinc, as well as PCBs, phenols, chlorophenols, toluene, trichlorethane, nitrobenzenes, and pesticides are suitable for EKR and recovery (Virkutyte et al., 2002).

During the EKR, contaminants are migrated by the combined mechanisms of electroosmosis, electromigration, electrophoresis, and diffusion (Acar and Alshawabkeh, 1993).

Electromigration is defined as the transportation of ions and ion complexes in solution toward the electrode of the opposite charge (Fig. 8.5). Cations move toward the cathode and anions move toward the anode. The ionic migration or electromigration depends on the ionic mobility, valence numbers, electrolyte concentration, and the strength of the electric field. Electromigration is comparatively faster than the other processes and is the dominant transport mechanism for ionic metals, polar organic molecules, ionic micelles, and colloidal electrolytes during remediation. The rate of movement of ions (V) can be expressed as (Virkutyte et al., 2002; Sharma and Reddy, 2004)

$$v = \frac{IV_i P_W}{A\tau\theta}$$

where I is the applied current, v_i is the ion velocity, A is the cross sectional area, P_w is the pore water resistivity, τ is the tortuosity, and Θ is the volumetric moisture content.

Electroosmosis is the net flux of soil moisture or groundwater induced by the electric field. Electroosmosis is a complex transport phenomenon that depends on the electric characteristics of the solid surface, the properties of the interstitial fluid, and the interaction between the solid surface and the components in solution. The soil particles are usually negatively charged and the positively charged cations in pore water align along the negative soil surfaces (Virkutyte et al., 2002). The water molecules in turn align around the cations till there are no excess cations left. The remaining water molecules end up around the negatively charged soil surface forming the boundary layer (Sharma and Reddy, 2004). When electric field is applied, the positively charged water molecules will move toward the cathode. As the cations move toward cathode, a shearing action takes place. The cations move through the pore water at high velocities and pull the water molecules along with them (Fig. 8.6). This results in the large transfer of water from anode to cathode. The electroosmotic flow depends on the dielectric constant and viscosity of pore fluid as well as the surface charge of the solid matrix represented by zeta potential. In the case of electropositive solid matrixes, the electroosmotic flow moves toward the anode. The zeta potential is a function of many parameters including the types

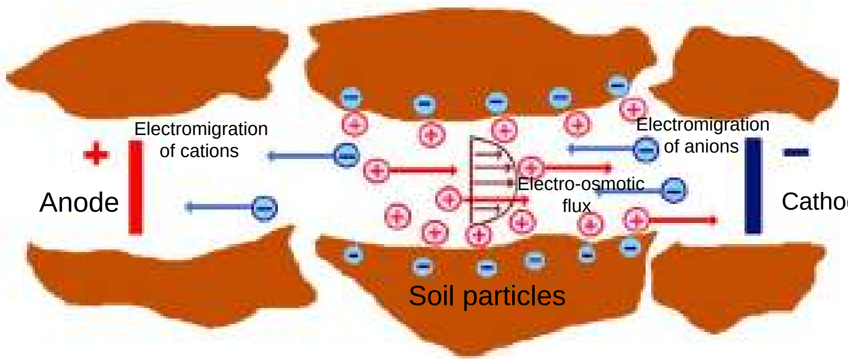

Figure 8.6 Transportation mechanism in electrokinetic remediation process.
Source: Adapted from Cameselle, C., Gouveia, S., Akretche, D.E., Belhadj, B., 2013. Advances in electrokinetic remediation for the removal of organic contaminants in soils. Organic Pollutants: Monitoring, Risk and Treatment. In Tech 209−229.

of clay minerals and ionic species that are present as well as the pH, ionic strength, and temperature. Electroosmosis is considered the dominant transport process for both organic and inorganic contaminants that are in dissolved, suspended, emulsified forms.

Electrophoresis is the transport of charged particles of colloids and bound contaminants under the influence of an electric field. Compared to electromigration and electroosmosis, mass transport by electrophoresis is negligible in low permeability soil systems. However, mass transport by electrophoresis may become significant in soil suspension systems and it is the mechanism for the transportation of colloids (including bacteria) and micelles.

Diffusion is different from other transport mechanisms, as migration is taking place due to a concentration gradient rather than to a voltage gradient. These concentration gradients are generated by the electromigration and electroosmosis of contaminants. Transport from this mechanism is often neglected considering its lower velocity compared to electromigration and electroosmosis. Diffusion depends on the tortuosity and porosity of the medium and the concentration of the species (Sharma and Reddy, 2004) (Fig. 8.6).

The application of an electric field to a porous matrix with moisture induces other chemical and physical processes. These processes include electrolysis, adsorption-desorption, precipitation-dissolution, and oxidation-reduction. Such reactions dramatically affect the speciation of the contaminants and therefore affect the transportation and contaminant removal efficiency.

8.2.1 Electrolysis

Electrolysis is the decomposition of water at electrodes when an electric field is applied. In this process oxidation takes place near anode generating hydrogen ions (H^+) and oxygen (O_2), and reduction takes place near cathode generating and hydroxyl ions (OH^-) and hydrogen (H_2). These reactions are shown by the following equations (Cameselle et al., 2013; Sharma and Reddy, 2004):

$$2H_2O \rightarrow 4e^- + O_2 + 4H^+ \quad E_0 = -1.229\ V$$

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \quad E_0 = -0.828\ V$$

The process of electrolysis leads to changes in the soil pH near the electrodes. The region near anode develops a low pH of about 2 whereas near the cathode it increases up to 11 or 12. The hydrogen and hydroxyl ions move both due to electromigration and diffusion. The hydrogen ions being smaller than the hydroxyl ions tend to travel faster leading to rapid acid front migration than the base front migration (Sharma and Reddy, 2004). The acid dissolves the usual cations in the soil or precipitates and helps cation removal. If the contaminants are anionic, the acid front would increase adsorption and reduce the contaminant removal. Both the acid and base front will influence the zeta potential of the soil impacting the flow.

8.2.2 Adsorption-desorption

Adsorption involves the movement of contaminants from solution to the soil particles. Generally, soils are negatively charged but it would depend on the pH of the soil (Acar et al., 1993). The net charge in soil will be zero for a particular value of pH and that is called the point of zero charge (PZC). If the pH value of ground water is less than PZC, adsorption of anions will be predominant and when the pH is above PZC, the adsorption of cations is significant. Thus, adsorption depends on factors including soil type, soil charge, contaminant, organic matter, and pore water characteristics.

Desorption is the reverse process of adsorption whereas contaminants transport from soil to the solution. When pH is below PZC desorption of cations are significant and vice versa. Due to extreme pH differences between the regions near the electrodes, the cationic adsorption and anionic desorption occur near cathode. The anionic adsorption and cationic desorption occur near anode.

8.2.3 Precipitation-dissolution

Precipitation is the formation of solid when the concentration of compound exceeds its solubility. Dissolution is the reverse process where compound forms a solution. Both processes are highly pH dependent and contaminants could be precipitated or dissolved during remediation. The dissolved contaminants would be easier to remove than the precipitated contaminants in soil.

8.2.4 Oxidation-reduction

Redox reactions take place during the remediation process. Area near anode experiences oxidation since electrons are lost and the area near cathode experiences reduction since there is an addition of electrons. In these reactions some metal cations precipitate near cathode. The solubility of some metal ions depends on their valence, thus, might have an impact on removal (Sharma and Reddy, 2004).

8.2.5 Advantages of the electrokinetic remediation technique

The in situ method is preferred since it would be less expensive. The fact that the soil need not be removed indicates that the amount of energy needed for this process would be comparatively lower than ex situ procedures. The process can target a specific area since the remediation will take place only between the electrodes. The technique is applicable for a wide range of contaminants since metal contaminants can be moved due to their charge and the non-charged contaminants are moved due to induced flow. Besides, electroosmotic flow though low permeability regions is significantly greater than the flow achieved by an ordinary hydraulic gradient, so the electroosmotic flow is much more efficient in low permeability soils. Since, a low current is used in the order of mA/cm^2 per cross sectional area it would be safer for the personnel working and also it would avoid the adverse effects of heating.

8.2.6 Disadvantages and challenges

However, regardless of promising benefits, the EKR has its own drawbacks. EKR process is highly dependent on acidic conditions, which favors the release of the metal contaminants into the solution phase. However, achieving these acidic conditions might be difficult when the soil buffering capacity is high. In addition, acidification of soils may not be environmentally friendly. Based on a study performed on a diesel contaminated soil, it was revealed that, a month after remediation, the pH of soil near anode was very low about 3.5 and was very high near cathode with a value of 10.8. This seemed to have an adverse effect on the microbial community in the soils though the soil was remediated. Another disadvantage is the remediation process is a very time-consuming application; the overall application time may vary from several days to even a few years.

8.2.7 Electrokinetic remediation for the removal of organic waste

EKR was first proposed and tested for the removal of heavy metals and other charged inorganic contaminants. However, the technique can be useful for the removal of organic contaminants from soil. The removal of organic contaminants from soil is limited by the neutrality of the molecules and the low solubility of most of the organic contaminants. The removal by electromigration and electroosmosis requires charged molecules and/or the solubilization in the interstitial fluid. This can be achieved with the addition of facilitating agents (surfactants, cosolvents, or any other chemical agents). Cosolvents can dissolve some organic contaminants that are not soluble in water. The surfactants can lower the surface tension of water improving the solubility of hydrophobic organic compounds. Several studies have focused on using enhanced electrokinetic process to remediate organic components produced by E-waste.

Saicheck and Reddy evaluated different surfactants/cosolvents for their ability to desorb and solubilize phenanthrene in enhanced electrokinetic process. Six different surfactant/cosolvent purging solutions were tested including Igepal CA-720 at two different concentrations, 3% and 5%, 5% Triton X-100, 3% Tween 80, 40% ethanol, and a 40% ethanol and 5% Igepal CA-720 mixture. They revealed surfactant structure has significant impact on phenanthrene removal whereas hydrophilic surfactants performed better. Surfactant concentration also showed an impact on desorption and solubilization of phenanthrene (Saichek and Reddy, 2004)

Li et al. studied the removal of phenanthrene by EKR using a cosolvent (n-butylamine, tetrahydrofuran, or acetone) added to the conducting fluid. The study revealed the presence of n-butylamine significantly enhanced the desorption and transport of organic contaminant with about 43% removal. The effect of acetone is less significant whereas as tetrahydrofuran showed the minimal enhancement (Li et al., 2000).

Chen et al. investigated the influence of citric acid and methyl-β-cyclodextrin (MCD) as enhancing agents during the remediation process of soil which are artificially contaminated with decabromodiphenyl ether (BDE-209) and copper (Cu) with an initial concentration of 50 and 1000 mg/kg, respectively. In this EKR process persulfate was used as an oxidant. It was observed that there was a significant removal of BDE-209 and Cu with highest BDE-209 decontamination (88.6%) was observed in the MCD-assisted process (Chen et al., 2019).

Ammami et al. studied the simultaneous removal of heavy metals and five polyaromatic hydrocarbons (PAH) using nitric acid and citric acid while using an anionic surfactant, sodium dodecyl sulfate (SDS), and a nonionic surfactant, Tween 20, to solubilize and mobilize PAHs. Nitric acid showed excellent PAH removal capacity (70.3%−89.7%) due to its capability to solubilize organic matter, to promote a good electroosmotic flow and to generate oxidative conditions that promote PAH degradation. However, as nitric acid is not environmentally friendly, a mixture of citric acid and Tween 20 is an alternative option which showed 53.6%−61.6% PAH removal (Ammami et al., 2013).

Fan et al. carried out enhanced EKR for soil contaminated with PCBs using Igepal CA-720 and persulfate as surfactant and oxidant respectively. The study showed that 2% of Igepal CA-720 and 20% of persulfate were the optimum dosage for PCBs extraction and remediation. In the study surfactant was added to the anode reservoir and oxidant was added to the cathode reservoir. Zero-valent iron was used as the activator of persulfate. The study revealed the Igepal CA-720 facilitated the partial solubilization of PCBs and caused migration toward cathode while persulfate was delivered from cathode to anode. The highest degradation of PCBs was 38% which was observed in the absence of the activator. The better activity in the absence of activator is ascribed to the consumption of oxidant by the activator, which inhibits its migration during EKR (Fan et al., 2014).

8.3 Electrokinetic remediation combined with other techniques

There are many techniques available for the remediation of contaminated soil and groundwater. They all have their own advantages and disadvantages. EKR is a technique that removes the contaminants from the contaminated soil by transportation (electroosmosis and electromigration). However, most organic pollutants are difficult to remediate due to their low solubility and strong absorption to organic matter and soil particles. To make the electrokinetic process more effective, it can be combined with other remediation techniques, so that the coupled remediation efficiency is higher than techniques applied individually. Some of the techniques which are feasible to combine with EKR include, oxidation/reduction, bioremediation, permeable reactive barriers, phytoremediation, and ultrasonication (Yeung and Gu, 2011).

8.3.1 Oxidation/reduction

In situ oxidation-reduction for the remediation of organic contaminants in soils have gained much interest. In this process selected reagents are introduced to the soil to degrade the contaminants to less toxic simple molecules by in situ chemical oxidation and reduction processes. As these reagents advance through the soil, they react with the organic contaminants resulting in smaller molecules usually less toxic than the original ones. Although the primary objective is to completely oxidize contaminants to carbon dioxide and water, in case the complete degradation is not possible, the simple molecules are considered enough as they can be degraded easily by microorganisms in the soil. Thus, this technology is very efficient solution for the degradation of complex organic contaminants. The technique is rapid, aggressive, and easy to apply, but the application in low permeability soils is limited due to the inadequate delivery of oxidants in such soils. By combining with EKR technique, oxidizing reagents such as ozone, hydrogen peroxide, or persulfate can be transported into the soil by electromigration and/or electroosmosis (Yukselen-Aksoy and Reddy, 2012; Cameselle et al., 2013).

One of the most widely studied and utilized oxidation technology is the Fenton process. In Fenton process a catalytic reaction between hydrogen peroxide H_2O_2 and Fe^{2+} ions are involved (Koprivanac and Kušić, 2007). There are two main procedures involved during the Fenton reaction. In the first step, hydroxyl free radicals are produced with the decomposition of H_2O_2 by the catalysis of Fe^{2+} followed by the oxidizing degradation of organic pollutants by produced hydroxyl free radicals as the second step (Huang et al., 2012).

The generated hydroxyl radicals are strong that react with most organic contaminants. The presence of Fe is catalytic. The hydroxyl radicals generated are strong and react with most organic contaminants. The radicals oxidize the organic molecule by abstracting hydrogen atoms or by adding themselves to double bonds and aromatic rings:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^{\bullet} + OH^{-}$$

$$RH + HO^{\bullet} \rightarrow H_2O + R^{\bullet}$$

$$R^{\bullet} + Fe^{3+} \rightarrow Fe^{2+} + \text{products}$$

There are many studies focused on degradation of organic contaminants by Fenton process combined with EKR. Kim et al. studied the coupling of Fenton process with electrochemical remediation to remediate phenanthrene-contaminated EPK kaolinite. They used iron minerals on soil particle surfaces as catalyst. The study revealed that the electrical current intensity is significantly changed by intermediate anions, that is, HO_2^- and $O_2^{\bullet -}$, generated by the Fenton-like reactions. An improvement in the stability of H_2O_2 and treatment efficiency of phenanthrene was observed by the addition of 0.01 N H_2SO_4 to the anode reservoir. More than a half of the spiked phenanthrene was destructed or extracted after 21 days of treatment. Therefore, the study demonstrated use of H_2O_2 and dilute acid, as an anode purging solution, is a feasible technology for the remediation of soil with low hydraulic conductivity, low acid/base buffer capacity, and high iron content (Kim et al., 2005). Further in another attempt to remediate phenanthrene-contaminated Hadong clay, a soil which has higher acid/base buffer capacity due to high carbonate content, it was revealed that the nature of the clay reduced the stability of H_2O_2 and treatment efficiency of phenanthrene. Further the study confirmed that the Fenton process is effective only at low pH of 3−5 range (Kim et al., 2006). Alcantara et al. studied the electrochemical remediation of phenanthrene-contaminated kaolinite of initial concentration of 500 mg/kg of soil. Initially negligible amount of remediation was observed with only electrochemical remediation. Afterwards, the soil was contaminated with Fe to generate Fenton-like reaction conditions and the anode and cathode reservoirs were filled with 10% H_2O_2. Under these conditions 99% overall extraction and destruction efficiency of phenanthrene was obtained in 14 days. It was also observed that without any control, pH was maintained at approximately 3.5 favoring the Fenton-like processes (Alcantara et al., 2008). Reddy and Karri. applied electrochemical remediation combined with Fenton-like process for simultaneous remediation of Ni and phenanthrene, each at a concentration of 500 mg/kg of dry soil. Experiments were conducted using H_2O_2 solution in different concentrations (5%, 10%, 20%, and 30%) using deionized water as control. Fe present naturally in soil was used as the catalyst. Oxidation of phenanthrene increased with concentration of H_2O_2 and a maximum of 56% oxidation was observed with 30% H_2O_2. They concluded that optimization of H_2O_2/catalyst concentration and electrical gradient applied, and control of soil pH are required to improve the efficiency of oxidation of phenanthrene and extraction of Ni simultaneously (Reddy and Karri, 2008).

The usage of persulfate as an oxidant has gained attraction due to its high redox potential (2.01 V) and no formation of toxic products. Under the ideal conditions, persulfate can generate powerful radicals that is very efficient in removing organic contaminants. Persulfate is relatively stable in soil allowing good distribution and contact time. Upon activation, persulfate can produce $OH^{\bullet}$ and $SO_4^{\bullet -}$ radicals which are more active as oxidants than persulfate itself. Heat, H_2O_2, high pH, and reduced metals (Fe^{2+}) can be used as activators for persulfate. Electromigration can be used to transport negatively charged persulfate in to the soil by adding to the cathode side. Alternatively, persulfate can be added to the anolyte and transported by electroosmosis (Cameselle and Gouveia, 2018).

Yukselen-Aksoy et al. studied the remediation of PCBs with persulfate as an oxidant in artificially contaminated two types of soil: kaolin and glacial till. They investigated the activation of persulfate using an elevated temperature (45°C) and a high pH at anode. The activation improved the degradation of PCB in kaolin, but it was insignificant in glacial till. The highest level of PCB oxidation in kaolin was 77.9% activated at elevated temperature in seven days. In glacial till the highest oxidation of 14.4% was achieved without any activation. The low persulfate oxidation of PCB was attributed to high buffering capacity, high organic content, and nonhomogeneous mineral content in glacial till (Yukselen-Aksoy and Reddy, 2012). Fan et al. revealed electroosmosis is more effective in uniform distribution of persulfate in decontamination of PCBs. Further in the study they evaluated the efficiency of different activators such as zero-valent iron, citric acid chelated Fe^{2+}, iron electrode, alkaline pH, and peroxide. The removal efficiency of PCBs followed the order of alkaline activation > peroxide activation > citric acid chelated Fe^{2+} activation > zero-valent iron activation > without activation > iron electrode activation, and the values were 40.5%, 35.6%, 34.1%, 32.4%, 30.8%, and 30.5%, respectively. The activation effect was highly dependent on the ratio of activator and persulfate (Fan et al., 2016).

8.3.2 Bioremediation

Bioremediation is the transformation of hazardous contaminants to less harmful forms with the use of microorganisms (mainly bacteria) and/or immobilize them under suitable environmental conditions (Yeung, 2010). To achieve a successful bioremediation, it requires a simultaneous existence of microorganisms, contaminants (food for the microorganism), electron acceptors, and essential nutrients for the microorganisms to grow. In soils of low hydraulic conductivity, it is challenging to supply microorganism and the required electron acceptors or nutrients to the contaminants, or to supply the contaminants to naturally occurring microorganisms. EKR technique can be used as a transportation medium to introduce the nutrients and other chemicals that may facilitate the bacterial growth and development as well as the supply of other chemicals that can contribute to the degradation of the contaminants (Lohner et al., 2009). The ability to directionally transport bacteria from injection points into the zones of contamination is a distinct advantage of electrokinetics-combined bioremediation as an in situ technique (Deflaun and Condee, 1997). Xu et al. revealed that ammonium and nitrate ions could be distributed more uniformly in phenanthrene-contaminated soil and 80% of the initial

200 mg/kg phenanthrene could be removed in 20 days by reversal of electrode polarity (Xu et al., 2010).

8.3.3 Permeable reactive barriers

Permeable reactive barriers (PRB) are passive remediation systems especially designed for the remediation of contaminated ground water. The technique involves digging a trench in the path of flowing groundwater and filling it with a permeable reactive material (Cameselle et al., 2013). As the contaminated groundwater passes through the PRB, contaminants interact with the active material in the PRB and being absorbed, precipitated, or degraded. In the design of a PRB, the nature of the contaminants should be considered in selecting a reactive material. For organic contaminants, active carbon or Fe^0 can be used. Organic contaminants are retained by the porous structure of the active carbon. The flow rate of groundwater and the reaction rate of the contaminants with the active material are deciding factors for the width of the barrier. The ground water should reside enough time in PBR for a complete removal of contaminants. The main advantages of the PRB are the stable operation for long treatment time and, very low investment and maintenance cost. In order to increase the efficiency of PRB process, it can be combined with EKR. Chang and Cheng applied the combined technology to remediate a soil specimen contaminated with perchloroethylene. The PRB active material consisted of iron and zinc nanoparticles. The dechlorination of perchloroethylene by iron and zinc nanoparticles was observed. However, ferric oxide and ferric hydroxides formed as products in the process limited the activity of the PRB and its operational life. However, the protons generated at the cathode solubilized ferric hydroxide improving the activity and duration of the PRB (Chang and Cheng, 2006). Chung and Lee used electrokinetics combined with PRB for the remediation of soils and groundwater contaminated with tetrachloroethylene. As the reactive material, a mixture of sand and a material which they called atomizing slag (consisted a mixture of oxides of Si, Fe, Ca, and Al) was used. The study resulted a removal of 90% of the tetrachloroethylene demonstrating the applicability of this technology in situ for decontamination of soils (Chung and Lee, 2007).

8.3.4 Phytoremediation

Phytoremediation is the use of plants to remove, degrade, or sequester inorganic and organic contaminants from soil and/or groundwater (Yeung, 2010). It is an emerging cost-effective sustainable technology alternative to conventional remediation technologies for the remediation of both heavy metals and organic contaminants. This technology is very attractive due to its low cost and energy requirements and convenient to implement in the field. However, due to the limited bioavailability that the contaminants have in the soil, for the successful application of this method, techniques have to be investigated to facilitate the transport of contaminants to the shoots and roots of plants. These limitations of phytoremediation technique can be overcome by combination with electrokinetics (Cameselle et al., 2013).

The application of an electric field mobilizes contaminants and nutrients, favoring the growth of plants and its remediation capacity. While enhancement in the bioavailability of nutrients and contaminants is achieved, precautions should be followed in selecting the intensity of electric field and chemical nature of the electrode not to damage the growing plants and soil microflora. Chirakkara et al. studied the coupled remediation of a soil contaminated with heavy metals and PAHs (Chirakkara et al., 2016). Acosta-Santoyo et al. demonstrated that very low electric field (about 0.2 DCV/cm) could enhance the germination of plants and 1 V/cm of AC could enhance the plant growth and remediation capacity (Acosta-Santoyo et al., 2017).

8.3.5 Ultrasonication

Acoustic energy can enhance the migration of contaminants in soil and facilitate their subsequent remediation and/or removal. The impact of this process include an increase in kinetic energy of soil pore fluid, causing rise in temperature, increase in volume and pressure of the soil pore fluid, decrease in viscosity of soil pore fluid, increasing the volume flow rate of the soil pore fluid, increase in molecular motion of contaminants, inducing disintegration and mobilization of contaminants adsorbed on soil particle surfaces, cavitation (forming bubbles) in soil pore fluid, and causing increase in porosity and hydraulic conductivity of soil (Yeung and Gu, 2011). Pham et al. studied the enhancement effect of coupled technology on the remediation of kaolin contaminated with a mixture of three POPs: hexachlorobenzene (HCB), phenanthrene, and fluoranthene. The results revealed that the remediation efficiencies for these three POPs by coupled technology were higher than those of electrochemical remediation alone. Although an increase in both the electric current intensity and electroosmotic volume flow rate was observed by ultrasonication, the remediation efficiency was increased for less than 10%. HCB was found to be the most difficult to extract because of its high stability, while fluoranthene was the easiest to extract (Pham et al., 2009). They have also studied the electrochemical remediation enhanced by ultrasonication or the surfactant 2-hydroxylpropyl-β-cyclodextrin to remediate soil contaminated with HCB and phenanthrene. They observed both contaminants could be mobilized by electrochemical remediation enhanced by either ultrasonication or surfactant. However, HCB was more difficult to extract because of its stability and low water-solubility. Moreover, better remediation of phenanthrene was obtained by ultrasonication than by surfactant, as ultrasound can degrade the contaminant through oxidation by free radicals (Pham et al., 2009). Chung et al. studied the simultaneous remediation of Pb and phenanthrene from contaminated natural clay using electrochemical remediation coupled with ultrasonication. The results revealed that both the fluid outflow rate and remediation efficiencies for both contaminants were increased by the coupled technology, compared to electrochemical remediation alone. The average outflow rate was increased from 120 mL/h to 143 mL/h, an increase of 19%. The average remediation efficiency for phenanthrene was increased from 85% to 90%, an increase of 5.9%.

8.4 Concluding remarks

Elevated concentrations of organic pollutants from E-waste is a growing concern that the mankind experiences. Such pollutants mainly consist of PCBs, PBDEs, PBBs, dioxins, and furans. These pollutants are considered as possible carcinogens, teratogens, and mutagens. Therefore promising techniques need to be followed in order to treat these pollutants. EKR is such a green remediation technology and it has been used for the treatment of soils contaminated not only with POPs but also with heavy metals. It is considered as a promising technology as it can be used in situ without doing soil excavation. Yet, the efficiency of EKR can be enhanced with certain modifications to the technique. Generally, EKR combined with other techniques exhibits better performances as different techniques contributes synergistically toward the remediation process.

References

Acar, Y.B., Alshawabkeh, A.N., 1993. Principles of electrokinetic remediation. Environ. Sci. Technol. 27, 2638−2647.

Acar, Y.B., Alshawabkeh, A.N., Gale, R.J., 1993. Fundamentals of extracting species from soils by electrokinetics. Waste Manag. 13, 141−151.

Acosta-Santoyo, G., Cameselle, C., Bustos, E., 2017. Electrokinetic - enhanced ryegrass cultures in soils polluted with organic and inorganic compounds. Environ. Res. 158, 118−125.

Alcantara, T., Pazos, M., Gouveia, S., Cameselle, C., Sanroman, M.A., 2008. Remediation of phenanthrene from contaminated kaolinite by electroremediation-Fenton technology. J Environ. Sci. Health A Tox. Hazard. Subst. Environ. Eng. 43, 901−906.

Ammami, M., Banamar, A., Wang, H., Bailleul, C., Legras, M., Derf, F., et al., 2013. Simultaneous electrokinetic removal of polycyclic aromatic hydrocarbons and metals from a sediment using mixed enhancing agents. Int. J. Environ. Sci. Technol. 11, 1801−1816.

Armstrong, B., Hutchinson, E., Unwin, J., Fletcher, T., 2004. Lung cancer risk after exposure to polycyclic aromatic hydrocarbons: a review and meta-analysis. Environ. Health Persp. 112, 970−978.

Boström, C.-E., Gerde, P., Hanberg, A., Jernström, B., Johansson, C., Kyrklund, T., et al., 2002. Cancer risk assessment, indicators, and guidelines for polycyclic aromatic hydrocarbons in the ambient air. Environ. Health Persp. 110 (Suppl 3), 451−488.

Cameselle, C., Gouveia, S., 2018. Electrokinetic remediation for the removal of organic contaminants in soils. Curr. Opin. Electrochem. 11, 41−47.

Cameselle, C., Reddy, K.R., 2009. Electrochemical Remediation Technologies for Polluted Soils, Sediments and Groundwater. Wiley, Hoboken, NJ.

Cameselle, C., Gouveia, S., Akretche, D.E., Belhadj, B., 2013. Advances in electrokinetic remediation for the removal of organic contaminants in soils. Organic Pollutants: Monitoring, Risk and Treatment. In Tech 209−229.

Chang, J.-H., Cheng, S.-F., 2006. The remediation performance of a specific electrokinetics integrated with zero-valent metals for perchloroethylene contaminated soils. J. Hazard. Mater. 131, 153−162.

Chen, F., Li, X., Ma, J., Qu, J., Yang, Y., Zhang, S., 2019. Remediation of soil co-contaminated with decabromodiphenyl ether (BDE-209) and copper by enhanced electrokinetics-persulfate process. J. Hazard. Mater. 369, 448−455.

Chirakkara, R.A., Cameselle, C., Reddy, K.R., 2016. Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants. Rev. Environ. Sci. Biotechnol. 15, 299−326.

Chung, H.I., Lee, M., 2007. A new method for remedial treatment of contaminated clayey soils by electrokinetics coupled with permeable reactive barriers. Electrochim. Acta 52, 3427−3431.

Cook, A., Ricca, A., Mattioda, A., Bouwman, J., Roser, J., Linnartz, H., et al., 2015. Photochemistry of polycyclic aromatic hydrocarbons in cosmic water ice: the role of PAH ionization and concentration. Astrophys. J. 799, 14.

De battisti, A., Ferro, S., 2007. Electrokinetic remediation: methods of remediation of soils and ground waters. Electrochim. Acta 52, 3345−3348.

Deflaun, M.F., Condee, C.W., 1997. Electrokinetic transport of bacteria. J. Hazard. Mater 55, 263−277.

Fan, G., Cang, L., Fang, G.-D., Zhou, D., 2014. Surfactant and oxidant enhanced electrokinetic remediation of a PCBs polluted soil. Separ. Purif. Technol. 123, 106−113.

Fan, G., Cang, L., Gomes, H.I., Zhou, D., 2016. Electrokinetic delivery of persulfate to remediate PCBs polluted soils: effect of different activation methods. Chemosphere 144, 138−147.

Hites, R.A., 2004. Polybrominated diphenyl ethers in the environment and in people: a meta-analysis of concentrations. Environ. Sci. Technol. 38, 945−956.

Huang, D., Xu, Q., Cheng, J., Lu, X., Zhang, H., 2012. Electrokinetic remediation and its combined technologies for removal of organic pollutants from contaminated soils. Int. J. Electrochem. Sci. 7, 4528−4544.

Kim, S.S., Kim, J.H., Han, S.J., 2005. Application of the electrokinetic-Fenton process for the remediation of kaolinite contaminated with phenanthrene. J. Hazard. Mater. 118, 121−131.

Kim, J.-H., Han, S.J., Kim, S.S., Yang, J.W., 2006. Effect of soil chemical properties on the remediation of phenanthrene-contaminated soil by electrokinetic-Fenton process. Chemosphere 63, 1667−1676.

Köhler, A., Erdmann, L., 2004. Expected environmental impacts of pervasive computing. Human Ecol. Risk Assess.: Int. J. 10, 831−852.

Koprivanac, N., Kušić, H., 2007. AOP as an effective tool for the minimization of hazardous organic pollutants in colored wastewater; chemical and photochemical processes. Hazardous Materials and Wastewater: Treatment, Removal and Analysis. Nova Science Publishers, Inc.

Li, A., Cheung, K., Reddy, K., 2000. Cosolvent-enhanced electrokinetic remediation of soils contaminated with phenanthrene. J. Environ. Eng. 126, 527−533.

Lohner, S.T., Tiehm, A., Jackman, S.A., Carter, P., 2009. Coupled electrokinetic−bioremediation: applied aspects. Electrochemical Remediation Technologies for Polluted Soils, Sediments and Groundwater. Wiley, New Jersey.

Masih, J., Singhvi, R., Kumar, K., Jain, V.K., Taneja, A., 2012. Seasonal variation and sources of polycyclic aromatic hydrocarbons (PAHs) in indoor and outdoor air in a semi arid tract of Northern India. Aerosol. Air Qual. Res. 12, 515−525.

Park, J.-S., Wade, T.L., Sweet, S., 2001. Atmospheric distribution of polycyclic aromatic hydrocarbons and deposition to Galveston Bay, Texas, USA. Atmosph. Environ. 35, 3241−3249.

Pham, T.D., Shrestha, R.A., Virkutyte, J., Sillanpää, M., 2009. Combined ultrasonication and electrokinetic remediation for persistent organic removal from contaminated kaolin. Electrochim. Acta 54, 1403−1407.

Ravindra, K., Sokhi, R., Van Grieken, R., 2008. Atmospheric polycyclic aromatic hydrocarbons: source attribution, emission factors and regulation. Atmosph. Environ. 42, 2895−2921.

Reddy, K.R., Karri, M.R., 2008. Effect of oxidant dosage on integrated electrochemical remediation of contaminant mixtures in soils. J. Environ. Sci. Health A Tox. Hazard. Subst. Environ. Eng 43, 881−893.

Safe, S., 1994. Polychlorinated biphenyls (PCBs): environmental impact, biochemical and toxic responses, and implications for risk assessment.

Saichek, R.E., Reddy, K.R., 2004. Evaluation of surfactants/cosolvents for desorption/solubilization of Phenanthrene in clayey soils. Int. J. Environ. Stud. 61, 587−604.

Sharma, H.D., Reddy, K.R., 2004. Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies. John Wiley & Sons, Hoboken, NJ.

Trushin, N., Alam, S., El-bayoumy, K., Krzeminski, J., Amin, S.G., Gullett, J., et al., 2012. Comparative metabolism of benzo[a]pyrene by human keratinocytes infected with high-risk human papillomavirus types 16 and 18 as episomal or integrated genomes. J. Carcinog. 11, 1-1.

Virkutyte, J., Sillanpää, M., Latostenmaa, P., 2002. Electrokinetic soil remediation: critical overview. Sci. Total Environ. 289, 97−121.

Xu, W., Wang, C., Liu, H., Zhang, Z., Sun, H., 2010. A laboratory feasibility study on a new electrokinetic nutrient injection pattern and bioremediation of phenanthrene in a clayey soil. J. Hazard. Mater 184, 798−804.

Yang, Q., Qiu, X., Li, R., Liu, S., Li, K., Wang, F., et al., 2013. Exposure to typical persistent organic pollutants from an electronic waste recycling site in Northern China. Chemosphere 91, 205−211.

Yeung, A.T., 2010. Remediation technologies for contaminated sites. In: Chen, Y., Zhan, L., Tang, X. (Eds.), Advances in Environmental Geotechnics. Springer, Berlin, Heidelberg, pp. 328−369.

Yeung, A.T., Gu, Y.Y., 2011. A review on techniques to enhance electrochemical remediation of contaminated soils. J. Hazard. Mater. 195, 11−29.

Yu, X.Z., Gao, Y., Wu, S.C., Zhang, H.B., Cheung, K.C., Wong, M.H., 2006. Distribution of polycyclic aromatic hydrocarbons in soils at Guiyu area of China, affected by recycling of electronic waste using primitive technologies. Chemosphere 65, 1500−1509.

Yukselen-Aksoy, Y., Reddy, K.R., 2012. Effect of soil composition on electrokinetically enhanced persulfate oxidation of polychlorobiphenyls. Electrochim. Acta 86, 164−169.

Zhang, Y., Tao, S., 2009. Global atmospheric emission inventory of polycyclic aromatic hydrocarbons (PAHs) for 2004. Atmosph. Environ. 43, 812−819.

Zhao, G., Xu, Y., Han, G., Ling, B., 2006. Biotransfer of persistent organic pollutants from a large site in China used for the disassembly of electronic and electrical waste. Environ. Geochem. Health 28, 341−351.

Zhao, G., Wang, Z., Dong, M.H., Rao, K., Luo, J., Wang, D., et al., 2008. PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. Sci. Total Environ. 397, 46−57.

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Mapping the emergence of research activities on E-waste: a scientometric analysis and an in-depth review

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9.1 Introduction

Electronic waste (E-waste) or waste electrical and electronic equipments (WEEE) is a major concern in today's world. The electronics industry is not only the fastest growing but also the largest manufacturing industry in the world today (Clarke et al., 2019). The amount of electrical and electronic equipments (EEEs) introduced into the market every single month in the recent years has been unparalleled. On account of the swelling population size, the patterns of consumption transformed drastically in the direction of a high demand for complex goods which in turn is connected to a massive resource extraction (De Meester et al., 2019). The volume of E-waste upsurges intensely due to the incessant upgrading of the electronic equipments, resulting in the United States being the first and China, the second largest producers of E-waste in the world at present (Wang et al., 2019). The ever-increasing volume of E-waste is a direct consequence of the intense growth in the electronics sector and the transformed consumption patterns of the citizens across the globe. The reduced lifecycles of the products accompanied by fast introductions of novel products and negligence of the consumers to bring back their cast-off products to the retailers or manufacturers for appropriate discarding is responsible for the escalating E-waste, generating grave human health and environmental threats (Kumar, 2019). E-waste consists of a number of toxic and hazardous metal components and persistent organic pollutants (POPs) having potential for bioaccumulation and biomagnification along the food chain (Borthakur, 2016). This makes E-waste a particularly perilous stream of waste in need of immediate addressing from environmental and health safety perspectives.

Considering the environmental and human health risks associated with E-waste, a number of developed countries attempt to resolve this problem of E-waste by donating or exporting the obsolete or used EEEs to the developing countries (Albuquerque et al., 2019). For instance, E-waste in China is not only the result of

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00017-6

the large domestic production but also the increasing concentration of imported E-waste from across the globe (Wang et al., 2018). The E-waste generation in an another major emerging economy, India, is no exception with both domestic generation and legal/illegal import of E-waste largely contributing to the total generation of this toxic category of waste in the country (Borthakur, 2015). Further, E-waste contains a considerable portion of precious and valuable metal components which, if extracted or recycled efficiently, have the potential to contribute to resource conservation (Borthakur, 2014). Nevertheless, recycling of E-waste has always been a challenge both for the developed and developing countries. For instance, abiding by the conventional forward logistics, the good manufacturers were traditionally not accountable for what occurs to their products once customer use them (Kinobe et al., 2015). Nevertheless, it has now been acknowledged universally that the increasing quantities of E-waste worldwide in conjunction with an absence of environmentally comprehensive recycling structures are a subject for serious apprehension (Kumar, 2019). Accordingly, a number of approaches and novels concepts are taken into consideration with an aim to responsibly address the current E-waste concerns. One such approach is the concept of reverse supply chain management where it is essential to adequately analyze the determinants of consumers' behavior toward ensuring successful recycling efforts. As argued by Kumar (2019, p. 378):

> — *The reverse supply chain of Electrical and Electronic Equipment (EEE) has been the focus of attention for policymakers, academics and manufacturers alike for many years [...] One of the greatest threats to the success of reverse supply chain management is the reluctance of consumers to participate in the recycling process. As the starting point of any reverse supply chain is the consumers' willingness and active participation in the recycling process, it becomes necessary to understand the factors that influence this behaviour.*

The E-waste and associated concerns started to gain attention during the recent decades and a number of countries have come up with their own policies to address this apprehension in adequate detail. Most of the E-waste policy relevant initiatives were undertaken by a few developed countries in the beginning which had relatively a systematic plan in place toward addressing all categories of waste. These countries soon recognized E-waste as an additional waste category and started innovative approaches to tackle it. This was subsequently followed by the developing world when their own E-waste problem started escalating somewhat beyond immediate control. The European Union (EU) has been a pioneer on ensuring responsible E-waste management practices and its legislation on E-waste has been a great reference point to several other countries across the globe. Describing the evolution of the EU's legislation, Ylä-Mella et al. (2015, p. 374) states:

> — *The primary goal of the European Union's (EU) waste legislation is to prevent waste generation and to promote re-use, recycling and other forms of recovery. That is also the case for waste electrical and electronic equipment (WEEE); the WEEE Directive (2002/96/EC) was implemented first time in*

January 2003. After some difficulties and unequal development of operational and legislative progress in the first years of implementation, the WEEE Directive has been transposed to national legislations and operational preconditions have been built up in all EU Member States. In addition, also Norway, Lichtenstein and Switzerland as countries of European Economic Area (EEA) have followed up the EU legislation.

It is imperative for the countries across the globe to ensure adequate measures to address the toxic stream of waste in the form of E-waste through responsible research and policy approaches. Accordingly, it becomes increasingly essential to study the development of research activities on E-waste especially during the past few years and identify the gaps and opportunities in the research approaches. In this chapter, we attempt to carry out a detailed scientometric analysis on E-waste research from the year 2000 to 2018. The purpose is to have an overview on the research activities on the topic across the years, identify the leading countries, institutions, and authors in this research area with their funding agencies and recognize many other such determinants of E-waste research toward having a holistic understanding of the research approaches on the topic.

9.2 Context of the study and methodology

As described in Section 9.1, E-waste is a major environmental and human health challenge in the present-day world. At the same time, the research focus on various dimensions of E-waste is relatively recent. Also, there is not much attention of the historical and current research trends on the topic. Accordingly, we attempted to perform a detail analysis on the development of E-waste research from the year 2000 to 2018 through a scientometric analysis using "Scopus" database. Developed by eminent research scholars such as Derek J. de Solla Price, Robert King Merton, and Eugene Garfield, "Scientometrics" is "the science about science, and as an academic field, it has established lines of inquiry, methodologies and a distinct identity" (Serenko et al., 2010, p. 5). Often also referred to as domain mapping or knowledge domain visualization, scientometric is a quantitative research method used to evaluate scientific publications arisen from citation-based domain visualization (Pollack and Adler, 2015). As further explained by (Chen et al., 2002, p. 26):

— *In* Little Science, Big Science[1]*, Derek de Solla Price (1963) raised some of the most fundamental questions that have led to the scientometric study today: Why should we not turn the tools of science on science itself? Why not measure and generalize, make hypotheses, and derive conclusions? [...] Its origin is in the quantitative study of science policy research, or the science of science, which focuses on a wide variety of quantitative measurements, or indicators, of science at large. [...] Scientometrics is the demographics of the*

[1] See http://derekdesollaprice.org/little-science-big-science-full-text/.

worldwide scientific community. [. . .] Research in scientometrics has also been reflective.

With the emergence of research activities across disciplines, scientometric technique established itself as an important quantitative methodology to analyze the growth and development of significant areas of research. We had decided to use "Scopus" database in order to carry out our scientometric analysis on E-waste research. There are a number of reasons for selecting "Scopus" over other journal indexing databases such as "Web of Science". The primary among them is the coverage of journals by Scopus. As argued by Borthakur and Govind (2018, p. 1054):

— *Over 22,700 peer-reviewed journals are indexed in 'Scopus', while 'Web of Science' indexes around 12,000 peer-reviewed journals. [. . .] The coverage of Scopus is significantly higher than that of the Web of Science as it is the largest abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings. Further, most of the Web of Science indexed journals are also indexed under Scopus.*

Through our literature search, we first identified four keywords which are often used synonymously in E-waste research. These keywords were "electronic waste", "E-waste", "waste electrical and electronic equipment," and "WEEE". The purpose was to have a comprehensive approach to ensure maximum inclusion of papers on our topic of concern. We had restricted our search from 2000 to 2018. The purpose of selecting this time range is the fact that E-waste research started gaining attention in the turn of the century and attain momentum since the year 2003. The impetus on E-waste research is encouraging especially in the past few years. Our search resulted in a total number of 5524 research documents published globally on E-waste from the year 2000 to 2018. We analyze this search result with respect to its year-wise, country-wise, and affiliation-wise distribution among many other such dimensions as described in detail in Section 9.3.

9.3 Results and discussion

9.3.1 Occurrence of the keywords

The keyword analysis was performed in order to assess the frequency of occurrence of the individual keywords within our search as shown in Table 9.1. The analysis was performed using the Scopus database. It has been observed that, quite expectedly, "electronic waste" is the most occurred keyword in our search. This is followed by the keyword "recycling". Both of these words are the only ones registering more than 2000 occurrences in our search with frequency of 2830 and 2480, respectively. The synonymous term of electronic waste such as "E-waste", "waste electrical and electronic equipment" and "WEEE" are also listed among the top 25 most frequently occurred keywords. The keywords such as "copper",

Table 9.1 Frequency of occurrence of keywords.

	Keywords	No. of occurrence
1	Electronic waste	2830
2	Recycling	2480
3	Electronic equipment	1359
4	Waste management	1210
5	Wastes	1129
6	E-waste	1375
7	Waste disposal	767
8	China	693
9	Controlled study	520
10	Waste electrical and electronic equipment	519
11	Copper	482
12	Printed circuit boards	463
13	Lead	460
14	Metals	431
15	Metal recovery	418
16	Environmental impact	411
17	Environmental monitoring	408
18	Leaching	403
19	Recovery	372
20	Organic pollutants	355
21	Waste treatment	351
22	WEEE	348
23	Flame retardants	316
24	Sustainable development	311

Source: Scopus (2019).

"printed circuit boards", "lead", "metal" and "metal recovery" register considerable occurrences in the search. Thus, through the keyword analysis, it could be postulated that majority of the research work on E-waste focuses on its recycling in terms of metal recovery, the hazardous nature of E-waste, and subsequent treatment. The presence of "China" as one of the most occurred keywords is noteworthy. China is the country producing maximum number of research papers on E-waste. In the subsequent sections of this chapter, it will be evident how China has progressed considerably as a pioneer in E-waste research and how Chinese universities lead in maximum research producing universities in the world.

9.3.2 Year-wise publication output of E-waste research

The research attention on E-waste is relatively recent. The focus on E-waste started gaining attention only at the turn of the century. The momentum in the research on topics concerning E-waste is adequately achieved since the year 2003 after which there is a near constant growth in E-waste research. It is worth mentioning that,

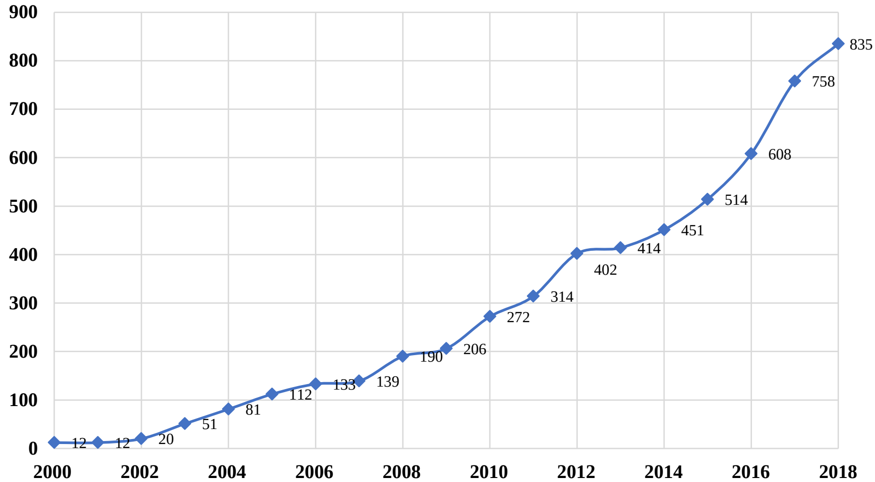

Figure 9.1 Year-wise world publication output.
Source: Scopus (2019).

starting with only 12 publications in the year 2000, the year 2018 observed a substantial 835 academic publications on the topic. This shows the significance of E-waste research in the present-day context. As the growth of E-waste is expected to continue in the near future, the research attention on the topic should also be maintained in order to deal with this toxic stream of waste. Over the years, the characteristics and specificities of this waste category have been constantly changed, making it one of the most difficult categories of waste to deal with in the present global environmental scenario. Especially with emergence of concepts such as "urban mines", studying the core characteristics of E-waste is becoming even more important from resource conservation perspective. The increase in the research focus on the topic over the last few years could be attributed to the increasing awareness on E-waste as both hazardous and valuable waste category. Accordingly, the present growth on E-waste research should encouraged to me maintain with proper funding opportunities (Fig. 9.1).

9.3.3 Top funding agencies on E-waste research

The Chinese institutes and organizations dominate the funding scene on E-waste research (see Table 9.2). Thus, it is not surprising that the Chinese universities and institutions are the top research producing units in the world today. National Natural Science Foundation of China (NSFC) is the largest funding agency on the topic with a remarkable 633 research papers acknowledged the NSFC as their funding provider. The Chinese Academy of Sciences (CAS) has been mentioned as a funding agency in 103 research papers. The difference in the number of scientific publications acknowledging these two funding agencies is considerably large. The NFAC has been mentioned by 530 research papers more than that of the CAS.

Table 9.2 Funding agencies.

	Name of the funding agency	Number of publications
1	National Natural Science Foundation of China (NSFC)	633
2	Chinese Academy of Sciences (CAS)	103
3	China Postdoctoral Science Foundation	54
4	Natural Science Foundation of Guangdong Province	54
5	Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)	53
6	National Science Foundation (NSF)	46
7	National Aerospace Science Foundation of China	38
8	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)	32
9	Medical Science and Technology Foundation of Guangdong Province	32
10	Japan Society for the Promotion of Science (JSPS)	30
11	Natural Science Foundation of Zhejiang Province	27
12	Ministry of Education, Culture, Sports, Science and Technology (MEXT)	26
13	National Research Foundation of Korea (NRF)	21
14	Hong Kong Baptist University (HKBU)	19
15	Australian Research Council (ARC)	17
16	Natural Sciences and Engineering Research Council of Canada (NSERC)	16
17	Council of Scientific and Industrial Research (CSIR)	15
18	Engineering and Physical Sciences Research Council (EPSRC)	15
19	Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP)	15
20	European Commission (EC)	14
21	European Social Fund (ESF)	14
22	Natural Science Foundation of Jiangsu Province	14
23	Chinese Academy of Agricultural Sciences (CAAS)	13
24	European Geosciences Union (EGU)	13
25	Natural Science Foundation of Beijing Municipality	13
26	Department of Education of Guangdong Province	12
27	Ministry of Education of the People's Republic of China (MOE)	12
28	Ministry of Science and Technology of the People's Republic of China (MOST)	12
29	Program for New Century Excellent Talents in University (NCET)	12
30	Research Grants Council, University Grants Committee (RGC, UGC)	12
31	Science and Technology Department of Zhejiang Province	12
32	Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences (RCEES, CAS)	11

Source: Scopus (2019).

This makes NFAC the leader in E-waste funding both globally and within China. Nevertheless, the CAS stands as the pioneer in the top affiliating organization on E-waste research in the world. A remarkable 876 research papers are produced by the CAS during the periods between 2000 and 2018 (see Fig. 9.3). China Postdoctoral Science Foundation and Natural Science Foundation of Guangdong Province are another two major agencies providing fund in E-waste research and each of them are acknowledged by 54 publications as key funding source.

With the top positions dominated by China, the Brazilian National Council for Scientific and Technological Development or Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the National Science Foundation are the two other organizations responsible for providing fund to a considerable about of research initiatives. It is important to note that apart from China, a number of other countries worldwide such as India and West African countries like Nigeria and Ghana are among the largest sufferers of E-waste pollution. Therefore funding agencies in these countries should play an active role in diverting their finance toward research on E-waste. E-waste generation is these countries are not attributed only to their domestic generation. Much of the E-waste in these countries are direct result of the Western consumption and subsequent trade of E-waste, mostly in the name of donation. Accordingly, it is also important for the funding agencies in the developed world to increase their focus toward addressing E-waste associated repercussions in many Asian and African low-income countries. On a positive note, there are increasing focus on these countries by several universities and funding agencies from the developed world. This is both encouraging and constructive.

9.3.4 Top research producing countries on E-waste

While analyzing the research trends on E-waste, it is essential to evaluate the country-wise distribution of research on the topic. Accordingly, Fig. 9.2 shows the countries producing more than 100 publications from the year 2000 to 2018.

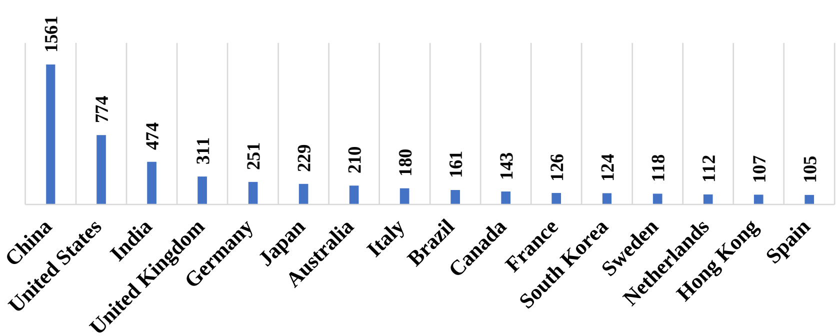

Figure 9.2 Countries producing more than 100 publications from the year 2000 to 2018. *Source*: Scopus (2019).

Among the top research producing countries on E-waste worldwide, China ranks first with a total number of 1561 publications from the year 2000 to 2018. China's research progress and development has been remarkable especially during the last decade. The second ranked the United States produced almost half of the amount of research papers that China had produced over the years with 774 publications on the topic. Another important country in the global E-waste scenario, India produced a total number of 474 research papers on E-waste and related concerns. It should be noteworthy that apart from China and India, Brazil is the only country from the global south producing more than 100 publications from the year 2000 to 2018. It should be realized and recognized that developing countries and emerging economies are mostly the countries facing stern E-waste hazard. Accordingly, more research attention by these countries are essential on topic concerning E-waste. The developed countries could aid in this progress by providing adequate financial assistance to the research institutes and universities in the low-income countries to carry out meaningful research on E-waste and associated apprehensions.

As China has emerged as the pioneer in E-waste research, we further attempted to evaluate China's collaborating partners on research concerning the topic. Accordingly, Table 9.3 shows a list of China's top 10 collaborating countries on E-waste associated research and development. The country has collaborated mostly with the United States which resulted in producing a total of 126 research papers on E-waste. As mentioned in Section 9.3.3, both the countries are listed as the top two most research producing countries in the world today. Apart from the United States, China had maximum collaboration with Hong Kong, the United Kingdom (UK), Australia, and Canada. Among the countries from the developing world, India and Pakistan are the two major collaborating countries with China and listed among the top ten collaborating countries with China. However, the research collaboration with the United States produced more than 10 times the number of publications as compared to that of India or Pakistan.

Table 9.3 China's collaborating countries.

	Collaborating country	**No. of publications**
1	United States	126
2	Hong Kong	52
3	United Kingdom	46
4	Australia	45
5	Canada	31
6	The Netherlands	26
7	Japan	22
8	Sweden	19
9	India	12
10	Pakistan	11

Source: Scopus (2019).

9.3.5 Top research institutes on E-waste

The affiliates of the Chinese Academy of Sciences (CAS) produced maximum number of research papers on E-waste during the period between 2000 and 2018 (see Fig. 9.3). The combined amount is a total number of 876 papers. This is followed by the prestigious Tsinghua University with 152 research papers on the topic. As a single institute, Tsinghua University's research performance on the topic outstands other institutes. Delft University of Technology is the only non-China based institute in the top 10 research producing institutes in the world. While considering the top 15 research institutes, there are three more institutes from Australia, Japan, and Nigeria, respectively, which figure in E-waste research. The presence of Nigeria, one of the worst E-waste affected countries in the world from West Africa, is inspiring. Nevertheless, the dominance of Chinese institutes in the areas of E-waste research is astonishing. It is essential to encourage the countries especially from Asia and Africa, who are centers of the E-waste pollution, to engage in more and more research on E-waste so that locale specific solutions could be sorted out.

9.3.6 Top journals publishing research on E-waste

Academic or research journals play a significant role in the development of a particular research area. During the recent past, a number of reputed journals have

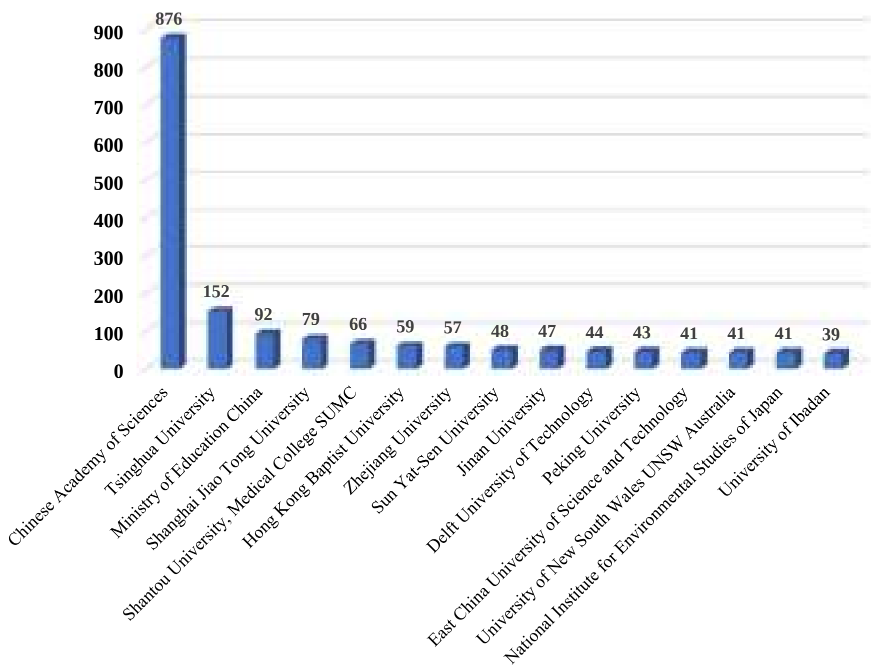

Figure 9.3 Top 15 Institutes on E-waste research.
Source: Scopus (2019).

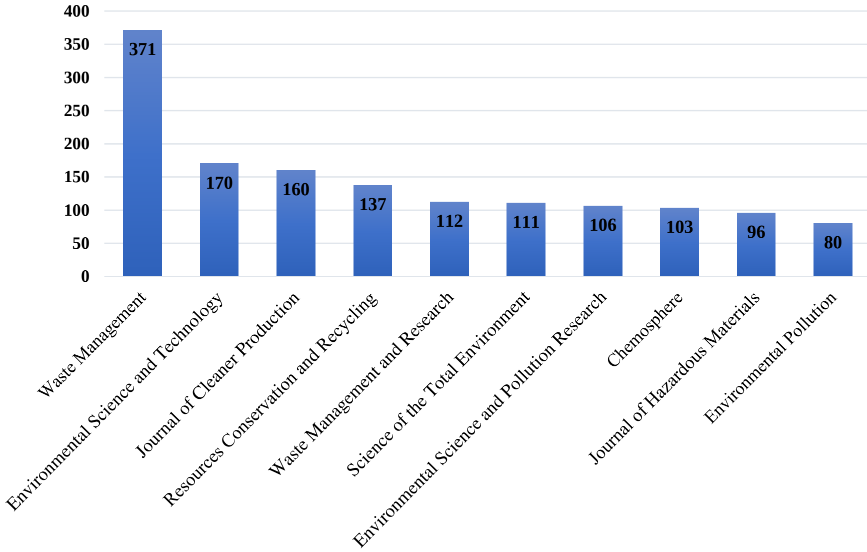

Figure 9.4 Top 10 journals publishing research on E-waste.
Source: Scopus (2019).

established themselves as pioneers in the growth of research on E-waste. We have carried out a primary analysis on the top research publishing journals on the topic (see Fig. 9.4). The journal "Waste Management" published by Elsevier ranks first among the top 10 journals on E-waste with a total number of 371 journal articles published from 2000 to 2018. The second ranked, "Environmental Science and Technology" by the American Chemical Society (ACS), produced less than half of the first ranked journal. However, it is noteworthy to mention here that "Waste Management" is a specific journal on waste categories, while the journal "Environmental Science and Technology" has a much broader scope. It is a positive sign that in this high ranked journal with a wider scope decided to publish ample articles on this emerging category of waste, that is, E-waste. This acts as a kind of recognition that E-waste is indeed a large concern across the globe and needs immediate attention. The other two journals in the form of "Journal of Cleaner Production" and "Resources Conservation and Recycling" have been two pioneering journals on E-waste, providing plentiful space to articles on E-waste and its associated areas. These interdisciplinary journals attract high authorship and accordingly, publications on these journals are able to achieve great attention both from the research and the policy community globally.

9.3.7 Top subject areas

Table 9.4 shows the subject areas under which maximum number of E-waste research has been produced during the period between 2000 and 2018. The subject

Table 9.4 Top subject areas on E-waste research.

Subject area	No. of publications
Environmental Science	3058
Engineering	1591
Chemistry	704
Materials Science	548
Energy	541
Chemical Engineering	451
Computer Science	425
Social Sciences	412
Business, Management and Accounting	405
Medicine	269
Earth and Planetary Sciences	238
Economics, Econometrics and Finance	222
Physics and Astronomy	206
Pharmacology, Toxicology and Pharmaceutics	162
Biochemistry, Genetics and Molecular Biology	149

Source: Scopus (2019).

"Environmental Science" tops the chart with a total of 3058 scientific publications on E-waste. This is followed by a distant second "Engineering" (barring "Chemical Engineering") under whose disciplinary purview, 1591 research papers have been produced. This amount is nearly half of what has been produced under "Environmental Science". Nevertheless, many researches on E-waste could be overlapping and have the potential to come under more than one subject area. A noteworthy concern here is the lack of "social science" based research approaches on the topics concerning E-waste. Only 412 research papers have been produced under this subject area during 2008−2018. Whereas, we would like to argue that social science-based research approaches such as consumers' purchase and disposal behavior of electronic goods, their level of awareness among many other considerations are essential to address some key elements of E-waste research. As argued by Borthakur and Govind (2017, p. 110):

— *[...] consumers' disposal behaviour and awareness are central to any successful E-waste management interventions without which no reuse/recycling efforts would be fully functional and satisfactory, no pollution abatement initiatives would be entirely successful, no policy instruments could be satisfactorily implemented, no detrimental health/environmental consequences of E-waste could be addressed sufficiently and chaotic dubious E-waste management processes would progress towards an erratic fate.*

9.3.8 Top authors in E-waste research

Table 9.5 lists down the top authors in E-waste research. It has been observed that out of the top 10 authors in the area of E-waste research, nine are from institutes or

Table 9.5 Top authors in E-waste research.

	Name of the author	Name of the affiliating institute	No. of publications
1	Mai, B.X.	Guangzhou Institute of Geochemistry Chinese Academy of Sciences, Guangzhou, China	82
2	Luo, X.J.	Guangzhou Institute of Geochemistry Chinese Academy of Sciences, Guangzhou, China	73
3	Huo, X.	Jinan University, Guangzhou, China	60
4	Xu, X.	Shantou University, Medical College (SUMC), Shantou, China	58
5	Li, J.	Tsinghua University, Beijing, China	52
6	Xu, Z.	Shanghai Jiao Tong University, Shanghai, China	52
7	Chen, S.J.	University of Science and Technology Beijing, Beijing, China	48
8	Wong, M.H.	The Education University of Hong Kong, Hong Kong, China	42
9	Sahajwalla, V.	University of New South Wales (UNSW) Australia, Sydney, Australia	36
10	Xeng, X	Tsinghua University, Beijing, China	36

Source: Scopus (2019).

universities based in China. Mai, B.X. from Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China tops the list with a total number of 82 publications on topics associated with E-waste. Luo, X.J from the same institute stands second with 73 publications on the topic in total. Two among the top 10 authors, Li, J. and Xeng, Z., are based at the Tsinghua University, Beijing. Sahajwalla, V. is the only author from an institute not based in China. She is based at the University of New South Wales (UNSW) Australia, Sydney, Australia. This remarkable dominance of Chinese researchers on E-waste associated topic shows the overall research interest on the subject by the country.

9.4 Conclusion

It is indisputable that E-waste is a major concern in the contemporary world. Responsible management of E-waste has attracted attention during the last decade owing to the environmental and human health hazards associated with it. Accordingly, it becomes imperative to analyze the research attention on the topic in a systematic manner. "Scientometrics" provides a good starting point here toward evaluating the gaps and opportunities in this particular research area. We decided to carry out this scientometric analysis for the time period from the year 2000 to 2018. The time range was selected considering the fact that before the turn of the millennium, there was hardly any research and policy attention on E-waste and related concerns. At that time, the concept of E-waste was too new to the world to divert its focus on the topic. However, the information technology and electronics sector already started thriving the decade before to their great potential. This means that the world already started producing E-waste in considerable volume by the year 2000. Accordingly, research focus started drifting to this area gradually and since the year 2003, a major escalation in E-waste research has been observed till date.

We started our analysis through a structured keyword search using the Scopus database. We first identified four keywords which are often used synonymously in E-waste research—"electronic waste", "E-waste", "waste electrical and electronic equipment," and "WEEE". This resulted in a total number of 5524 research papers on the topic. These research papers were further analyzed for year-wise, country-wise, institute-wise distribution among others. Within these research papers too, we started analyzing the frequency of the other individual keywords occurred in these research papers. We found that, quite presumably, "electronic waste" is the most occurred keyword in our search. This is followed by the keyword "recycling". Both of these words are the only ones registering more than 2000 occurrences in our search with frequency of 2830 and 2480, respectively. Our detailed analysis of the keywords, constantly occurring in our search, convey that majority of the research work on E-waste focuses on its recycling in terms of metal recovery, the hazardous nature of E-waste and subsequent treatment. This is substantiated by the "subject-wise" distribution of E-waste research in this chapter.

Regarding the year-wise distribution of E-waste research during the past few years, we observe that starting with only 12 publications in the year 2000, the year 2018 observed a substantial 835 academic publications on the topic. The increase in the research focus on the topic over the last few years could be attributed to the increasing awareness on E-waste as both hazardous and valuable waste category. This research attention seems to progress unaffected in the coming years as many significant dimensions of research on E-waste are still in their infancy. Among the research institutes and universities working on E-waste, the Chinese universities and institutions are the top research producing units in the world today. National Natural Science Foundation of China (NSFC) is the largest funding agency on the topic with a remarkable 633 research papers acknowledged the NSFC as their funding provider. This is followed by the prestigious Chinese Academy of Sciences (CAS). The Brazilian National Council for Scientific and Technological Development or Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the National Science Foundation are the two other organizations responsible for providing fund to a considerable about of research initiatives.

Quite evidently, the affiliates of the Chinese Academy of Sciences (CAS) produced maximum number of research papers on E-waste during the period between 2000 and 2018. The combined amount of research documents published by the CAS stands at an astounding 876 papers. This is followed by the prestigious

Tsinghua University with 152 research papers on the topic. As a single institute, Tsinghua University's research performance on the topic outstands other institutes. Delft University of Technology is the only non-China based institute in the top 10 research producing institutes in the world. Among the top research producing countries on E-waste worldwide, China ranks first with a total number of 1561 publications from the year 2000 to 2018. China's research progress and development has been remarkable especially during the last decade. The second ranked, the United States, produced almost half of the amount of research papers that China had produced over the years with 774 publications on the topic. It should be noteworthy that apart from China and India, Brazil is the only country from the global south producing more than 100 publications from the year 2000 to 2018. It should be realized and recognized that developing countries and emerging economies are mostly the countries facing stern E-waste hazard. Accordingly, more research attention by these countries are essential on topic concerning E-waste.

Among the research journal "Waste Management" published by Elsevier ranks first among the top 10 journals allocating substantial space to the research on E-waste with a total number of 371 journal articles published from 2000 to 2018. This is followed by the "Environmental Science and Technology" by the American Chemical Society (ACS). In the subject-wise distribution of E-waste research, "Environmental Science" tops the chart with a total of 3058 scientific publications on E-waste. This is followed by a distant second "Engineering" (barring "Chemical Engineering") under whose disciplinary purview, 1591 research papers have been produced. A noteworthy concern here is the lack of "social science" based research approaches on the topics concerning E-waste. Only 412 research papers have been produced under this subject area during 2008–2018. However, social science-based research approaches in terms of consumers' participation, behavior, and awareness among many others are important factors determining successful E-waste management in a particular set-up. Finally, it has been observed that out of the top 10 authors in the area of E-waste research, nine are from institutes or universities based in China. Mai, B.X. from Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China tops the list with a total number of 82 publications on topics associated with E-waste. This signifies the dominance of China in the global research scenario on E-waste.

In this chapter, we attempted to identify the trajectory of E-waste research through a systematic analysis. We argue that such analysis is imperative to carry out from time to time in order to provide the researchers an idea about the research scenario with the broader topic. Such a practice also ensures that researchers and policymakers are effectively notified or alerted on the significant subtopics which remain less addressed or even unaddressed by the global or regional research and policy community. Overall, scientometric analysis could act as a sounding board for a comprehensive research attention on E-waste.

References

Albuquerque, C.A., Mello, C.H.P., Paes, V.C., Balestrassi, P.P., Souza, L.B., 2019. Electronic junk: best practice of recycling and production forecast case study in Brazil. In: Mula, J., Barbastefano, R., Díaz-Madroñero, M., Poler, R. (Eds.), New Global Perspectives on Industrial Engineering and Management. Springer International Publishing, Cham, pp. 127–134.

Borthakur, A., 2014. Generation and management of electronic waste in the city of Pune, India. Bull. Sci. Technol. Soc. 34, 43–52.

Borthakur, A., 2015. Generation and management of electronic waste in India: an assessment from stakeholders' perspective. J. Dev. Soc. 31, 220–248.

Borthakur, A., 2016. Health and environmental hazards of electronic waste in India. J. Environ. Health 78, 18–23.

Borthakur, A., Govind, M., 2017. Emerging trends in consumers' e-waste disposal behaviour and awareness: a worldwide overview with special focus on India. Resour. Conserv. Recycl. 117, 102–113.

Borthakur, A., Govind, M., 2018. Public understandings of E-waste and its disposal in urban India: From a review towards a conceptual framework. J. Clean. Prod. 172, 1053–1066.

Chen, C., Mccain, K., White, H., Lin, X., 2002. Mapping scientometrics (1981–2001). Proc. Am. Soc. Inform. Sci. Technol. 39, 25–34.

Clarke, C., Williams, I.D., Turner, D.A., 2019. Evaluating the carbon footprint of WEEE management in the UK. Resour. Conserv. Recycl. 141, 465–473.

De meester, S., Nachtergaele, P., Debaveye, S., Vos, P., Dewulf, J., 2019. Using material flow analysis and life cycle assessment in decision support: a case study on WEEE valorization in Belgium. Resour. Conserv. Recycl. 142, 1–9.

Kinobe, J.R., Gebresenbet, G., Niwagaba, C.B., Vinnerås, B., 2015. Reverse logistics system and recycling potential at a landfill: a case study from Kampala City. Waste Manage. 42, 82–92.

Kumar, A., 2019. Exploring young adults' e-waste recycling behaviour using an extended theory of planned behaviour model: a cross-cultural study. Resour. Conserv. Recycl. 141, 378–389.

Pollack, J., Adler, D., 2015. Emergent trends and passing fads in project management research: a scientometric analysis of changes in the field. Int. J. Proj. Manage. 33, 236–248.

Serenko, A., Bontis, N., Booker, L., Sadeddin, K., Hardie, T., 2010. A scientometric analysis of knowledge management and intellectual capital academic literature (1994–2008). J. Knowl. Manage. 14 (1), 3–23.

Wang, Z., Guo, D., Wang, X., Zhang, B., Wang, B., 2018. How does information publicity influence residents' behaviour intentions around e-waste recycling? Resour. Conserv. Recycl. 133, 1–9.

Wang, B., Ren, C., Dong, X., Zhang, B., Wang, Z., 2019. Determinants shaping willingness towards on-line recycling behaviour: an empirical study of household e-waste recycling in China. Resour. Conserv. Recycl. 143, 218–225.

Ylä-Mella, J., Keiski, R.L., Pongrácz, E., 2015. Electronic waste recovery in Finland: Consumers' perceptions towards recycling and re-use of mobile phones. Waste Manage. 45, 374–384.

Waste electrical and electronic equipment in India: diversity, flows, and resource recovery approaches

10

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The electrical and electronic waste (E-waste) is one of the fastest growing waste streams in the world. The increasing "market penetration" in developing countries, "replacement market" in developed countries, and "high obsolescence rate" make E-waste as one of the fastest growing waste streams. Sustainable development goals of UNESCO address the National Environmental Policy (NEP). Thus, there is a need to facilitate the recovery and/or reuse of useful materials from waste generated from a process and/or from the use of any material thereby, reducing the wastes destined for final disposal and to ensure the environmentally sound management of all materials. The NEP also encourages giving legal recognition and strengthening the informal sectors for collection and recycling of various materials. In particular considering the high recyclable potential of E-waste, such wastes should be subject to recycling following state of the art technologies for resource recovery. Environmental issues and trade associated with E-waste and resource recovery approaches are covered in this chapter

10.1 Resource recovery approaches

1. Pyrometallurgy
2. Extraction technology (mild or non-invasive)
3. Biometallurgy
4. Electrochemistry
5. Super critical technology

E-waste offers an economic opportunity as well as toxicity. The gold in the world's E-waste thrash contain more than a 10% of the gold mined globally each year. However, much of this precious metal is simply buried in landfills. The Hazardous Substances Management Division (HSMD) is the nodal point within the Ministry for management of chemical emergencies and hazardous substances. The

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00008-5

Figure 10.1 Hierarchy in the MoEF&CC for E-waste and hazardous susbstances management.

main objective of the Division is to promote safe management and use of hazardous substances including hazardous chemicals and hazardous wastes, in order to avoid damage to health and environment. The Division is also the nodal point for the following four International Conventions, viz. Basel Convention on Control of transboundary movement of Hazardous waste and their disposal; Rotterdam Convention on Prior Informed Consent Procedure for certain Chemicals and Pesticides in International trade; Stockholm Convention on Persistent Organic Pollutants; and the Minamata Convention on Mercury and Strategic Approach to International Chemicals Management (Fig. 10.1) (Table 10.1).

10.2 Current Indian scenario

According to ASSOCHAM (Associated Chambers of Commerce & Industry of India)-KPMG (Klynveld Peat Marwick Goerdeler) by 2020 Indias E-waste from old mobiles and computers will rise by about 1800% and 500% respectively by 2020 as compared to the levels in the year 2007.

India discarded approximately 1,800,000 [lakh] metric tonnes of E-waste in 2016 which is about 12% to the global E-waste production. India is the fifth largest producer of E-waste in the world and recycles less than 2% of the total E-waste it produces annually, the Ministry of Environment, Forest and Climate Change rolled out the E-waste (Management) Rules in 2016 with the aim of reducing E-waste production and increasing recycling in the most efficient manner. Under these rules, the government introduced Extended Producers Responsibility (EPR) which makes producers liable to collect 30% to 70% (over 7 years) of the E-waste they produce, reveals the ASSOCHAM-KPMG joint study.

The industry is unable to cope up with these targets as majority of the E-waste collected in India is managed by an unorganized sector. Also, informal channels of recycling/reuse of electronics such as repair shops, used product dealers, and

Table 10.1 E-waste recycling, resource recovery, and best management practices.

2018	Awasthi and Li	Assessing resident awareness on E-waste management in Bangalore, India: a preliminary case study
2018	Bakhiyi et al.	Question of E-waste opened a Pandora's box
2018	Cai et al.	Polybrominated diphenyl ethers [PBDE] emission from E-wastes during the pyrolysis
2018	Cao et al.	Increased memory T cell populations in Pb-exposed children from an E-waste recycling area
2018	Chakraborty et al.	PCBs and polychlorinated dibenzo-p-dioxins (PCDDs) dibenzo-p-furans [PCDD/Fs] in soil from informal E-waste recycling sites and open dumpsites in India
2018	Dias et al.	Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme
2018	Islam and Huda	Reverse logistics and closed-loop supply chain of Waste Electrical and Electronic Equipment (WEEE)/ E-waste
2018	Jeon et al.	Gold recovery from shredder light fraction of E-waste recycling plant by flotation-ammonium thiosulfate leaching
2018	Li et al.	Proteomic evaluation of human umbilical cord tissue exposed to polybrominated diphenyl ethers in an E-waste recycling area
2018a,b	Liu et al.	Microbial community structure and function in sediments from E-waste contaminated rivers at Guiyu area of China
2018a,b	Liu et al.	Halogenated organic pollutants in aquatic, amphibious, and terrestrial organisms from an E-waste site
2018	Roslan et al.	The use of an electrogenerative process as a greener method for recovery of gold(III) from the E-waste
2018	Sahajwalla and Gaikwad	The present and future of E-waste plastics recycling
2018	Shen et al.	Chemical pyrolysis of E-waste plastics: char characterization
2018	Singh et al.	Health risk assessment of the workers exposed to the heavy metals in E-waste recycling sites of Chandigarh and Ludhiana, Punjab, India
2018	Tong et al.	Towards an inclusive circular economy: quantifying the spatial flows of E-waste through the informal sector in China
2018	Torres et al.	Effect of temperature on copper, iron and lead leaching from E-waste using citrate solutions
2018	Wang et al.	Factors influencing the diurnal atmospheric concentrations and soil-air exchange of PBDEs at an E-waste recycling site in China
2018	Wu et al.	Regional risk assessment of trace elements in farmland soils associated with improper E-waste recycling activities in Southern China

(*Continued*)

Table 10.1 (Continued)

2018	Yan et al.	Urinary metabolites of phosphate flame retardants in workers occupied with E-waste recycling and incineration
2018	Yu et al.	Associations between PBDEs exposure from house dust and human semen quality at an E-waste areas in South China: a pilot study
2018	Zhang	Maternal urinary cadmium levels during pregnancy associated with risk of sex-dependent birth outcomes from an E-waste pollution site in China
2018	Radulovic Verena	Portrayals in print: media depictions of the informal sector's involvement in managing E-waste in India
2017	Alvarez-de-los-Mozos and Renteria	Robots in E-waste management
2017	Bindschedler et al.	Fungal biorecovery of gold from E-waste
2017	Borthakur and Govind	Emerging trends in consumers' E-waste disposal behavior and awareness
2017	Cui et al.	Speciation and leaching of trace metal contaminants from E-waste contaminated soils
2017a,b	Fowler	Magnitude of the global E-waste problem
2017a,b	Fowler	Risk assessment/risk communication approaches for E-waste sites
2017	Golev and Glen	Corder quantifying metal values in E-waste in Australia: the value chain perspective
2017	He et al.	Organic contaminants and heavy metals in indoor dust from E-waste recycling, rural, and urban areas in South China
2017a,b	Jiang et al.	The influence of E-waste recycling on the molecular ecological network of soil microbial communities in Pakistan and China
2017a,b	Kumar et al.	E-waste: an overview on generation, collection, legislation and recycling practices
2017a,b	Li et al.	Accumulation of polybrominated diphenyl ethers in breast milk of women from an E-waste recycling center in China
2017	Patel et al.	Study on mechanical properties of environment friendly aluminium E-waste composite with fly ash and e-glass fiber
2017	Petridis et al.	Investigating the factors that affect the time of maximum rejection rate of E-waste using survival analysis
2017	Shirodkar and Terkar	Stepped recycling: the solution for E-waste management and sustainable manufacturing in India
2017	Tansel	From electronic consumer products to E-wastes: global outlook, waste quantities, recycling challenges
2017	Tesfaye et al.	Improving urban mining practices for optimal recovery of resources from E-waste

2017a,b,c	Wang et al.	Barriers for household E-waste collection in China: perspectives from formal collecting enterprises in Liaoning Province
2017a,b,c	Wang et al.	Factors influencing the atmospheric concentrations of PCBs at an abandoned E-waste recycling site in South China
2017a,b	Zeng et al.	A simplified method to evaluate the recycling potential of E-waste
2017a,b	Zeng et al.	Decreased lung function with mediation of blood parameters linked to E-waste lead and cadmium exposure in preschool children
2017a,b, c,d,e,f	Zhang et al.	Elevated lead levels from E-waste exposure are linked to decreased olfactory memory in children
2017a,b, c,d,e,f	Zhang et al.	Airborne PCDD/Fs in two E-waste recycling regions after stricter environmental regulations
2017e	Zhang	Alteration of the number and percentage of innate immune cells in preschool children from an E-waste recycling area
2017f	Zhang	An environmentally friendly ball milling process for recovery of valuable metals from E-waste scraps
2016	Amankwah-Amoah	Global business and emerging economies
2016	Cao et al.	Extended producer responsibility system in China improves E-waste recycling: government policies, enterprise, and public awareness
2016	Debnath et al.	E-waste management: a potential route to green computing
2016	Garlapati	E-waste in India and developed countries: management, recycling, business and biotechnological initiatives
2016	Lu et al.	Associations between polycyclic aromatic hydrocarbon (PAH) exposure and oxidative stress in people living near E-waste recycling facilities in China
2016	Manjunath	Partial replacement of E-plastic waste as coarse-aggregate in concrete
2016	Mary and Meenambal	Inventorization of E-waste and developing a Policy: bulk consumer perspective
2016	Pascale et al.	E-waste informal recycling: an emerging source of lead exposure in South America
2016	Rhee et al.	Beneficial use practice of E-wastes in Republic of Korea
2016	Suzuki et al.	Comprehensive evaluation of dioxins and dioxin-like compounds in surface soils and river sediments from E-waste-processing sites in a village in northern Vietnam: heading towards the environmentally sound management of E-waste
2016	Wang et al.	Enhanced bioleaching efficiency of metals from E-wastes driven by biochar
2016	Wang et al.	Determinants of residents' E-waste recycling behavior intentions: evidence from China

(*Continued*)

Table 10.1 (Continued)

2016	Zeng and Li	Measuring the recyclability of E-waste: an innovative method and its implications
2016	Zhong and Huang	The empirical research on the consumers' willingness to participate in E-waste recycling with a points reward system
2015	Abdollahi et al.	Enhancement of electronic protection to reduce E-waste
2015	Baldé et al.	The global E-waste
2015	Cucchiella et al.	Recycling of WEEEs: an economic assessment of present and future E-waste streams
2015	Dwivedy et al.	Modeling and assessment of E-waste take-back strategies in India
2015	Kasper et al.	Electronic waste recycling
2015	Kasapo et al.	E-waste flow among selected institutions of higher learning using material flow analysis model
2015	Reddy et al.	Producing abjection: E-waste improvement schemes and informal recyclers of Bangalore
2015	Song and Li	A review on human health consequences of metals exposure to E-waste in China
2015	Veit et al.	Electronic waste recycling techniques, *In Topics in Mining, Metallurgy and Materials Engineering*
2015	Zeng et al.	Solving E-waste problem using an integrated mobile recycling plant
2014	Bhat et al.	E-waste consciousness and disposal in Pune City
2014	Chi et al.	E-waste collection channels and household recycling behaviors in Taizhou of China
2014	Estrada-Ayub J et al.	Decision factors for E-waste in Northern Mexico: to waste or trade
2014	Jibiri et al.	Assessment of radiation exposure levels at Alaba E-waste dumpsite in comparison with municipal waste dumpsites in southwest Nigeria
2014	Perkins et al.	E-waste: a global hazard
2014	Yue et al.	Chen Polybrominated diphenyl ethers in e-waste: level and transfer in a typical E-waste recycling site in Shanghai, Eastern ChinaWaste
2013	Jinhui et al.	Regional or global WEEE recycling: where to go?
2013	Kiddee et al.	Electronic waste management approaches: an overview
2013	Masahiro et al.	Metals in WEEE: characterization and sub- stance flow analysis in waste treatment processes
2013	Milovantseva et al.	E-waste bans and U.S. households' preferences for disposing of their E-waste
2013	Qu et al.	A review of developing an E-wastes collection system in Dalian, China
2013	Rafia et al.	Survey and analysis of public knowl- edge, awareness and willingness to pay in Kuala Lumpur, Malaysia e a case study on house- hold WEEE management

2012	Oliveira et al.	Collection and recycling of electronic scrap: a worldwide overview and comparison with the Brazilian situation
2012	Tuncuk et al.	Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling
2011	Tsydenova and Bengtsson	Chemical hazards associated with treatment of waste electrical and electronic equipment
2010	Sepúlveda	A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India
2009	Robinson	E-waste: an assessment of global production and environmental impacts
2008	Cui and Zhang	Metallurgical recovery of metals from electronic waste: a review
2008	Spalvins	Impact of electronic waste disposal on lead concentrations in landfill leachate
2007	Hageluken	Recycling of e-scrap in a global environment: opportunities and challenges
2007	Wong	Export of toxic chemicals—a review of the case of uncontrolled electronic waste recycling
2006	Hageluken	Recycling of electronic scrap at umicore's integrated metals smelter and refinery
2004	IRGSSA	Management, handling and practices of E-waste recycling in Delhi. IRGSSA, India
2002	Nakazawa et al.	Bioleaching of waste printed wiring board using *Thiobacillus ferrooxidans*
2002a,b	Veit et al.	Using mechanical processing in recycling printed wiring boards
2002a,b	Veit et al.	Recycling of metals from PCB by dense medium separation processes
2001	Brandl	Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi

e-commerce portal vendors collect a significant proportion of the discarded electronics for reuse and cannibalization of parts and components, adds the study.

Accompanied by the huge size of the population and rising electronics users in the country, managing an unorganized sector to achieve such high targets may not be feasible. Thus, the ASSOCHAM suggests that the government may look at collaborating with the industry to draw out formal/standard operating procedures and a phased approach toward the agenda of reducing E-wastes to the lowest.

Alternatively, the government may also refer methods adopted by other countries for efficient collection and recycling of E-wastes. For example, South Korea, one of the largest producer of electronics managed to recycle 21% of the total 0.8 million tonnes of E-waste that it produced in 2015, noted the joint study.

Seoul recycles all the E-waste that it produces. It has set up the Seoul Resource Center which receives 20% of the Seoul's E-waste for extraction of valuable metals such as gold and copper. The remaining 80% of Seoul's E-waste is used entirely for landfilling. The government may also evaluate privatization of recycling like in the United Kingdom wherein a private company, Concept governed by the public body, Electrical and Electronic Equipment (WEEE) Directive has been handed over the responsibility of collecting and recycling E-wastes in the UK, mentioned the study.

The industry is of the view that the government may increase the Merchandise Exports from India Scheme (MEIS) incentive and introduce new incentives to attract more players in the market and to encourage the existing players to ramp up manufacturing implementation targets of E-waste collection need to be reviewed, as against the current requirement, to ensure compliance across the industry.

The electronics industry has emerged as the fastest growing segment of Indian industry both in terms of production and exports. The share of software services in electronics and IT sector has gone up from 38.7% in 1998–99 to 61.8% in 2003–04. A review of the industry statistics shows that in 1990–91, hardware accounted for nearly 50% of total IT revenues while software's share was 22%. The scenario changed by 1994–95, with hardware share falling to 38% and software's share rising to 41%. This shift in the IT industry began with liberalization, and the opening up of Indian markets together with which there was a change in India's import policies vis-à-vis hardware leading to substitution of domestically produced hardware by imports. Since the early 1990s, the software industry has been growing at a compound annual growth rate of over 46% (supply chain management, 1999). Output of computers in value terms, for example, increased by 36.0%, 19.7%, and 57.6% in 2000–01, 2002–03, and 2003–04, respectively. Within this segment, the IT industry is prime mover with an annual growth rate of 42.4% between 1995 and 2000. By the end of financial year 2005–06, India had an installed base of 4.64 million desktops, about 431 thousand notebooks and 89 thousand servers. According to the estimates made by the Manufacturers Association of Information Technology (MAIT), the Indian PC industry is growing at a 25% compounded annual growth rate.

The E-waste inventory based on this obsolescence rate and installed base in India for the year 2005 has been estimated to be 146,180 tonnes. This is expected

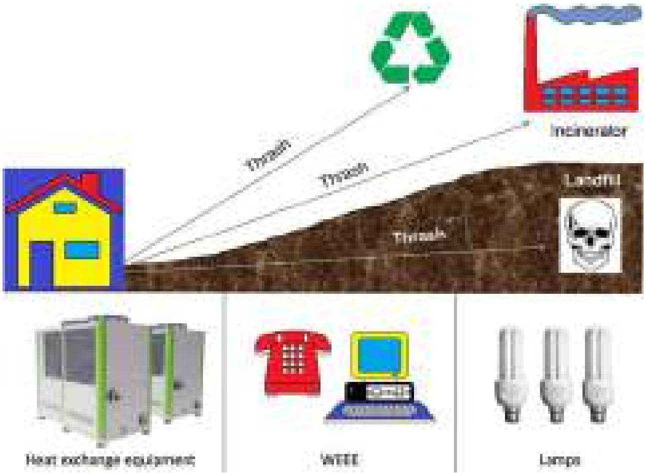


Figure 10.2 Disposal (landfill and incineration) of E-waste.

to exceed 800,000 tonnes by 2012. *There is a lack of authentic and comprehensive data on E-waste availability for domestic generation of E-waste and the various State Pollution Control Boards have initiated the exercise to collect data on E-waste generation.*

Sixty-five cities in India generate more than 60% of the total E-waste generated in India. Ten states generate 70% of the total E-waste generated in India. Maharashtra ranks first followed by Tamil Nadu, Andhra Pradesh, Uttar Pradesh, West Bengal, Delhi, Karnataka, Gujarat, Madhya Pradesh, and Punjab in the list of E-waste generating states in India. Among top ten cities generating E-waste, Mumbai ranks first followed by Delhi, Bangalore, Chennai, Kolkata, Ahmedabad, Hyderabad, Pune, Surat, and Nagpur. There are two small E-waste dismantling facilities are functioning in Chennai and Bangalore. There is no large scale organized E-waste recycling facility in India and the entire recycling exists in unorganized sector (Fig. 10.2).

10.3 E-waste management in India

The Ministry of Environment and Forest has notified E-waste Rules in May 2011, which has come into force with effect from 1st May 2012. The concept of EPR has been enshrined in these rules. As per these Rules the producers are required to collect E-waste generated from the end of life of their products by setting up collections centers or take back systems either individually or collectively. E-waste recycling can be undertaken only in facilities authorized and registered with State Pollution Control Boards/Pollution Control Committee (PCCs). Wastes generated are required to be sold to a registered or authorized recycler or reprocessor having

Table 10.2 Global E-waste generation - population versus weight.

Year	E-waste generated (Mt)	Population (billion)	E-waste generated (kg/inh.)
2010	33.8	6.8	5.0
2011	35.8	6.9	5.2
2012	37.8	6.9	5.4
2013	39.8	7.0	5.7
2014	41.8	7.1	5.9
2015	*43.8*	*7.2*	*6.1*
2016	*45.7*	*7.3*	*6.3*
2017	*47.8*	*7.4*	*6.5*
2018	*49.8*	*7.4*	*6.7*

Source: Data 2015 onwards are forecasts. Baldé, C.P., Wang, F., Kuehr, R., Huisman, J. (2015), The global E-waste monitor – 2014, United Nations University, IAS – SCYCLE, Bonn, Germany.

environmentally sound facilities. The rule has provision for setting up of Collection Center individually or jointly; or by a registered society or a designated agency; or by an association to collect E-waste.

These rules are the main instrument to ensure environmentally sound management of E-waste. Under these rules EPR authorizations have been granted to 128 Producers which are spread in 11 states. 134 collection centers are set-up in 19 States.

10.3.1 Batteries management

The Batteries (Management & Handling) Rules, 2001 was notified in May, 2001 to regulated the collection, characterization, and recycling as well as import of used lead acid batteries in the country. These rules inter-alia make it mandatory for consumers to return used batteries. All manufacture/assemblers/reconditioners/importers of lead acid batteries are responsible for collecting used batteries against new ones sold as per a schedule defined in the rules. Such used lead acid batteries can be auctioned/sold only to recyclers registered with the Ministry on the basis of their possessing environmentally sound facilities for recycling/recovery (Table 10.2).

E-waste in India grew by about 30%
India contributes about 12% to the global E-waste production
India recycles less than 2% of the E-waste it produces

10.4 Environmental regulations for E-waste in India

E-waste comprises of wastes generated from used electronic devices and household appliances which are not fit for their original intended use and are destined for recovery, recycling, or disposal. Such wastes encompasses wide range of electrical

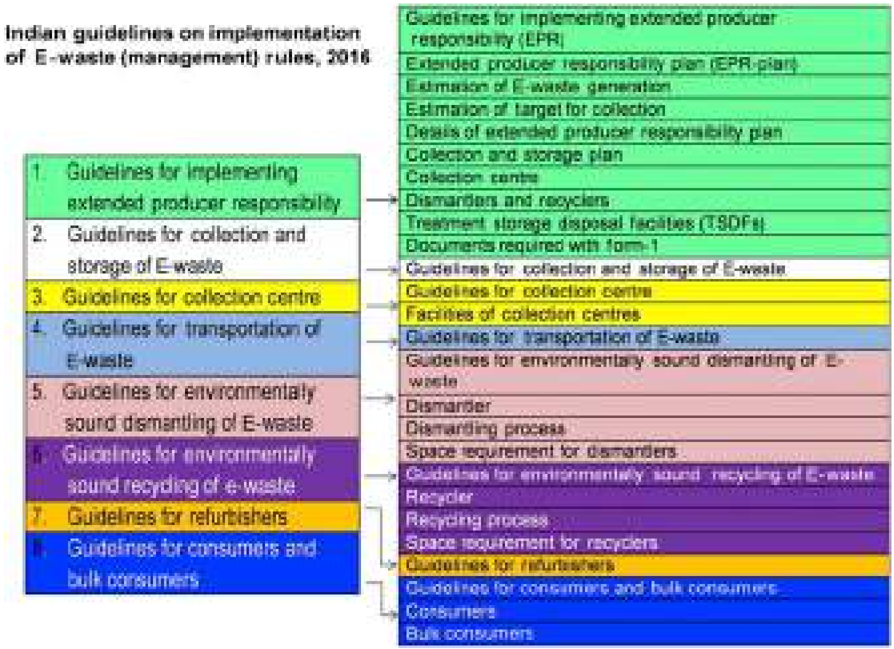


Figure 10.3 Indian guidelines on implementation of E-waste management.

and electronic devises such as computers, hand held cellular phones, personal stereos, including large household appliances such as refrigerators and air conditioners. E-wastes contain over 1000 different substances many of which are toxic and potentially hazardous to environment and human health, if these are not handled in an environmentally sound manner.

The growth of E-waste has significant economic and social impacts. There is no large scale organized E-waste recycling facility in India and there are two small E-waste dismantling facilities are functioning in Chennai and Bangalore, while most of the E-waste recycling units are operating in unorganized sector.

Schedules 1, 2, and 3 cover E-waste are given below (Figs. 10.3 and 10.4).

10.5 Schedule 1

Although there is no direct reference of electronic waste in any column of Schedule 1 (which defines hazardous waste generated through different industrial processes), the "disposal process" of E-waste could be characterized as hazardous processes. The indicative list of these processes is given below.

- Secondary production and/or use of Zinc
- Secondary production of copper
- Secondary production of lead

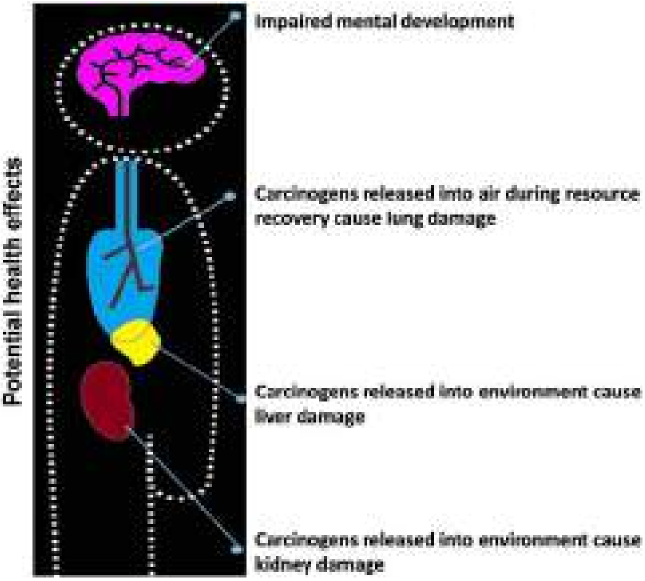


Figure 10.4 Potential health effects of E-waste.
Data source: Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-waste Monitor – 2014, United Nations University, IAS – SCYCLE, Bonn, Germany. ISBN Print: 978-92-808-4555-6. Thanks are du to United Nations University under a Creative Commons Attribution-Noncommercial-Share Alike 3.

- Production and/or use of cadmium and arsenic and their compounds
- Production of primary and secondary aluminum
- Production of iron and steel including other ferrous alloys (electric furnaces, steel rolling, and finishing mills, coke oven, and by-product plan)
- Production or industrial use of materials made with organo silicon compounds
- Electronic industry
- Waste treatment processes, for example, incineration, distillation, separation, and concentration techniques

As per these regulations, once a waste product is classified as hazardous according to industrial process listed in Schedule 1, it is exempted from the concentration limit requirement set by Schedule 2 of Act, and is considered hazardous irrespective of its concentrations.

10.6 Schedule 2

The Schedule 2 of the Hazardous Waste Management and Handling Rules 2003 lists waste substances which should be considered hazardous unless their concentration is less than the limit indicated in the said Schedule. The various classes of substances listed in this Schedule relevant to E-waste are covered in Class A, B, C, D, and E are given below. E-waste or its fractions coming broadly under Class A and B are given below.

10.7 Class A: concentration limit: $\geq$50 mg/kg

The indicative waste list, which could be part of E-waste or its fractions under this class are given below.

- Antimony and antimony compounds
- Beryllium and beryllium compounds
- Cadmium and cadmium compounds
- Chromium (VI) compounds
- Mercury and mercury compounds
- Halogenated compounds of aromatic rings, for example, polychlorinated biphenyls
- Polychloroteriphenyls and their derivatives
- Halogenated aromatic compounds

On March 22, 2018, the Ministry of Environment, Forest and Climate Change, Government of India, New Delhi notified that the collection, storage, transportation, segregation, refurbishment, dismantling, recycling and disposal of E-waste shall be in accordance with the guidelines published by the "Central Pollution Control Board" issued notification for rule 23 and Schedule 3 (Table 10.3).

List of Hazardous Waste to be applicable only for imports and exports are mentioned in schedule 3. It define hazardous waste as "Wastes listed in lists 'A' and 'B' of part A of schedule 3 applicable only in case(s)of export/import of hazardous wastes in accordance with rule 12, 13, and 14 only if they possess any of the hazardous characteristics in part B of said schedule." This clause defines hazardous waste

Table 10.3 MoEF&CC Govt. of India notification of Schedule 3 sated March 22, 2018.

Year	E-waste collection target (weight)
2017–18	10% of the quantity of waste generation as indicated in Extended Producer Responsibility Plan
2018–19	20% of the quantity of waste generation as indicated in Extended Producer Responsibility Plan
2019–20	30% of the quantity of waste generation as indicated in Extended Producer Responsibility Plan
2020–21	40%of the quantity of waste generation as indicated in Extended Producer Responsibility Plan
2021–22	50% of the quantity of waste generation as indicated in Extended Producer Responsibility Plan
2022–23	60% of the quantity of waste generation as indicated in Extended Producer Responsibility Plan
2023 onwards	70% of the quantity of waste generation as indicated in Extended Producer Responsibility Plan

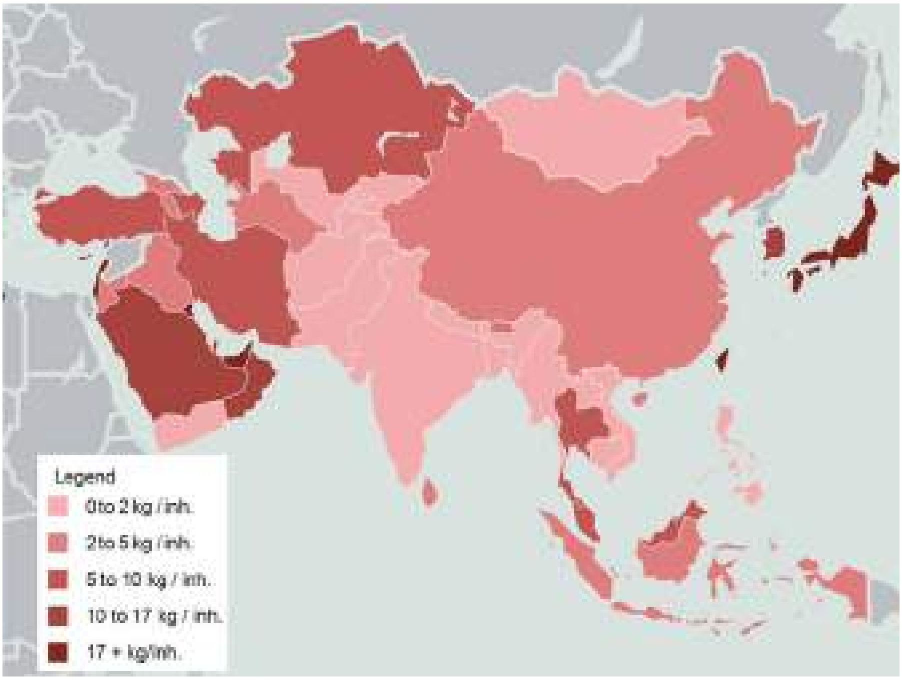


Figure 10.5 Asia has 49 countries with 4.4 billion inhabitants producing 4.2 kg of E-waste per inhabitant (inh.) 40.7% of world's E-waste is generated in Asia. It is estimated that 2.7 Mt documented to be collected and recycled.
Data source from: Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-waste Monitor—2014, United Nations University, IAS—SCYCLE, Bonn, Germany. ISBN Print: 978-92-808-4555-6.

for the purpose of import and export. It has divided hazardous waste into two parts, A and B. Part A of the schedule deals with two lists of waste to be applicable only for imports and exports purpose. Export and import of items listed in List A and B of part A are permitted only as raw materials for recycling or reuse (Fig. 10.5).

Based on the outcome of the studies carried out and the consensus arrived at the National Workshop on electronic waste management held in March 2004 and June 2005 organized by CPCB and Ministry of Environment & Forests, an assessment was made of the existing practice in the E-waste management.

10.8 Classification of E-waste

10.8.1 Composition of E-waste

It contains more than 1000 different substances, which fall under "hazardous" and "nonhazardous" categories. Broadly, it consists of ferrous and nonferrous metals,

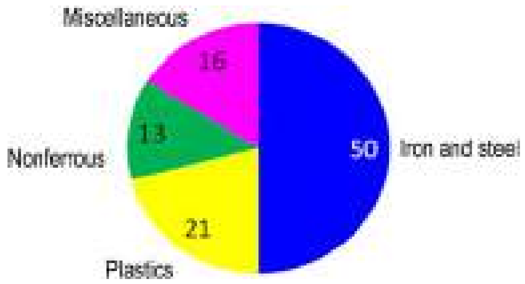


Figure 10.6 Composition of E-waste.

plastics, glass, printed circuit boards, concrete and ceramics, rubber and other items (Fig. 10.6).

Nonferrous metals consist of metals like copper, aluminum and precious metals consist of metals like silver, gold, platinum, and palladium. The presence of elements like lead, mercury, arsenic, cadmium, selenium, and hexavalent chromium and flame retardants beyond threshold quantities in E-waste classifies them as hazardous waste.

10.9 Components of E-waste

E-waste has been categorized into three main categories, viz. large household appliances, IT and telecom, and consumer equipment. Refrigerator and washing machine represent large household appliances; personal computer, monitor, and laptop represent IT and telecom, while television represents consumer equipment (Fig. 10.7).

1. Radioactive substances, refractory ceramic fibers, electrolyte capacitors (over L/D 25 mm), textile, and magnetron are not present in any item.
2. Plastic, circuit board, and external electric cables are present in majority of items (BFR).
3. Containing plastic is present in refrigerator, laptop, and television.
4. Refrigerators are unique items because of presence of CFC/HCFC/HFC/HC, cooling, insulation, incandescent lamp, and compressor.
5. Heating element is found in washing machine, while thermostat is found in both refrigerator and washing machine.
6. Fluorescent lamp is found only in laptop.
7. Metal and motor are found in majority of items except refrigerator.
8. Transformer is not found in washing machine and refrigerator.
9. CRT is found in personal computer and TV, while LCD is found in PC and TV.
10. Batteries are found in PC and laptop.
11. Concrete is found in washing machine.
12. Rubber is found in refrigerator and washing machine.
13. Wiring/electrical is found in all the items.

Large household appliance (refrigerator) may consist of electric motor, a circuit board, a transformer, capacitor, thermal insulation, switches, wiring, and plastic casing that contain flame retardants. A typical washing machine may consist of the metal

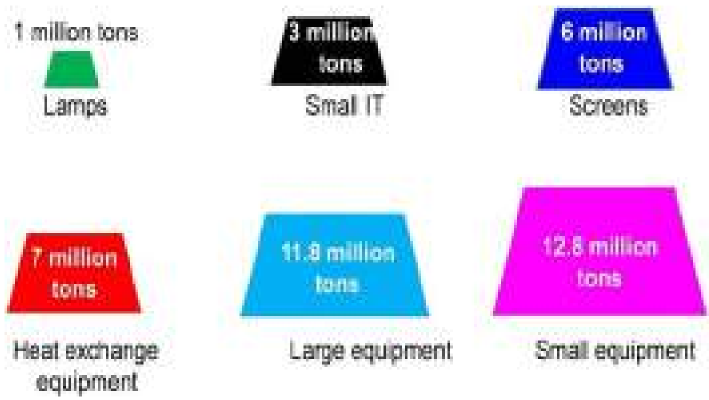


Figure 10.7 Total E-waste categories. Redrawn from Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-waste Monitor −2014, United Nations University, IAS − SCYCLE, Bonn, Germany. ISBN Print: 978-92-808-4555-6.

casing, concrete ballast, inner and outer drums, a motor, a pump, washing cycle controller unit, switches, and other components. The latest trend in these appliances is the phase out of the use of ODS and improvement of energy efficiency. Old washing machines are likely to contain large capacitors, while in relatively new machines, variable speed motors are controlled from the circuit board. IT and telecom equipments sector is observing a trend of "micro miniaturization," while CRTs are being replaced by LCD screens (Table 10.4) indicates that the range of different items found in E-waste is diverse classifying it a waste of complex nature. However, it shows that E-waste from these items can be dismantled into relatively small number of common components for further treatments. The composition and the overall hazardousness of each item of E-waste is shown in Figure 10.8.

The possible substance of concern, which may be found in selected E-waste item is given in Figure 10.8.

The substances within the above mentioned components, which cause most concern are the heavy metals such as lead, mercury, cadmium and chromium (VI), halogenated substances (e.g., CFCs), polychlorinated biphenyls, plastics, and circuit boards that contain brominated flame retardants (BFRs). BFR can give rise to dioxins and furans during incineration. Other materials and substances that can be present are arsenic, asbestos, nickel, and copper. These substances may act as a catalyst to increase the formation of dioxins during incineration (Figs. 10.9 and 10.10).

Environmentally sound E-waste treatment technologies are used at three levels as described below:

First level treatment
Second level treatment
Third level treatment

All the three levels of E-waste treatment are based on material flow. The material flows from first level to third level treatment. Each level treatment consists of

Table 10.4 Components in WEEE (by category).

	Large household appliances		*IT and Telecom (personal computer)*			**Consumer equipment**
	Refrigerator	**Washing machine**	**Base and keyboard**	**Monitor**	**Laptop**	**Television**
Metal	■	■	■	–	–	■
Motor/compressor	■	■	■		■	–
Cooling	■	–	–	–	–	–
Plastic	■	■	■	■	■	■
Insulation	■	–	–	–	–	–
Glass	■	■	–	–	–	–
CRT	–	–	–	■	–	■
LCD	–	–	–	■	■	–
Rubber	■	■	–	–	–	–
Wiring/electrical	■	■	■	–	■	■
Concrete		■				
Transformer	–	–	■	■	■	■
Circuit board	–	■	■	■	■	■
Fluorescent lamp (ineballast)	–	–	–	–	■	–
Incandescent lamp	■	–	–	–	–	–
Heating element		■	–	–	–	–
Thermostat	■	■	–	–	–	–
BFR—containing plastic	■				■	■
Batteries	–	–	■	–	■	–
CFC, HCFC, HFC, HC	■	–	–	–	–	–
External electric cables (over L/D 25 mm)	–	○	–	–	–	–

■Present as a component; Refractory ceramic fibers; Radioactive substances; Electrolyte CapacitorsPossible hazardous substances present in E-waste; possible presence as a component.
Source: Anonymous, 2008. Guidelines for Environmentally Sound Management of E-Waste (as Approved Vide MoEF Letter No. 23-23/2007-HSMD dt. March 12, 2008). Ministry of Environment, Forests and Climate Change, Central Pollution Control Board, Delhi. Adapted from Guidelines for environmentally sound management of E-Waste (As approved vide MoEF letter No. 23-23/2007-HSMD dt. March 12, 2008) Ministry of Environment, Forests and Climate Change. Central Pollution Control Board. Delhi, 2008.

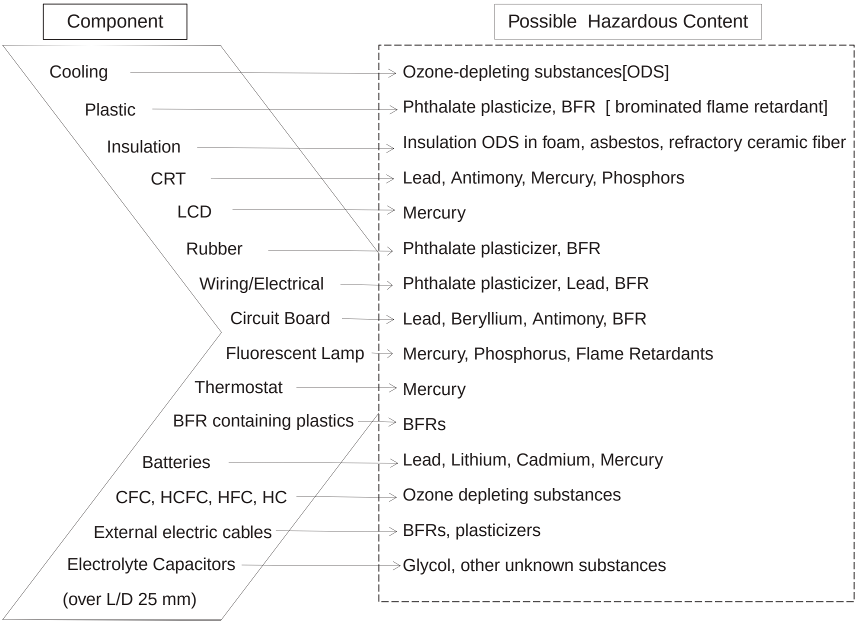


Figure 10.8 Possible hazardous substances in components. Adapted from Guidelines for environmentally sound management of E-waste (As approved vide MoEF letter No. 23-23/2007-HSMD dt. March 12, 2008) Ministry of Environment, Forests and Climate Change. Central Pollution Control Board. Delhi, 2008.

unit operations, where E-waste is treated and output of first level treatment serves as input to second level treatment. After the third level treatment, the residues are disposed of either in TSDF or incinerated. The efficiency of operations at first and second level determines the quantity of residues going to TSDF or incineration. The simplified version of all the three treatments is shown in Figs. 10.11 and 10.12.

EST at each level of treatment is described in terms of input, unit operations, output and emissions (Fig. 10.13).

Unit operations: There are three units operations at first level of E-waste treatment:

1. Decontamination: removal of all liquids and gases
2. Dismantling: manual/mechanized breaking
3. Segregation

All the three unit operations are dry processes, which do not require usage of water.

1. Decontamination

   The first treatment step is to decontaminate E-waste and render it nonhazardous. This involves removal of all types of liquids and gases (if any) under negative pressure, their recovery, and storage.

Figure 10.9 (A−H) E-waste, collection, dismantling, shredding for resource recovery in E-waste.

Figure 10.10 Environmentally sound treatment technologies for E-waste.

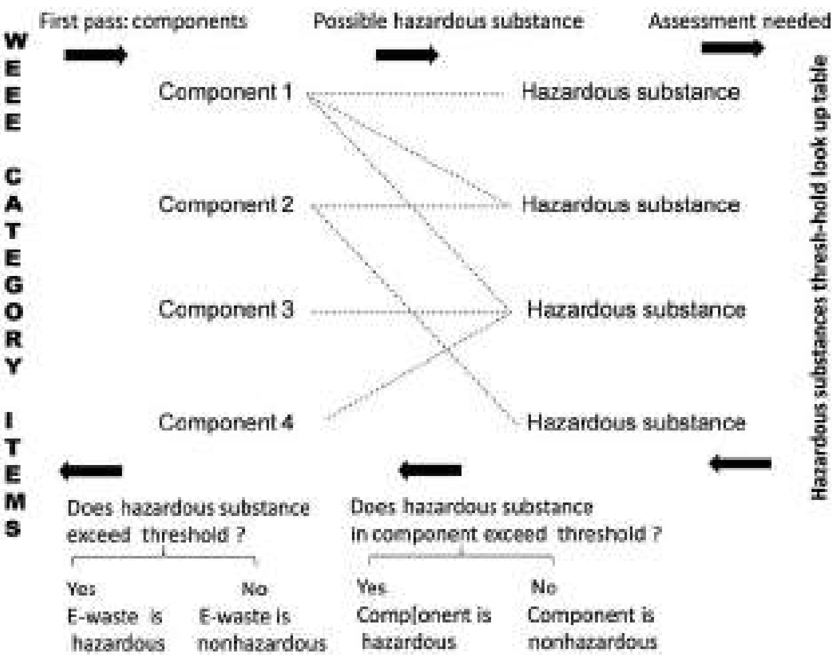


Figure 10.11 Approach and methodology for assessment of hazardousness of E-waste.

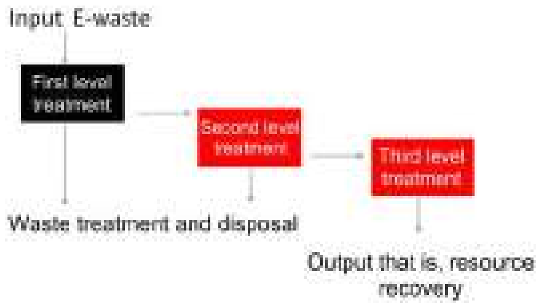


Figure 10.12 Simplified version of EST for E-waste.

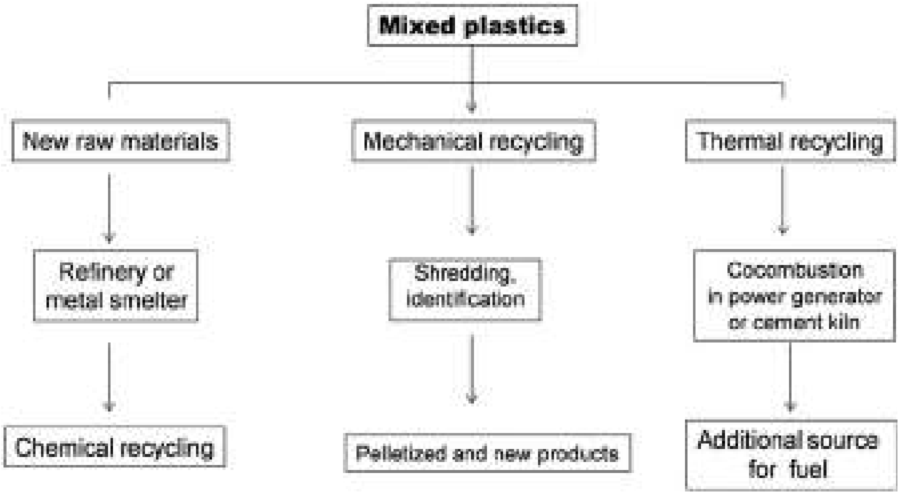


Figure 10.13 Recycling of mixed plastics in E-waste.

2. Dismantling

The decontaminated E-waste or the E-waste requiring no decontamination are dismantled to remove the components from the used equipments. The dismantling process could be manual or mechanized requiring adequate safety measures to be followed in the operations.

3. Segregation

After dismantling the components are segregated into hazardous and nonhazardous components of E-waste fractions to be sent for third level treatment.

10.10 EST for second level treatment

Input: Decontaminated E-waste consisting segregated nonhazardous E-waste like plastic, CRT, circuit board, and cables (Figure 10.14).

Input/WEEE residues	Unit Operation/ Disposal/Recycling Technique	Output
Sorted Plastic	Recycling	Plastic Product
Plastic Mixture	Energy Recovery Incineration	Energy Recovery
Plastic Mixture with FR	Incineration	Energy Recovery
CRT	Breaking/Recycling	Glass Cullet
Lead Smelting	Secondary Lead Smelter	Lead
Ferrous metal scrap	Secondary steel/iron recycling	Iron
Non Ferrous metal Scrap	Secondary copper and aluminum smelting	Copper/Aluminum
Precious Metals	Au/Ag separation(refining)	Gold/Silver/Platinum and Palladium
Batteries (Lead Acid/Ni MH and Li ion)	Lead recovery and smelting Remelting and separation	Lead
CFC	Recovery/Reuse and Incineration	CFC/Energy recovery
Oil	Recovery/Reuse and Incineration	Oil recovery/energy
Capacitors	Incineration	Energy recovery
Mercury	Separation and Distillation	Mercury

Figure 10.14 Input/output and unit operations for third level treatment of E-waste. Adapted from Guidelines for environmentally sound management of E-waste (As approved vide MoEF letter No. 23-23/2007-HSMD dt. March 12, 2008) Ministry of Environment, Forests and Climate Change. Central Pollution Control Board. Delhi, 2008.

Unit operations: There are three unit operations at second level of E-waste treatment

1. Hammering
2. Shredding
3. Special treatment processes comprising of
   a. CRT treatment consisting of separation of funnels and screen glass.
   b. Electromagnetic separation.
   c. Eddy current separation.
   d. Density separation using water.

10.11 Technology currently used in India

For non CRT E-waste: the two E-waste treatment facilities in India use the following technologies:

1. Dismantling
2. Pulverization/hammering
3. Shredding
4. Density separation using water

The CRT treatment technology as used by CRT manufacturer in India for discarded CRTs, is shown in Fig. 10.15.

CPCB established guidelines for establishment of integrated E-waste recycling and treatment facility in different locations of India and total units are 178 (Fig. 10.16).

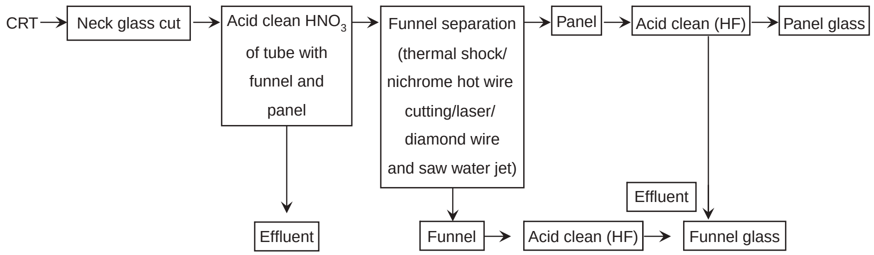


Figure 10.15 The CRT treatment technology as used in India for discarded CRTs.

Average weight and composition of selected appliances (typical)
Recoverable quantity of elements in a PC (typical)
Recoverable quantity of elements in a TV (typical)
Recoverable materials from refrigerators (typical) (Figs. 10.17–10.20).

Mechanical processing, hydrometallurgy, supercritical fluids: supercritical fluids are substances that are submitted to pressures and temperature that exceed their critical points.

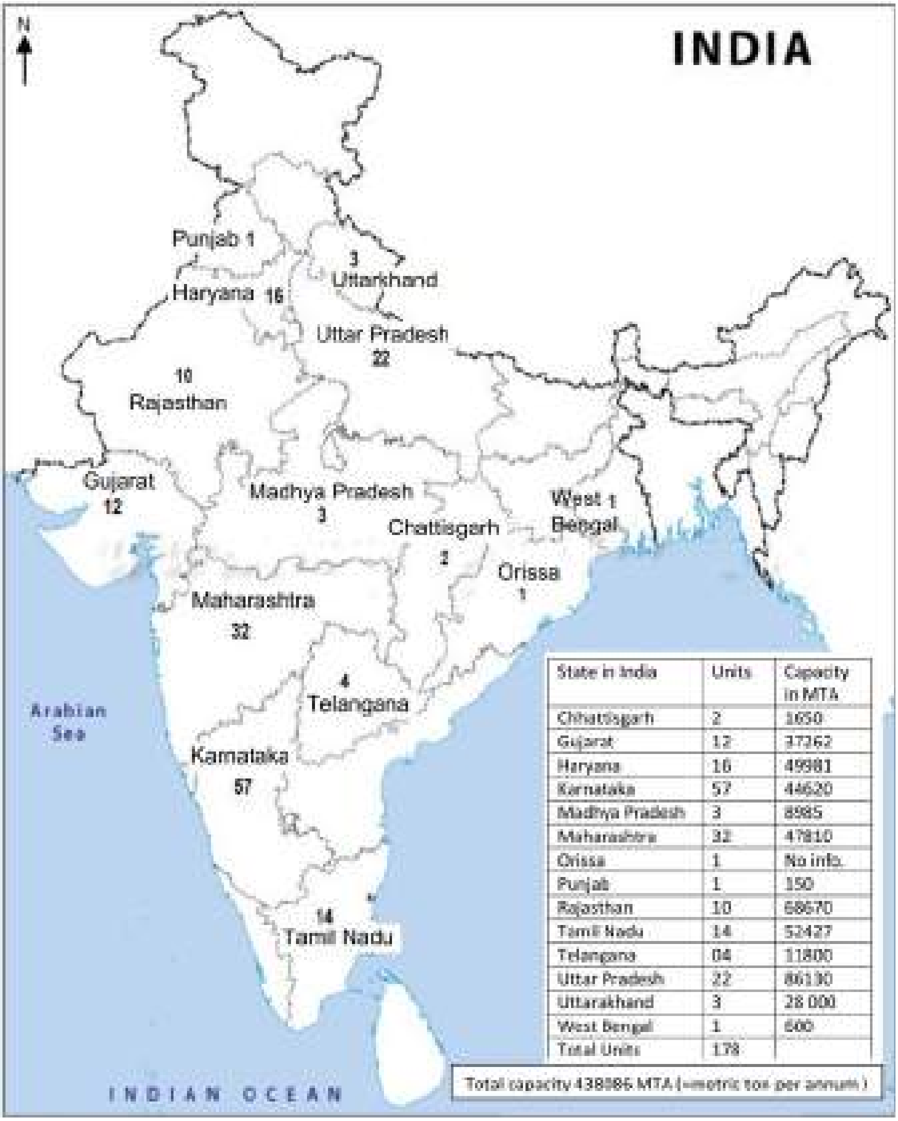
Electrometallurgy and Pyrometallurgy
Biotechnology, or a combination of various techniques.
Electronic waste: generation, management and waste recycling
Processing techniques
Mechanical processing
Leaching processes
Electrometallurgical processing
Pyrometallurgical processing
Bioleaching of electrical and electronic waste microorganisms (MOOS)
Batteries
Material selection and separation methods based on mineral processing techniques.

Electronic waste processing is very complex due to the great heterogeneity of its composition and its poor compatibility with the environment. The first step is usually manual disassembly, where certain components (casings, external cables, CRTs, PCBs, and batteries.) are separated. Following disassembly, the technologies used for the treatment and recycling of electronic waste include mechanical, chemical and thermal processes. For metals recovery there are four main routes: mechanical processing, hydrometallurgy, electrometallurgy, and pyrometallurgy. There are also references in the literature on biotechnology, or a combination of techniques.

10.12 Mechanical processing

10.12.1 Biotechnology

Bacteria such as (*Thiobacillus thiooxidans, ferroxidans*) and fungus (*Aspergillus niger*, *Penicillium simplicissimum*) grow in the presence of this type of residue. In this study, high quantities of metals, such as Cu, Ni, Zn, and Al, were leached. The



State in India	Units	Capacity in MTA
Chhattisgarh	2	1650
Gujarat	12	37262
Haryana	16	49981
Karnataka	57	44620
Madhya Pradesh	3	8985
Maharashtra	32	47810
Orissa	1	No info.
Punjab	1	150
Rajasthan	10	68670
Tamil Nadu	14	52427
Telangana	04	11800
Uttar Pradesh	22	86130
Uttarakhand	3	28 000
West Bengal	1	600
Total Units	178	

Figure 10.16 Registered E-waste dismantlers/recyclers in different provinces of India.

main limitations of biohydrometallurgical processes are the long periods necessary for the leaching and the need of the metal to be exposed, that is, the metals content must be mainly located on the surface layer (Fig. 10.21).

The advantages of electrometallurgical processes are:

- Few steps
- Higher selectivity for desired metals

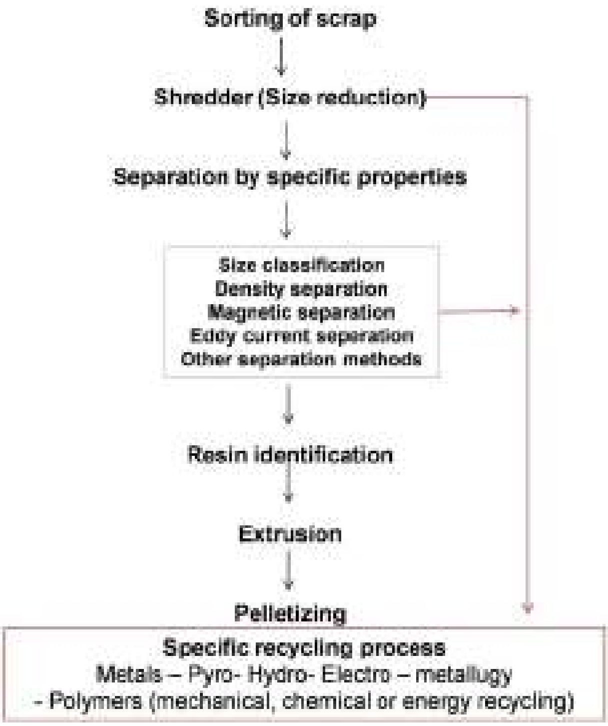


Figure 10.17 Various unit processes for resource recovery from E-waste.

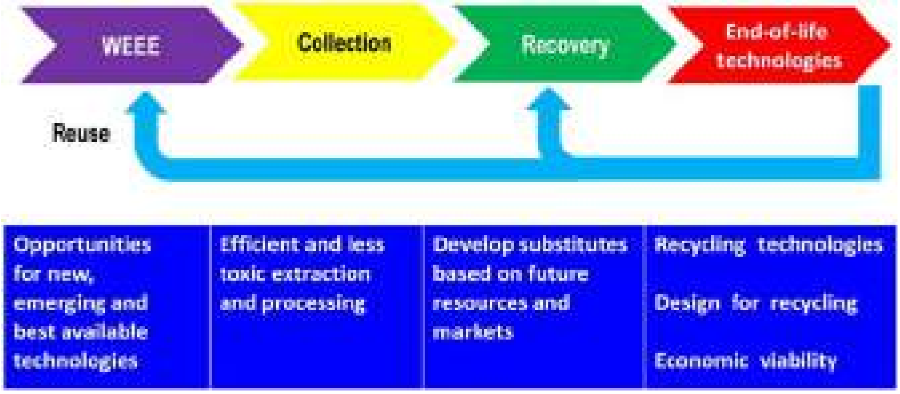


Figure 10.18 Recycling from end-of-life technologies alone cannot meet the demand. Opportunities for new, emerging, and best available technologies, efficient and less toxic extraction and processing substitutes based on future resources and markets, design for recycling and economic viability.

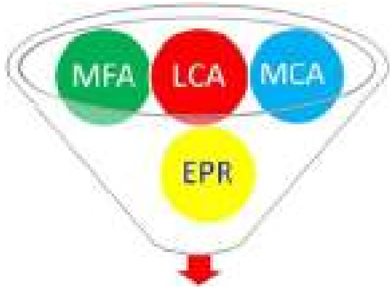


Figure 10.19 Multiple strategies for optimized management of WEEE. *EPR*, Extended produce responsibility; *LCA*, life cycle assessmet; *MCA*, multi criteria analysis; *MFA*, material flow alaysis.

- The electrolyte can be reused
- Pure metals can be obtained.

The main limitation is the need of a pretreatment (usually based on mechanical and hydrometallurgical processes).

10.13 Pyrometallurgy

Pyrometallurgical processing has some advantages, such as applicability to any type of electronic waste, no need for pretreatment and few steps in the process. Some of the methods involving thermal processing of electronic waste, may cause the following problems:

Polymers and other insulating materials become a source of air pollution through the formation of dioxins and furans.

Some metals can be lost through volatilization of their chlorides.

Ceramic and glass components present in the scrap increase the amount of slag in the furnace, increasing the losses of precious and base metals.

Recovery of some metals is low (e.g., Sn and Pb) or almost impossible (e.g., Al and Zn).

www.usepa.gov/epaoswer/hazwaste/recycle/ecycling/index.htm
www.defra.gov.uk/environment/waste/index.htm
www.ec.gc.ca
www.environment.gov.au
http://ec.europa.eu/environment/waste/weee/index_en.htm
www.ewasteguide.info
www.basel.int
www.unep.org
http://www.unep.ch/ozone/index.shtml
www.cpcb.nic.in/Hazardous%20Waste/default_Hazardous_Waste.html

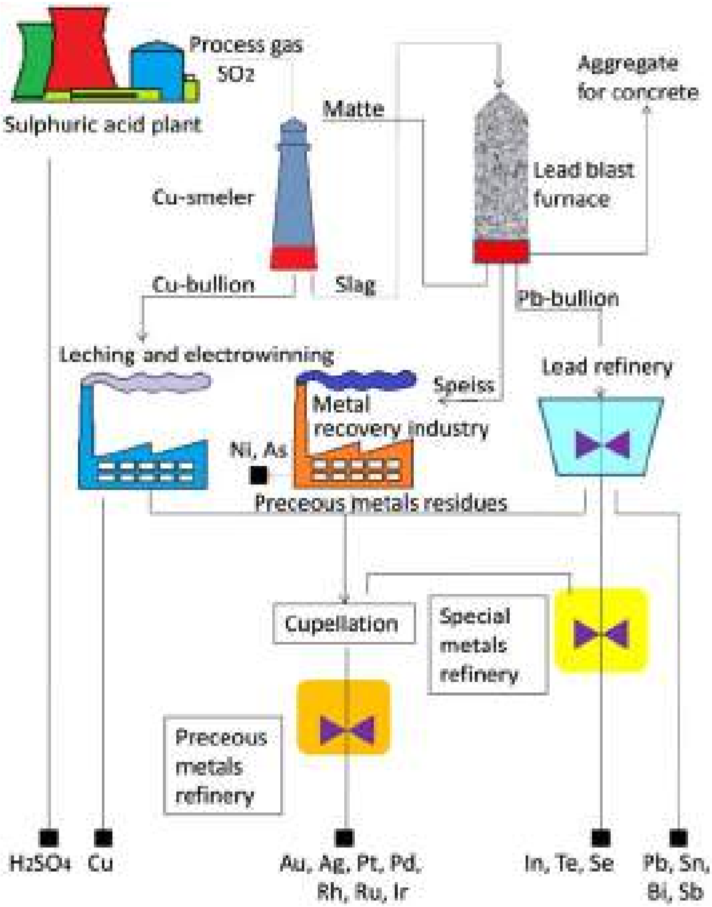


Figure 10.20 The first step is usually manual disassembly, where certain components (casings, external cables, CRTs, PCBs, and batteries) are separated. Following disassembly, the technologies used for the treatment and recycling of electronic waste include mechanical, chemical, and thermal processes. For metals recovery the main routes are as follows: mechanical processing, hydrometallurgy, supercritical fluids, electrometallurgy, pyrometallurgy, biotechnology, or a combination of various techniques including bioleaching using microorganisms.

http://www.basel.int/industry/mppiwp/guid-info/index.html
http://www.saicm.org
http://www.basel.int/about.html
http://www.mercuryconvention.org/
http://www.pic.int/en/ViewPage.asp?id = 104
http://www.pops.int

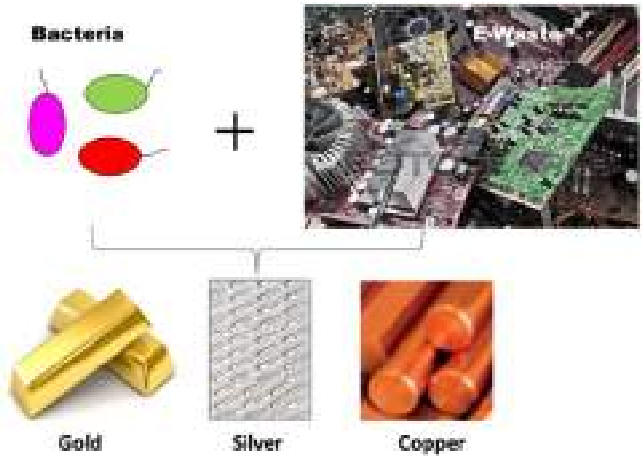


Figure 10.21 Metal bioleaching from E-waste using microorganisms, for example, *Acidiphilium acidophilum*.

Acknowledgments

Thanks are due to Central Pollution Control Board. New Delhi "Guidelines for Environmentally Sound Management of E-waste" (as approved vide MoEF letter No. 23-23/2007-HSMD date March 12, 2008) Ministry of Environment & Forests on which this chapter is based. Thanks are also due to Baldé, C.P., Wang, F., Kuehr, R., Huisman, J. (2015), The global E-waste monitor – 2014, United Nations University, IAS – SCYCLE, Bonn, Germany. ISBN Print: 978-92-808-4555-6, Electronic: 978-92-808-4556-3

References

Abdollahi, Y., Said, S.B.M., Sairi, N.A., Sabri, M.F.B.M., Aziz, R.S., 2015. Enhancement of electronic protection to reduce e-waste. J. Indust. Eng. Chem. 29, 400–407.

Alvarez-de-los-Mozos, E., Renteria, A., 2017. Collaborative robots in e-waste management. Proc. Manuf. 11, 55–62.

Amankwah-Amoah, J., 2016. Global business and emerging economies: towards a new perspective on the effects of e-waste. Technol. Forecast. Soc. Change 105, 20–26.

Bakhiyi, B., Gravel, S., Ceballos, D., Flynn, M.A., Zayed, J., 2018. Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges. Environ. Int. 110, 173–192.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-Waste Monitor – 2014. United Nations University, IAS – SCYCLE, Bonn, Germany, ISBN Print: 978-92-808-4555-6.

Bhat, V., Yogesh Patil, Y., 2014. E-waste consciousness and disposal practices among residents of Pune City. Proc. Soc. Behav. Sci. 133, 491–498.

Bindschedler, S., Bouquet, T.Q.T.V., Job, D., Joseph, E., Junier, P., 2017. Fungal biorecovery of gold from e-waste. Adv. Appl. Microb. 99, 53–81.

Borthakur, A., Govind, M., 2017. Emerging trends in consumers' e-waste disposal behaviour and awareness: a worldwide overview with special focus on India. Resour. Conserv. Recycl. 117, 102–113.
Brandl, H., Bosshard, R., Wegmann, M., 2001. Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 59, 319–326.
Cai, C.Y., Yu, S.Y., Liu, Y., Tao, S., Liu, W.X., 2018. PBDE emission from e-wastes during the pyrolytic process: emission factor, compositional profile, size distribution, and gas-particle partitioning. Environ. Pollut. 235, 419–428.
Cao, J., Lu, B., Chen, Y., Zhang, X., Schnoor, J.L., 2016. Extended producer responsibility system in China improves e-waste recycling: government policies, enterprise, and public awareness. Renew. Sustain. Energy Rev. 62, 882–894.
Cao, J., Xu, X., Zhang, Y., Zeng, Z., Huo, X., 2018. Increased memory T cell populations in Pb-exposed children from an e-waste-recycling area. Sci. Total Environ. 616–617, 988–995.
Chakraborty, P., Selvaraj, S., Nakamura, M., Prithiviraj, B., Bang, J.J., 2018. PCBs and PCDD/Fs in soil from informal e-waste recycling sites and open dumpsites in India: levels, congener profiles and health risk assessment. Sci. Total Environ. 621, 930–938.
Chi, X., Wang, M.Y.L., Reuter, M.A., 2014. E-waste collection channels and household recycling behaviors in Taizhou of China Xinwen Chi' Journal of Cleaner Production, vol. 80, pp. 87–5. https://doi.org/10.1016/j.jclepro.2014.05.056.
Cucchiella, F., D'Adamo, I., Koh, S.C.L., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272.
Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: a review. J. Hazard. Mater. 158, 228–256.
Cui, J.-L., Luo, C.-L., Tang, C.W.-Y., Chan, T.-S., Li, X.-D., 2017. Speciation and leaching of trace metal contaminants from e-waste contaminated soils. J. Hazard. Mater. 329, 150–158.
Debnath, B., Roychoudhuri, R., Ghosh, S.K., 2016. E-waste management: a potential route to green computing. Proc. Environ. Sci. 35, 669–675.
Dias, P., BernardesAM, Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian e-waste recycling scheme. J. Clean. Prod. 197, 750–764.
Dwivedy, M., Suchde, P., Mittal, R.K., 2015. Modeling and assessment of e-waste take-back strategies in India. Resour. Conserv. Recycl. 96, 11–18.
Estrada-Ayub, J.A., Kahhat, R., 2014. Decision factors for e-waste in Northern Mexico: to waste or trade. Resour. Conserv. Recycl. 86, 93–106.
Fowler, B.A., 2017a. Magnitude of the global e-waste problem. Electron. Waste 1–15.
Fowler, B.A., 2017b. Chapter 5: Risk assessment/risk communication approaches for e-waste sites electronic waste, In Electronic Waste Toxicology and Public Health Issues. Elsevier, pp. 63–70.
Garlapati, V.K., 2016. E-waste in India and developed countries: management, recycling, business and biotechnological initiatives. Renew. Sustain. Energy Rev. 54, 874–881.
Golev, A., Glen, D., 2017. Corder quantifying metal values in e-waste in Australia: the value chain perspective. Miner. Eng. 107, 81–87.
Hageluken, C., 2006. Recycling of electronic scrap at umicore's integrated metals smelter and refinery. World Metall. ERZMETALL 59 (3), 152–161.

Hageluken, C., 2007. Recycling of e-scrap in a global environment: opportunities and challenges. In: Rajeshwari, K.V., Basu, S., Johri, R. (Eds.), Tackling E-Waste Towards Efficient Management Techniques. TERI Press, New Delhi, pp. 87−104.

He, C.-T., Zheng, X.-B., Yan, X., Zheng, J., Mai, B.-X., 2017. Organic contaminants and heavy metals in indoor dust from e-waste recycling, rural, and urban areas in South China: spatial characteristics and implications for human exposure. Ecotoxicol. Environ. Saf. 140, 109−115.

IRGSSA, 2004. Management, Handling and Practices of E-Waste Recycling in Delhi. IRGSSA, India.

Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment (WEEE)/E-waste: a comprehensive literature review. Resour. Conserv. Recycl. 137, 48−75.

Jeon, S., Ito, M., Tabelin, C.D., Rogrit Pongsumrankul, R., Naoki Hiroyoshi, N., 2018. Gold recovery from shredder light fraction of e-waste recycling plant by flotation-ammonium thiosulfate leaching. Waste Manag. 77, 195−202.

Jiang, L., Cheng, Z., Zhang, D., Song, Zhang, G., 2017a. The influence of e-waste recycling on the molecular ecological network of soil microbial communities in Pakistan and China. Environ. Pollut. 231, 173−181.

Jiang, Z., Ren, Q., Li, H., Chen, Q., 2017b. Silicon carbide waste as a source of mixture materials for cement mortar. Front. Environ. Sci. Eng. 11 (5), 2. Available from: https://doi.org/10.1007/s11783-017-0974-y.

Jibiri, N.N., Isinkaye, M.O., Momoh, H.A., 2014. Assessment of radiation exposure levels at Alaba e-waste dumpsite in comparison with municipal waste dumpsites in southwest Nigeria. J. Radiat. Res. Appl. Sci. 7, 536−541.

Jinhui, L., Brenda, N.L.N., Lili, L., Nana, Z., Keli, Y., Lixia, Z., 2013. Regional or global WEEE recycling: where to go? Waste Manag. 33, 923−934.

Kasper, A.C., Gabriel, A.P., de Oliveira, E.L.B., de Freitas Juchneski, N.C., Veit, H.M., 2015. Electronic waste recycling. In: Veit, H.M., Moura Bernardes, A. (Eds.), Electronic Waste: In Topics in Mining. Metallurgy and Materials Engineering, pp. 87−128. Available from: https://doi.org/10.1007/978-3-319-15714-6_9.

Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an over- view. Waste Manag. 33, 1237−1250.

Kumar, A., Choudhary, V., Khanna, R., Cayumil, R., Ikram-ul-Haq, M., Sahajwalla, V., et al., 2017a. Recycling polymeric waste from electronic and automotive sectors into value added products. Front. Environ. Sci. Eng. 11 (5), 4. Available from: https://doi.org/10.1007/s11783-017-0991-x.

Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017b. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32−42.

Li, J., Wang, Z., Jiang, B., 2017a. Managing economic and social profit of cooperative models in three-echelon reverse supply chain for waste electrical and electronic equipment. Front. Environ. Sci. Eng. 11 (5), 12. Available from: https://doi.org/10.1007/s11783-017-0999-2.

Li, X., Tian, Y., Zhang, Y., Ben, Y., Lv, Q., 2017b. Accumulation of polybrominated diphenyl ethers in breast milk of women from an e-waste recycling center in China. J. Environ. Sci. 52, 305−313.

Li, M., Huo, X., Pan, Y., Cai, H., Xu, X., 2018. Proteomic evaluation of human umbilical cord tissue exposed to polybrominated diphenyl ethers in an e-waste recycling area. Environ. Int. 111, 362−371.

Liu, J., Xi, X., Shu, H.-Y., Lin, X.-R., Huang, L.-N., 2018a. Microbial community structure and function in sediments from e-waste contaminated rivers at Guiyu area of China. Environ. Pollut. 235, 171–179.

Liu, Y., Luo, X.-J., Huang, L.-Q., Tao, L., Mai, B.-X., 2018b. Halogenated organic pollutants in aquatic, amphibious, and terrestrial organisms from an e-waste site: habitat-dependent accumulation and maternal transfer in water snake. Environ. Pollut. 241, 1063–1070.

Lu, S.-Y., Li, Y.-X., Zhang, J.-Q.T., Qiu, R.-L., 2016. Associations between polycyclic aromatic hydrocarbon (PAH) exposure and oxidative stress in people living near e-waste recycling facilities in China. Environ. Int. 94, 161–169.

Manjunath, B.T.A., 2016. Partial replacement of e-plastic waste as coarse-aggregate in concrete. Proc. Environ. Sci. 35, 731–739.

Mary, J.S., Meenambal, T., 2016. Inventorisation of e-waste and developing a policy: bulk consumer perspective.. Proc. Environ. Sci. 35, 643–655.

Masahiro, O., Hirofumi, S., Atsushi, T., 2013. Toxic metals in WEEE: characterization and sub-stance flow analysis in waste treatment processes. Sci. Total Environ. 463–464, 1124–1132.

Milovantseva, N., Saphores, J.-D., 2013. E-waste bans and U.S. households' preferences for disposing of their e-waste. J. Environ. Manag. 124, 8–16.

Nakazawa, H., Shouming, W., Kudo, Y., 2002. Bioleaching of waste printed wiring board using thiobacillus ferrooxidans. In: Recycling and Waste Treatment in Mineral and Metal Processing: Technical and Enomic Aspects. Lulea, pp. 16–20.

Oliveira, C.R., Bernardes, A.M., Gerbase, A.E., 2012. Collection and recycling of electronic scrap: a worldwide overview and comparison with the Brazilian situation. Waste Manag 32, 1592–1610.

Pascale, A., Sosa, A., Bares, C., Battocletti, A., Feola, G., 2016. E-waste informal recycling: an emerging source of lead exposure in South America. Ann. Global Health 82, 197–201.

Patel, S., Rana, R.S., Singh, S.K., 2017. Study on mechanical properties of environment friendly aluminium e-waste composite with fly ash and e-glass fiber. Mater. Today: Proc. 4, 3441–3450.

Perkins, D.N., Drisse, M.-N.B., Nxele, T., Sly, P.D., 2014. E-waste: a global hazard. Ann. Global Health 80, 286–295.

Petridis, K., Petridis, N., Stiakakis, E., Dey, P., 2017. Investigating the factors that affect the time of maximum rejection rate of e-waste using survival analysis. Comput. Indust. Eng. 108, 15–26.

Qu, Y., Zhu, Q., Sarkis, J., Geng, Y., Zhong, Y., 2013. A review of developing an e-wastes collection system in Dalian, China. J. Clean. Prod. 52, 176–184.

Rafia, A., Muhammad, M.M., Rulia, A., Jarita, B.D., 2013. Survey and analysis of public knowl- edge, awareness and willingness to pay in Kuala Lumpur, Malaysia: a case study on house- hold WEEE management. J. Clean Prod. 52, 185–193.

Reddy, R.N., 2015. Producing abjection: e-waste improvement schemes and informal recyclers of Bangalore. Geoforum 62, 166–174.

Rhee, S.-W., 2016. Beneficial use practice of e-wastes in Republic of Korea. Proc. Environ. Sci. 31, 707–714.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–191.

Roslan, N.A., Faiz Suah, F.B.M., Noita Mohamed, N., 2018. The use of an electrogenerative process as a greener method for recovery of gold(III) from the e-waste. Sep. Purif. Technol. 182, 1–8.

Sahajwalla, V., Gaikwad, V., 2018. The present and future of e-waste plastics recycling. Curr. Opin. Green Sustain. Chem. 13, 102–107.

Sepúlveda, A., Schluep, M., Renaud, F.G., Streicher, M., Kuehr, R., Hagelüken, C., et al., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India, Environmental Impact Assessment Review 30 (2010) 28–41.

Shen, Y., Chen, X., Ge, X., Chen, M., 2018. Chemical pyrolysis of e-waste plastics: char characterization. J. Environ. Manag. 214, 94–103.

Shirodkar, N., Terkar, R., 2017. Stepped recycling: the solution for e-waste management and sustainable manufacturing in India. Mater. Today: Proc. 4, 8911–8917.

Singh, M., Thind, P.S., John, S., 2018. Health risk assessment of the workers exposed to the heavy metals in e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India. Chemosphere 203, 426–433.

Song, Q., Li, J., 2015. A review on human health consequences of metals exposure to e-waste in China. Environ. Pollut. 196, 450–461.

Spalvins, E., 2008. Impact of electronic waste disposal on lead concentrations in landfill Leachate. Environ. Sci. Technol. 42, 7452–7458.

Suzuki, G., Someya, M., Matsukami, H., Tue, N.M., Takigami, H., 2016. Comprehensive evaluation of dioxins and dioxin-like compounds in surface soils and river sediments from e-waste-processing sites in a village in northern Vietnam: heading towards the environmentally sound management of e-waste. Emerg. Contamin. 2 (2), 98–108.

Tansel, B., 2017. From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45.

Tesfaye, F., Lindberg, D., Hamuyuni, J., Taskinen, P., Hupa, L., 2017. Improving urban mining practices for optimal recovery of resources from e-waste. Miner. Eng. 111, 209–221.

Tong, X., Wang, T., Chen, T., Wang, Y., 2018. Towards an inclusive circular economy: quantifying the spatial flows of e-waste through the informal sector in China. Resour. Conserv. Recycl. 135, 163–171.

Torres, R., Segura-Bailón, B., Lapidus, G.T., 2018. Effect of temperature on copper, iron and lead leaching from e-waste using citrate solutions. Waste Manag. 71, 420–425.

Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31, 45–58.

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25 (1), 28–37.

Veit, H.M., 2015. Processing techniques. In: Veit, H.M., Bernardes, A.M. (Eds.), Electronic Waste: In Topics in Mining, Metallurgy and Materials Engineering. Springer International Publishing, Switzerland159 pp. Available from: https://doi.org.10.1007/978-3-319-15714-6.

Veit, H.M., Pereira, C.C., Bernardes, A.M., 2002a. Using mechanical processing in recycling printed wiring boards. JOM 54 (6), 45–47.

Veit, H.M., Pereira, C.C., Hörlle, L.F., Bernardes, A.M., 2002b. Recycling of metals from PCB by dense medium separation processes. In: Recycling and Waste Treatment in Mineral and Metal Processing: Technical and Economic Aspects. Lulea, pp. 16–20.

Wang, S., Zheng, Y., Yan, W., Chen, L., Zhao, F., 2016. Enhanced bioleaching efficiency of metals from e-wastes driven by biochar. J. Hazard. Mater. 320, 393–400.

Wang, M., Tan, Q., Chiang, J.F., Li, J., 2017a. Recovery of rare and precious metals from urban mines: a review. Front. Environ. Sci. Eng. 11 (5), 1. Available from: https://doi.org/10.1007/s11783-017-0963-1.

Wang, W., Tian, Y., Zhu, Q., Zhong, Y., 2017b. Barriers for household e-waste collection in China: perspectives from formal collecting enterprises in Liaoning Province. J. Clean. Prod. 153, 299–308.
Wang, Y., Wu, X., Hou, M., Zhao, H., Zhang, G., 2017c. Factors influencing the atmospheric concentrations of PCBs at an abandoned e-waste recycling site in South China. Sci. Total Environ. 578, 34–39.
Wang, Y., Hou, M., Zhao, H., Zhang, Q., Wu, X., 2018. Factors influencing the diurnal atmospheric concentrations and soil-air exchange of PBDEs at an e-waste recycling site in China. Atmosph. Pollut. Res. 9, 166–171.
Yan, X., Zheng, X., Wang, M., Zheng, J., Xu, R., Zhuang, X., Lin, Y., Rena, M., 2018. Urinary metabolites of phosphate flame retardants in workers occupied with e-waste recycling and incineration. Chemosphere 200, 569–575.
Zeng, X., Li, J., 2016. Measuring the recyclability of e-waste: an innovative method and its implications. J. Clean. Prod. 131, 156–162.
Zeng, X., Song, Q., Li, J., Yuan, W., Liu, L., 2015. Solving e-waste problem using an integrated mobile recycling plant. J. Clean. Prod. 90, 55–59.
Zeng, X., Fang, F., Li, J., Gong, R., 2017a. A simplified method to evaluate the recycling potential of e-waste. J. Clean. Prod. 168, 1518–1524.
Zeng, X., Xu, X., Boezen, H.M., Vonk, J.M., Huo, X., 2017b. Decreased lung function with mediation of blood parameters linked to e-waste lead and cadmium exposure in preschool children. Environ. Pollut. 230, 838–848.
Zhang, B., Huo, X., Xu, L., Cheng, Z., Xu, X., 2017a. Elevated lead levels from e-waste exposure are linked to decreased olfactory memory in children. Environ. Pollut. 231, 1112–1121.
Zhang, M., Feng, G., Yin, W., Xie, B., Cai, Z., 2017b. Airborne PCDD/Fs in two e-waste recycling regions after stricter environmental regulations. J. Environ. Sci. 62, 3–10.
Zhang, M., Guixian Feng, G., Wenhua Yin, W., Bing Xie, B., Zongwei Cai, Z., 2017c. Airborne PCDD/ Fs in two e-waste recycling regions after stricter environmental regulations. J. Environ. Sci. 62, 3–10.
Zhang, W., Liu, Z., Xia, J., Li, F., He, W., Li, G., et al., 2017d. Preparing graphene from anode graphite of spent lithium-ion batteries. Front. Environ. Sci. Eng. 11 (5), 6. Available from: https://doi.org/10.1007/s11783-017-0993-8.
Zhang, Y., Xu, X., Sun, D., Cao, J., Huo, X., 2017e. Alteration of the number and percentage of innate immune cells in preschool children from an e-waste recycling area. Ecotoxicol. Environ. Saf. 145, 615–622.
Zhang, Z.-Y., Zhang, F.-S., Yao, T.Q., 2017f. An environmentally friendly ball milling process for recovery of valuable metals from e-waste scraps. Waste Manag. 68, 490–497.
Zhang, Y., Xu, X., Chen, A., Davuljigari, C.B., Huo, X., Francisco Pena-Pereira, F., et al., 2018. Maternal urinary cadmium levels during pregnancy associated with risk of sex-dependent birth outcomes from an e-waste pollution site in China. Reprod. Toxicol. 75, 49–55.
Zhong, H., Huang, L., 2016. The empirical research on the consumers' willingness to participate in e-waste recycling with a points reward system. Energy Proc. 104, 475–480.

Further reading

Anonymous, 2008. Guidelines for Environmentally Sound Management of E-Waste (As approved vide MoEF letter No. 23-23/2007-HSMD dt. March 12, 2008) Ministry of Environment & Forests. Central Pollution Control Board, New Delhi, p. 86.

Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., The Global E-Waste Monitor, 2017. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna. ISBN Electronic Version: 978-92-808-9054-9.

Benedetti, M., Cafiero, L., Angelis, D.D., Dell'Era, A., Pasquali, M., Stendardo, S., et al., 2017. Pyrolysis of WEEE plastics using catalysts produced from fly ash of coal gasification. Front. Environ. Sci. Eng. 11 (5), 11. Available from: https://doi.org/10.1007/s11783-017-0998-3.

Borowski, N., Trentmann, A., Brinkmann, F., Sturtz, M., Friedrich, B., 2018. Metallurgical effects of introducing powdered WEEE to amolten slag bath. J Sustain. Metall. . Available from: https://doi.org/10.1007/s40831-018-0159-3.

Capraz, O., Polat, O., Gungor, A., 2017. Performance evaluation of waste electrical and electronic equipment disassembly layout configurations using simulation. Front. Environ. Sci. Eng. 11 (5), 5. Available from: https://doi.org/10.1007/s11783-017-0992-9.

Distin, P.A., 1995. Metals recovery from electronic scrap using mineral processing methods. In: 34th Annual Conference of Metallurgists of CIM. Vancouver, Canada, pp. 245−252.

Felix, N., Riet, C.V., 1994. Recycling of electronic scrap at um's hoboken smelter. In: International Precious Metals Conference. Vancouver, Canada, pp 159−169.

Friedrich, B., 2018. Preface to innovations in WEEE recycling. J. Sustain. Metall. 4, 155−156. Available from: https://doi.org/10.1007/s40831-018-0182-4.

Gloe, K., Mühl, P., Knothe, M., 1990. Recovery of precious metals from electronic scrap, in par- ticular from waste products of the thick-layer technique. Hydrometallurgy 25, 99−110.

Hayes, P.C., 1993. Process Principles in Minerals and Materials Production. Hayes Publishing Co, Brisbane, p. 29.

Hoffmann, J.E., 1992. Recovering precious metals from electronic scrap. JOM 44 (7), 43−48.

Kasapo, P., Nordin, N.A.M., 2015. E-waste flow among selected institutions of higher learning using material flow analysis model. Resour. Conserv. Recycl. 105, 177−185.

Li, Y., Duan, Y.-D., Huang, F., Yang, J., Chen, L., 2014. Polybrominated diphenyl ethers in e-waste: level and transfer in a typical e-waste recycling site in Shanghai. Eastern China. Waste Manag. 34, 1059−1065.

Lu, B., Song, X., Yang, J., Yang, D., 2017. Comparison on end-of-life strategies of WEEE in China based on LCA. Front. Environ. Sci. Eng. 11 (5), 7. Available from: https://doi.org/10.1007/s11783-017-0994-7.

Lu, X., Xu, X., Zhang, Y., Zhang, Y., Huo, X., 2018. Elevated inflammatory Lp-PLA2 and IL-6 link e-waste Pb toxicity to cardiovascular risk factors in preschool children. Environ. Pollut. 234, 601−609.

Pablo Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian e-waste recycling scheme. J. Clean. Prod. 197, 750−764.

Pozzo, R.L., Malicsi, A.S., Iwasaki, I., 1991. Removal of lead from printed circuit board scrap by an electrodissolution-delamination method. Resour. Conserv. Recycl. 5, 21−34.

Ruan, J., Dong, L., Zheng, J., Zhang, T., Xu, Z., 2017. Key factors of eddy current separation for recovering aluminum from crushed e-waste. Waste Manag. 60, 84−90.

Sum, E.Y.L., 1991. The recovery of metals from electronic scrap. JOM, Abstract, pp. 53−61.

Tenório, J.A.S., Menetti, R.P., Chaves, A.P., 1997. Production of non-ferrous metallic concentrates from electronic scrap. TMS Ann. Meet. EUA, Orlando, pp. 505−509.

Vanegas, P., Peeters, J.R., Cattrysse, D., Dewulf, W., Duflou, J.R., 2017. Improvement potential of today's WEEE recycling performance: the case of LCD TVs in Belgium. Front. Environ. Sci. Eng. 11 (5), 13. Available from: https://doi.org/10.1007/s11783-017-1000-0.

Vouvoudi, E.C., Rousi, A.T., Achilias, D.S., 2017. Thermal degradation characteristics and products obtained after pyrolysis of specific polymers found in Waste Electrical and Electronic Equipment. Front. Environ. Sci. Eng. 11 (5), 9. Available from: https://doi.org/10.1007/s11783-017-0996-5.

Zhang, S., Forssberg, E., 1997. Mechanical separation-oriented characterization of electronic scrap. Resour. Conserv. Recycl. 21, 247−269.

Zhang, S., Forssberg, E., 1999. Intelligent liberation and classification of electronic scrap. Powder. Technol. 105, 295−301.

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Socio-technological challenges in formalization of E-waste recycling in India

11

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E-waste is mainly recycled in two sectors: the informal and the formal sector. In the developed countries E-waste is processed by the formal sector while informal recycling is dominantly practiced in the developing countries like Africa, Nigia, Malaysia, China, and India. The main objective of this study is to explore the technologies used in recycling of E-waste in the formal sector in India and to identify the major challenges faced by the formal recyclers during operation. To have a better understanding of the recycling process and problems associated with formal E-waste recycling, two registered formal recycling organizations in Delhi-NCR, that is, Attero Recycling Pvt. Ltd. and SIMS Recycling Solutions were visited and interviewed. Secondary data regarding the techniques used for recycling and challenges faced by the other formal recyclers in India were also collected and analyzed to have a broader understanding of major issues related with E-waste recycling in the country.

The major findings of this study indicate that the formal recyclers have to face stiff competition from the informal recyclers who have a better approach to the consumers. Lack of awareness, strict implementation and monitoring are the major issues faced by these recyclers. Hence, the study suggests proper implementation of the law and raising awareness regarding the benefits of proper recycling of E-waste in the country.

11.1 Introduction

Sustainable E-waste recycling and management has emerged as a major environmental challenge especially in developing countries like Malaysia, Indonesia, Nigeria, India, and China in the last two decades. The developed countries, to a large extent, have been successful in overcoming this problem through proper implementation of E-waste management policies and formalization of recycling and material recovery process. In developing countries like India, the E-waste recycling is still dominantly performed in the informal sector due to availability of cheap labor, lack of awareness among people, and the ineffective implementation of the existing rules by the monitoring agencies/institutions. There are many social and

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00016-4

environmental repercussions of informal processing of hazardous substances like E-waste. Since the informal sector is not registered, labor laws, occupational health standards, and the social security measures could not be extended to the workers involved in E-waste recycling. Moreover, the workers involved are not trained for handling such type of hazardous waste and fall to the consequences of improper dismantling and recycling. Though many awareness campaigns and efforts to educate the E-waste workers have been taken up by some NGOs working in this area, there is still rampant processing of E-waste in crude manner.

In pursuance of the E-waste (Management and Handling) Rules 2011 which came into effect from May 1, 2012, the state agencies (Central and State Pollution Control Boards) started the registration of companies interested in collection, dismantling, and recycling of E-waste in the country. Although the number of registered recyclers/collectors has grown throughout the country, the major portion of E-waste is still flowing to the informal sector.

As per the CPCB latest data (2016), there are 178 registered E-waste recyclers/dismantlers spread throughout the country with their total capacity of approximately 438,086 MT of recycling annually (Table 11.1). The total E-waste generated (internally and also imported) in India was 332,979 MT in 2007 which increased up to 713,770 MT in 2015 and it is projected that by 2025 the volume of E-waste in India would be 1,851,337 MT (Chatterjee, 2011). It is not only the shortage of the recycling capacity of the formal sector, it has been also reported that most

Table 11.1 Registered formal recyclers/dismantlers in India with permitted recycling capacity (as on December 29, 2016).

S. No.	State	No. of registered recyclers/dismantlers	Total permitted capacity of in (metric ton per year)
1	Chhattisgarh	02	1650
2	Gujarat	12	37,262.12
3	Haryana	16	49,981
4	Karnataka	57	44,620.5
5	Maharashtra	32	47,810
6	Madhya Pradesh	03	8985
7	Odisha	01	N.A.
8	Punjab	01	150
9	Rajasthan	10	68,670
10	Tamil Nadu	14	52,427
11	Telangana	04	11,800
12	Uttar Pradesh	22	86,130
13	Uttarakhand	3	28,000
14	West Bengal	1	600
15	**Total**	**178**	**438,085.62 (approximately 438,086)**

Source: http://cpcb.nic.in/cpcbold/List_of_E-waste_Recycler_as_on_29.12.2016.pdf.

of the formal recyclers are operating at underutilized capacity of their plants (Agarwal and Nair, 2015).

This has become a major challenge for the formal recycling organizations as it is difficult for them to get adequate volume of E-waste. As a result most of the existing plants are working underutilization of their capacity. In this study we attempted to explore the challenges involved in formalization of E-waste recycling in India. While analyzing the recycling process and techniques adopted by the registered recyclers, we made a comparative analysis with informal sectors/actors to explicate the challenges. We found that there are not only legal challenges, but also social, economic, and political challenges that need to be addressed in making of any policy or programs for formalization of E-waste recycling in India.

The study also discusses the major formal recyclers which are registered under CPCB to understand their functioning, the technologies they use and challenges faced by them during operation. To get in depth understanding to their functioning case study has been done on two formal recyclers in Delhi-NCR: Attero Recyclers Pvt. Ltd and SIMS Recycling Solutions. This study would also try to explore the issues and major problems in the process of formalization of the E-waste recyclers in the country.

11.2 Review of literature: recycling of E-waste in India

In India 95% of E-waste is recycled by the informal sector and only 5% is processed through the formal channel (Rochat et al., 2008). The workers in the informal sector use very crude and dangerous methods for treatment of E-waste. They dismantle old electronic equipment with electric drill, cutter, hammer, and screw driver into components parts such as monitor, hard drive, CD drives, wires, cables circuit boards, transformers, charger, battery, and plastic and metal frame. They sell these items for reuse or to workshops for further recycling. The circuit board of computers and other large appliances are heated over coal fires to melt the solder to release valuable electronic components, such as diodes, resistor, and microchips. The microchips and other parts are soaked into concentrated acid to reclaim the precious gold and palladium and the residue waste acids are discharge into nearby field or waterbodies. Wires and cables are stripped or simply burnt to extract metals. Printer cartridges are ripped apart for their tonner and recyclable aluminum, steel, and plastic parts. The different category of plastics are sorted manually by workers on the basis of rigidity, color, and luster and the plastic which could not be sorted visually are burnt and classified by the burning odor. These primitive methods of E-waste processing exposes not only the workers but the nearby residents also to the toxic pollutants emanating from the E-waste processing. The processing of E-waste in the informal sector is not only health and environmental hazards but also give a very low recovery of precious materials from E-waste (Yu et al., 2010).

Some scholars have suggested that customers need to be given incentives to return their end of life (EOL) e-products back to the collection center by enforcing a buy-back policy. Once a product reaches the end of its useful life, the producers would buy it back from the consumers at a price higher than that of the informal sector, thereby cutting off the supply to this sector and ensuring that E-waste goes to the right channel. This additional cost to the manufacturer could be offset by increasing the selling price of new products (Dwivedy et al., 2015:13). It has been found that consumers in developing countries look for economic benefits for discarding their E-waste (Wang et al., 2010; Dwivedi and Mittal, 2013) and hence imposing any recycling fee would be strongly resisted by them. Dwivedy et al. (2015) in their study found that EPR model practiced in developed countries is likely to fail in India because it imposes cost to consumers. Therefore individual take back scheme based on payment to consumers seem workable in Indian context.

Because of these problems it is necessary to increase the public awareness about the effects of exposure from the deadly chemicals emanating from the processing of E-waste. It is more important to adopt responsible management strategies to minimize the E-waste production and making the E-waste components more easily recyclable and reusable.

According to a study by *Toxics Link*, these operations are very well connected to the supply chain processes of sourcing the raw materials to finding markets for the recovered materials (Sinha and Mahesh, 2007). This study states that the actual processing of E-waste is done in small clusters usually on the periphery of the city. Another study by Srivastava et al. (2011) also states that the operations carried out by the informal workers include collection of E-waste, sorting, transportation, and dismantling and finally recovery of materials. The material recovery processes include open burning, acid bath, and heating of lead solders (Sinha and Mahesh, 2007).

The formal sector in India uses both manual and automated technologies for dismantling, segregation and recycling of E-waste. The workers employed are trained for this job. These methods are safe for both the environment and the workers involved.

The general steps followed by the formal sector for recycling of E-waste are collection, disassembly or segregation, and recycling.

The processes used in the informal sector are considered harmful for both human health as well as the environment. Hence, formalization of this sector has been recommended in many studies (Khattar et al., 2007; Rochat et al., 2008; Raghupaty et al., 2010; Chaturvedi et al., 2010; Williams et al., 2013) in order to prevent the hazardous impact of improper E-waste recycling. Besides the health and environmental consequences of informal E-waste processing, the industry is also often affected with the negative employment, spatial, and economic correlates of informality. While earning can be good, especially for the poor and illiterate, less educated, the work place typically have poor health and safety condition, job stability, and social security benefits, and child labor is prevalent (Umair et al., 2015; Pandey and Govind, 2014). It has been also noted that the regions that host informal recycling hubs often have uncontrolled dismantling and disposal sites, with noise, emissions, and rubbish marring the landscape and causing tensions within communities.

The industry is often predicted on criminal and corrupt activities to assure the supply, transport, and sale of materials, and the operation of dubious facilities, while tax evasion means that revenues are not fed into systems intended to provide broader infrastructure, services, and investment. The negative sides of informal sectors have been widely studied and emphasized but the positive sides and the pathways for transitioning from informal to formal recycling has not been explored adequately particularly in developing countries, particularly when informal sector is dominating.

E-waste recycling has been able to provide a much needed source of income to population unable to find formal employment. For instance, Duan and Eugster (2007) estimated that in 2005, five million people were employed in the E-waste reuse industry in China, and in 2007 an additional 0.7 million in the E-waste recycling industry.

To understand the problems in formalizing this sector, it is important to have the knowledge about the functioning of the formal sector. Some of the major recycling companies and the technologies and approaches used by them in India have been discussed in Sections 11.2.1−11.2.2.

11.2.1 Predominance of informal sector

Many studies have noted the existence of informal, hazardous recycling practices of E-waste in the developing countries (Puckett et al., 2002; Osibanjo and Nnorom, 2007; Gullett et al., 2007; Sepulveda et al., 2010) and have highlighted the associated problems of crude recycling process on the health and environment. While recognizing the problems of informal recycling of E-waste, many scholars have underlined the importance of formalization of E-waste recycling in India. Jha et al. (2011) in their study underlined the importance of the use of environmentally safe technologies for recycling of E-waste and extraction of precious metal from E-waste. They estimated the scope and prospective of E-waste recycling in the formal sector in Chaterjee and Kumar (2009) analyzed the informal as well as formal E-waste recycling practices in India and suggested linking of the two sectors to make recycling sustainable in Indian context.

Reddy (2013) in his study pointed out how the upcoming regulation in E-waste recycling has disconnected the informal workers from their livelihood. While studying the plight of informal E-waste recyclers in Bangalore, he found that there were many informal recyclers who wanted to get themselves registered. He noted that the informal recyclers are required to undergo lengthy and complex process/"tough struggle" in order to complete the registration process and in this process they also lose their territorial claim over the collection of E-waste. The process of formalization have given the "big players" a monopoly in E-waste recycling business. Despite formalization there is no audit for the authorized recyclers and hence they adopt "self-regulatory standards" (Reddy, 2013). Reddy (2013) noted that the informal recyclers have not benefited from formalization rather they become vulnerable to losing their livelihood. However, Reddy (2013) did not point out what types of recycling technology formal recyclers are using and how that helped them to maximize their profits and offer competitive price to consumers/disposers for selling their E-wastes to them.

Thus, one can see it that most of the studies have emphasized on the need for formalization of informal E-waste sector, but very few studies that have analyzed the problems faced by E-waste recyclers in the formal sector. In Indian context, although scholars have suggested the importance of linking informal sector with formal sector, there is very little understanding about the challenges of formalizing the informal sector or linking it with the formal sector. Wang and Huisman (2010) in their study of two pilot projects in China tried to understand the issues related to formalization of E-waste recyclers. Based on the experience of developed countries these two pilot projects were started in 2009 in China to formalize the collection of E-waste and to adopt environmentally safe technologies for E-waste recycling. This study suggested to make the provision of subsidy for the "formal recyclers" to collect E-waste from the consumers as it may help them to have some profitable business and encourage them for more collection. The authors also recommend adoption of a locally viable recycling strategy that can involve the local informal recyclers and provide them training to work under environment as well as health safety norms. The study also counts public education regarding E-waste awareness as an important tool to solve this issue.

Lundgren (2012) conducted a study for ILO to understand the problems associated with the E-waste recycling and argued for formalization of E-waste recycling in developing countries like China.

The process of integrating the informal sector with the formal sector is a challenging task at multiple level. On one hand, there is scarce information about the diversity of networking amongst the informal recyclers and their distribution of task and finances among various stakeholders.

11.2.2 Formal and informal interaction

In the literature, one may find a continuum of the degree of integration of informal E-waste recyclers with the formal recyclers. This ranges from those advocating a prohibition of informal recycling, through those ignoring their existence, to those where the sector is recognized but pressed to conform to and compete with the formal sector and to those who argue to integrate the strengths of the informal sector with the formal. In the other words, the approach could be seen as hostile, disconnected, interacting, and synergetic (Davis and Garb, 2015).

Hence, the present study tries to explore the possible hurdles in the process of organizing the informal E-waste recyclers in India, challenges and concerns of the formal E-waste recyclers specifically in the Delhi-NCR. Previous studies available in this area and insights from the interviews conducted helped this study to focus on the challenges associated with recycling of E-waste in the formal sector in India.

11.3 Methodology

In order to understand the challenges involved in the formalization of E-waste recycling, we conducted interviews (in formal as well as informal settings) with the formal recyclers, policy makers, and officials involved in the implementation of the regulatory provisions and the individual and bulk consumers. Consumers were asked about their disposal process of E-waste and to conduct this research data have been collected from both primary as well as secondary sources. For primary data the formal recyclers in the Delhi-NCR were interviewed and a semistructured questionnaire was also used to gather the required information. Along with this notifications and guidelines issued by Government of India were also analyzed. The prevalent methods and techniques of E-waste recycling in India were explored based on previous studies and reports. In order to explore the problems of formal recyclers we studied two-registered formal recyclers in NCR.

11.4 Formal recycling technologies used in India

As discussed earlier, there are at present total 178 registered formal E-waste recyclers/dismantlers in India. These recyclers have adopted environmentally safe methods for treating the E-waste. For collection of E-waste, the formal recyclers are either contacted by the bulk consumers, household consumers or government or private offices or they bid for procuring the E-waste from government and private organizations. Many of these recyclers either have their own collection vehicles or hire it from the logistics company. Some of the recyclers also provide door to door collection as a part of their collection drives or awareness programs. For disassembly, either manual or semiautomated methods are employed. The workers who are involved in dismantling of E-waste are provided with safety gadgets like eye shields, safety jackets, gloves, and ear plugs.

A general flow chart of E-waste recycling process adopted in formal recycling facilities in India has been depicted in Fig. 11.1.

According to this process, initially the collected E-waste is segregated according to the parent product and then it is sent for dismantling. The components like solder, battery, and cables are obtained after dismantling the electronic gadgets. The components like PCBs and plastics are put through mechanical shredding to separate the ferrous, nonferrous, and plastic materials. The shredded materials are further crushed and then sent for segregation where the precious metals like gold, silver, and palladium are recovered. In India most of the recyclers do not have the capacity for the extraction of pure metals from the crushed E-waste and they export the material to recycling companies in the developed countries like Umicore, Xtrata, and TESSAM for further processing (Sinha et al). These components are further sent for recycling to obtain metals like tin, lead, nickel, and lithium. The hazardous substances present which cannot be recycled are sent to the hazardous waste treatment facilities.

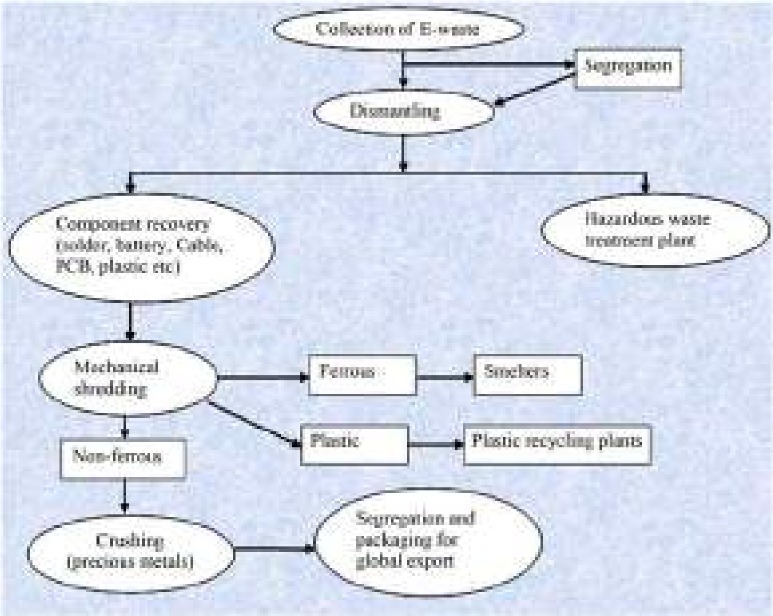

Figure 11.1 E-waste recycling process in formal sector in India.
Source: Compiled from various sources.

Recycling of PCBs is an important process in the E-waste recycling industry as it contains precious metals like gold and silver. The first step in this process includes grinding of segregated PCB into desired particle size by mechanical process which includes physical impaction,[1] shredding,[2] and granulation. Further concentration of the precious metals is done by various separation techniques. Magnetic separation technique is used to separate the ferrous elements from the crushed PCBs while the aluminum particles are separated by using eddy current process (Chaterjee and Kumar, 2009). This metal rich powder then passes through electrostatic separation technique to remove the plastic parts. After this step the metal rich powder is sent for metal recovery. This is done either by hydrometallurgical or pyro-metallurgical methods. In hydrometallurgy chemical processing is done while in pyro-metallurgical process, metals are extracted using thermal treatment. In thermal treatment, the problem of disposing liquid effluents is avoided. Hence, thermal incineration combined with pyro-metallurgical treatments is used commercially for extraction of metals from PCBs. The hydrometallurgical methods are also used for metal recovery. In this process, thermal processing is followed by

[1] Physical impaction comprises methods which break down products to enable the recovery of reusable and recyclable parts, components, and materials.

[2] Shredding is the breakdown of the product into pieces via fragmentation, ripping, or tearing which may then be sorted into differing material streams with dissimilar subsequent processing demands.

electrolytic refining for purification of copper. For the recovery of gold from PCB, cyanide solution is generally used.

Generally the above mentioned methods are used in formal E-waste recycling in India. However, research is going on to develop better techniques which are more environmentally safe. Various biological and hybrid techniques have been suggested different studies (Bhatt et al., 2012; Pant et al., 2012) that need to be tested on field to confirm its commercial use. Therefore to explore the problems in the process of recycling E-waste in the formal sector case study of two registered recyclers in Delhi NCR was conducted. The following paragraphs discuss the challenges faced by these recyclers during recycling and management of E-waste in the country.

11.5 Formalization of E-waste recycling in India

In the recent years Government of India has taken several steps for formalization of E-waste recycling, in India. The first serious step to formalize the process was the enactment of E-waste (Management and Handling) Rules 2011 which came into effect from May 1, 2012. The rule made the registration of E-waste recyclers a mandatory process without which they may not be allowed to process the E-waste. The recyclers were made to ensure that their facility and the recycling process complied with the standards or guidelines as prescribed by the Central Pollution Control Board from time to time. In the case of state recyclers ware required to obtain registration from the SPCBs. The rule also enjoined upon all registered recyclers to make all the records available to the Central or State Pollution Control Boards or Pollution Control Committees of Union territories for their inspection. They also need to ensure that the residue generated should be disposed of only at authorized common hazardous waste Treatment Storage Disposal Facility (TSDF). In addition to these responsibilities, the recyclers were also required to file annual returns in Form 3 to the SPCB or Pollution Control Committee as the case may be on or before 29 June following the financial year to which those returns relate. However, various issues like social and economic implications, positive and negative drivers of current E-waste scenario in India have not been addressed properly. Since most of the recycling activities are taking place in the informal sector the rule does not mention steps for formalization of these informal activities. There is also no clarity in the mode of collecting E-waste from the consumers, which may create problem. Furthermore no role for the informal sector which process a large segment of E-waste has been mentioned in the new rule.

Considering some of the shortcomings of the E-waste (Management and Handling) Rules, 2011 some modifications were made in 2015 and the new rules were published as “E-waste (Management) Rules 2016” which came into effect from October 1, 2016. The new rules have added some more responsibilities for the E-waste recyclers. As per the new rules the recyclers will be responsible to ensure that no environmental damage is caused during the storage and transportation of

E-waste and the recycling process do not cause any adverse effect on health and environment. They have also to make sure that the fractions or materials which are not recycled in their facility are transferred to respective authorized recyclers. More stringent provision were made for the recyclers to maintain the record of the total E-waste collected, dismantled, recycled, and sent to authorized recyclers in Form 2 and copying the same to the CPCB or SPCB as the case may be.

As a consequence of the new regulation many E-waste recyclers have applied for registration either with the State Pollution Control Boards or the Central Pollution Control Board. As a consequence, the number of registered formal recyclers/dismantler with Central Pollution Control Board (CPCB) has increased to 178 in the country. The State-wise distribution of the registered recyclers/dismantlers has been given in Fig. 11.2.

It can be observed from the list that Karnataka has the largest number of registered recyclers/dismantlers in the country followed by Maharashtra and Uttar Pradesh. Each formally registered recycler has been permitted by the Ministry of Environment and Forest to process a certain quantity of E-waste annually. The permissible volume has been given in Table 11.1.

From Table 11.1 it can be observed that the total annual volume of E-waste permitted to be recycled at the available registered E-waste recycling facilities is approximately 438,086 metric tons. On the other hand the E-waste generation in India in the year 2013 was estimated to be 589,893 metric tons and for the year 2015 the projected figure was 713,770 metric tons (Silva, 2012). This shows that there is a huge gap between the capacity of registered recyclers and the amount of E-waste generated annually. This problem is further aggravated when the registered recyclers face the problem of underutilization of their installed or permitted

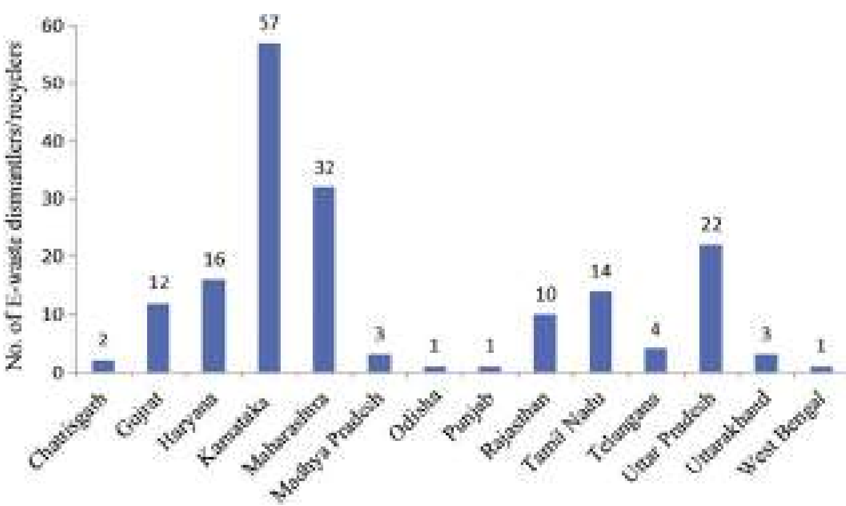

Figure 11.2 State-wise distribution of registered recyclers/dismantlers in India.
Source: CPCB Data as on 29.12.2016 (Available at: cpcb.nic.in).

capacity. The previous studies (Arora, 2008), (Christian, 2012) have pointed out that due to the flexible regulatory mechanisms and lack of awareness among the consumers, a large chunk of E-waste is diverted toward informal sector. The formal recyclers need finances to maintain the infrastructure of the recycling plants due to which they cannot compete with the value for E-waste provided by the scrap dealers.

There are many reasons why the local scrap dealers are able to pay more for the E-waste than the registered dealers. The local scrap dealers sell their E-waste to informal recyclers who use very crude and hazardous recycling techniques like open incineration and acid stripping for extracting metals from E-waste. In this process they use concentrated acids (sulfuric and nitric acid) and other poisonous chemicals which over the time end up polluting the environment. Such primitive methods for metal extraction result in incomplete processing of E-waste which lead to pollution, health hazards. As they lack funds and technical expertise these informal recyclers end up performing inefficient metal extraction. Since transporting the residue and effluents safely to the registered TSDFs is not feasible for the informal recyclers, they dispose them in nearby waterbodies or dump in landfills. The toxins thus leach into the soil and groundwater and pollute the ecosystem.

Another reason for informal sector paying more for the E-waste is that they do not require to make any investment in infrastructure or safety measure. Recycling establishment in the informal recycling sector typically have a scrap yard setup, where workers handle toxic E-waste components under hazardous working conditions, sometimes even without proper ventilation or lighting (Pandey and Govind, 2014). Workers keep their hands dipped for long hours in poisonous chemicals and are exposed to fumes of concentrated acids while processing E-waste. Safety gear like gloves, ventilations fans, and face masks are unheard of as these setups do not invest in the required protective gear for handling toxic materials. This puts workers at a risk of developing serious health conditions like asthma, bronchitis, and even cancer.

In order to cut down the cost, the informal sector employs large number of women and children for collecting and dismantling E-waste. One can see many young children collecting/breaking integrated circuits, capacitors from PCB with their bare hand, without taking any form of protection from the hazardous toxins in E-waste. Since these children are still in a developing stage they are at a higher risk of absorbing high proportion of hazardous chemicals developing severe medical conditions.

On the other hand, the registered recyclers are subjected to a highly regulated operation as it involves disposal and recycling of toxic and hazardous electronic components. Government and environmental bodies regularly conduct audits to ensure that E-waste recycling facilities deploy environmentally responsible and safe recycling processes. However, E-waste recycling operations in the informal sector are not regulated by any environmental or government bodies, as it would require them to invest in adopting green and eco-friendly E-waste recycling processes.

Since E-waste recycling establishments in the informal sector are unregulated and unregistered with the respective government bodies, they also evade taxes.

Registered recyclers on the other hand are subject to taxes under law for establishing E-waste recycling facilities. These are the primary reasons for E-waste recyclers in the informal unorganized sector being able to pay consumers more for their E-waste as compared to registered E-waste recyclers. The cost conscious consumers in India required to be sensitized for disposing of their E-waste through registered and authorized dealers.

11.6 Initiatives for formalization of E-waste recycling in India

Despite the enforcement of the E-waste Management and Handling Rules 2011 and 2016, most of the E-waste recyclers in the country are still operating through the informal sector. In the recent years the government in collaboration with some NGOs like GIZ-ASEM has undertaken the responsibility to create awareness about the hazards of E-waste among the informal workers.[3] Some of these organizations are *Toxics Link*, *Chintan* and *WEEE Recycle* (an association of GIZ and MAIT). These NGOs are involved in interacting with the informal recyclers as well as the general public to create awareness about the hazards of informal recycling of E-waste. Chintan, for instance, worked in association with Delhi Pollution Control Committee for formalization of informal E-waste recyclers in Delhi. Similarly, *Toxics Link* is an NGO working on waste and pollution issues. The *Toxic Link* has led several awareness programs in schools and colleges and has initiated training programs for different stakeholders associated with E-waste management throughout the country.

They have organized various workshops on the benefits of formalization as a result of which some members from HRWA and 4 R have formed two formal collection and dismantling companies named *E-waste HRA Pvt. Ltd*. (2010) and *Green E-waste Recyclers Pvt. Ltd*. (2011) in Delhi. These two recyclers collect and segregate the E-waste and then channelize it to authorized formal recyclers.

The *E-waste HRA Pvt. Ltd*. has set up its center in Delhi to collect, segregate, and store the E-waste from about two hundred and fifty informal collectors and dismantlers. The E-waste collected is then auctioned to the formal recyclers (Garide, 2014). The company has also signed letter of intent with *SIMS Recycling Pvt. Ltd*. and *Earth Sense Recyclers*, two formal E-waste recyclers of Delhi-NCR (Resources-Formalization of Informal Sector), for further treatment of E-waste. The other company, that is, *Green E-waste Recyclers Pvt. Ltd*. was formed in 2011 and is also engaged in collection, segregation, and storage of E-waste. The collected material is then transferred to authorized dismantlers and recyclers of E-waste. The

[3] ASEM is a joint program of the MoEF, Govt. of India and German International Cooperation (GIZ) on behalf of the Federal Ministry for Economic Cooperation and Development, Germany. This program focuses on the urban and industrial environmental management in India.

company has also applied to get registered as an E-waste dismantler (Sohail and Vasudev, 2013).

Similarly in Bangalore, *EWarDD* and *Eco BiRRD* have been registered as the formal E-waste recycling companies changing from their informal status. Besides these few cases, the shift from informal to formal has not taken place on a wider scale due to several problems. The informal sector in India is still very large and very few are aware of the harmful impact as well as the benefits of formalization. This may be the reason that these initiatives could not inspire a majority of informal E-waste recyclers to get registered.

11.7 Challenges faced by formal recyclers in Delhi-NCR

In order to understand the challenges faced by the formal recyclers in India we conducted a few case study in NCR. In Section 11.7, we have discussed in details about their challenges. An informal interviews were conducted with the officials at the Noida office to understand their procedure of E-waste handling and the challenges they face.

11.7.1 Attero Recyclers Pvt. Ltd

The Attero Recyclers Pvt. Ltd. was established in the year 2007 and is India's largest integrated end to end electronics assets management company situated in Roorkee (Uttarakhand). It provides services like customized end to end solutions for E-waste management, electronics asset recovery, data security, and electronics reverse logistics along with repair, refurbishment, and retailing of electronics. It is an ISO14001[4] and OHSAS 18001[5] certified company. *Attero* has a 100,000 square feet state-of-the- art facility for E-waste management at Roorkee (Uttarakhand) with having first of its kind of metallurgical process. Along with complete processing of E-waste they also provide facility for picking up E-waste from the premises of the consumers.

Attero claimed that its reverse logistics can move about 10,000,000 pounds of material each month. It also provides an online/offline channel for collection of E-waste from the end use consumers. It has its offices in Noida, Bangalore, Mumbai, and Roorkee in India and one also in Los Angeles, United States. It has been reported that *Attero* collects E-waste from about 500 cities and has its collection centers across 22 states throughout the country (Jacob, 2013). The company collects

[4] ISO 14001 sets out the criteria for environmental management system. It maps out a framework that a company/organization can follow to set up an effective environmental management system. It provides assurance to company management, employees, and external stakeholders that environmental impact is being measures and improved.

[5] OHSAS 18001stands for Occupational Health and Safety Assessment Series. It is an internationally applied British Standard for occupational health and safety management systems. It is intended to help an organization to control occupational health and safety risks.

the E-waste at major collection centers (http://mait.com/ewaste/collection-centers.html) and from there it sends the E-waste to its Central recycling plant located at Roorkee (Uttarakhand). Its each collection center is authorized by the Pollution Control Boards of the respective government of the state. The collected E-waste is stored at these centers, lined up, and then transported to the recycling plant. The total recycling capacity of the plant was told to be 35,000 metric tons but due to the lack of availability of enough waste material, they recycle only 12,000 metric tons. One of its official informed that the main sources of their E-waste collection are the bulk consumers and the manufacturers.

11.7.2 SIMS Recycling Solutions (Noida)

SIMS was founded in the year 1917 in Sydney by a recycled metals dealer and was initially a scrap metal recycling company. Later the company expanded its business in Europe and North America. In 2008, *SIMS* Group merged with an American scrap metal recycling company, Metal Management, to form Sims Metal Management Limited. It was in the year 2002 that it became Sims Recycling Solutions in UK to handle the issue of E-waste. The company was established in India in 2008 when Trishriraya (Chennai) became SIMS Recycling Solutions first center in India. In 2010, Sims acquired TIC Group in India (Delhi). Currently, *SIMS* has over 40 facilities throughout the globe and recycles approximately 735,000 tons of E-waste each year. In India, *SIMS* has its centers in Bangalore, Chennai, and Delhi. For this study, the Delhi center was selected. The official interviewed at *SIMS* informed that they mainly get E-waste from government offices along with some other bulk consumers. *SIMS* has been recognized as a registered recycler by Delhi Pollution Control board and hence, the consumers contact them through the government website. The company is permitted to collect about 500−1000 metric tons of E-waste annually in India but practically they are able to collect only about 200 metric tons. *SIMS* at Noida has permission only for dismantling and segregation of E-waste. At this site, the equipments are dismantled in various components and for this process they use both manual force and machines.

The common problem, that most of the respondents from the companies narrated, was the competition from the informal recyclers in the city. They suggested that most of the households as well as the bulk consumers including the IT companies prefer to sell their E-waste to the scrap dealers as they pay more value for their waste than what we may pay them. "We cannot buy the E-waste at high rates as we have to make a large investment for operating and maintaining the recycling plant as per the norms and standard set by the government," stated the interviewed official.

Many studies have indicated that due to lack of awareness about the hazardous nature of E-waste among the public, they dispose of their E-waste through informal dealers. For instance, Kwatra et al. (2014) conducted a study in Delhi and observed that though 58% of the respondents, most of which were associated with the field of environmental science, were aware about the term "E-waste" only 4% could describe the exact issue and the problems related to it. The authors also found

Table 11.2 Differences in the rate of procurement by informal and formal E-waste collector.

Items	Price offered by informal market (in Rs.)	Price offered by formal recyclers (in Rs.)	Difference in price (in Rs.)
Hard disk	45 per piece	Rs. 20 per piece	25
CPU	300−400 per unit	100 per unit	200−300
Mobile phone (fully intact without battery)	1000 per kg	600 per kg	400
Mobile phone boards (plates)	1900 per kg	800 per kg	1100
Chargers	100−250 per kg	20 per kg	80−230
Refrigerators	1000	Offered no money due to cost of disposal.	1000
Television	Depends on screen size. Rs. 500−1000	Free of cost due to leaded glass and cost of disposal	500−1000

Source: Field work data collected from the scrap dealers and formal recyclers.

respondents who were using Internet were more familiar with the term E-waste than those to those who were not using the Internet. When they were told about the hazardous nature of E-waste most of the respondents agreed that some action should be taken to solve this problem. A similar study (Saritha et al., 2015) was conducted in Vishakhapatnam to understand the level of awareness on E-waste among the respondent and it was found that 90% were unaware about the issue. The authors also indicated that 75% of the respondents store their E-waste because they don't know the proper mode of disposal.

Similarly, another research (Venkatraman, 2015) conducted on a group of students in Mumbai and it was reported that about 62% of the respondents do not know the details about the electronic waste or E-waste though they were familiar with the term.

Most of our respondents also informed that lack of awareness among the public about the E-waste and the benefits of proper recycling were the major problem they face in getting sufficient amount of E-waste for proper recycling and as a result their recycling plants run under the permitted capacity. Some specific problems were also listed by these recyclers which are discussed as follows.

The respondents from *Attero* recycling unit also felt that there is little support from the government side to create awareness among the public. According to them, they can reach a larger mass if the Government runs a nationwide campaign for raising awareness for E-waste, its hazards and benefits of proper recycling. In addition to underutilization of their processing, some Recyclers (like *SIMS*) also face problem in transporting the E-waste as they do not have their own transport services and they are required to hire from the logistics company which made their operation very expensive (Table 11.2).

Although it is mandatory for all recyclers to be registered, most of the informal recyclers are hesitant to get registered as it may require them to install the proper machinery/infrastructure and to follow all the guidelines for processing of E-waste. Being in the informal sector, they are not bound to follow the labor laws that would be applicable to their workers if they get formalized. In that case, they have to pay them a minimum daily wage, social insurance, and to provide other safety measure in case of any injury/accidents. Moreover, the employers in the informal sector neither pay any taxes nor participate in any government run insurance schemes or social welfare for their workers (Wilson et al., 2006). These are the reasons they are continuing with their old practices. The profit margin is very high for these informal employers. Formalization may reduce their profit as they would be placed at the lower value addition chain. This may be the reason that these workers do not go for registration.

The formal recyclers also faced harassment, as one of the official told us during our interview, by the monitoring agency in the name of checking the safety and security of workers and the environmental pollution. In India due to lack of strict implementation of the existing rules has proven a major challenge in the formalization of the process. Providing proper training to the informal workers to induct them in to the formal recycling companies is also a major challenge. First they need to be given a proper education about the harmful effects of E-waste and then a proper training to practice scientific and safe methods during the processing E-waste. In cities like Delhi, a large number of people are involved in informal recycling of E-waste. In such a case, recognizing and organizing these workers may prove to be a difficult task due to the fact that they work in small clusters at different places all over the city.

Due to a large number of people involved in this process, providing safety measures and establishing of proper recycling facility required a huge investment fund, which is a challenge for a developing country like India. The informal workers also cannot afford to establish the facilities themselves due to which they have evolved low cost methods for recycling which is also hazardous for their health as well as the environment.

Apart from management and monitoring issues there may be some problems from the point of view of these informal workers. These issues may be one of the major reasons behind the hesitation of these workers to work as formal entity. It is presumed that during formalization all the workers and employers may not get the job. Hence, their employment and source of livelihood would be affected.

Thus, these factors may result in affecting or slowing down the process of formalization. Instead of complete formalization, linking the informal and formal channels may prove to be a better option. This study suggests that if the awareness regarding the hazards of improper recycling is spread to a large population, it is would be easier to collect E-waste through formal sector.

This study focuses on the formal E-waste recycling sector and indicates that though the E-waste (Management and Handling) Rule 2011 has been implemented there are still many steps that need to be taken in this regard. Lack of awareness among the consumers is a major hurdle in the functioning of these formal recycling facilities. This study also finds out lack of strict implementation and monitoring, competition from the vast chain of informal recyclers as a major challenge for these recyclers. It has also tried to throw some light on the formalization issue that has been recommended by both Government and Nongovernment bodies since 2011. The study points toward the problems that may come during formalization, that is, locating and recognizing the informal clusters, raising awareness among the large population in India and lack of financial aid. The most important issue is taking the informal recyclers into confidence about making them join the formal sector by making them aware about the benefits.

11.8 Conclusion

E-waste recycling in the formal sector has gained some importance after 2011 when the E-waste Rules 2011 were implemented making it obligatory for all the existing E-waste recyclers in India to get registered with the Pollution Control Boards of the respective states. Earlier may studies were conducted related to the E-waste recycling in the informal sector, the processes involved, its health and environmental impacts. This study has tried to explore the concerns of the formal recyclers in the country and the challenges they face in operating these facilities. Formalization of the informal sector has been suggested by many scholars but there are various problems associated with this process. With the help of interviews conducted with some of the registered E-waste recyclers it was observed that the implementation of the rules is not being done with required seriousness. Lack of monitoring has led to many registrations but there is no check on the processes adopted by these organizations. Hence, this chapter suggests that along with encouraging formal recycling process, the government as well as nongovernmental bodies should also continue to spread awareness among the informal recyclers in order to make them join the formal stream. There is strong requirement of proper monitoring of these recycling plants to ensure environmentally sound methods being practiced.

References

Agarwal, V., Nair, A., 2015. IT sector largest generator of e-waste; underutilised recycling capacity. *The Economic Times*. 9 Feburary. Available at: <https://economictimes.indiatimes.com/news/politics-and-nation/it-sector-largest-generator-of-e-waste-underutilised-recycling-capacity/articleshow/46172152.cms>.

Arora, R., 2008. Best practices for e-waste management in developing nations, GTZ-ASEM Report, pp. 1–25. Available at: <http://www.smallb.in/sites/default/files/knowledge_base/bestpracticesforEwasteManagement-developingnations.pdf>.

Bhat, V., et al., 2012. Development of an integrated model to recover precious metals from electronic scrap- a novel strategy for e-waste management. Procedia Soc. Behav. Sci. 37, 397–406.

Chatterjee, S., 2011, Electronic waste and India. Available at: deity.gov.in/sites/upload_files/EWaste_Sep11_892011.pdf.

Chaterjee, S., Kumar, K., 2009. Effective electronic waste management and recycling process involving formal and non-formal sectors. Int. J. Phys. Sci. 4 (13), 893−905.

Chaturvedi, A., et al., 2010. Mainstreaming the informal sector in e-waste management, *Urban Industrial and Hospital Waste Management Project*, Ahmadabad, 7−8 May. Available at: <http://www.weeerecycle.in/publications/research_papers/Informal_Sector_in_E-Waste_Ahmedabad_Conference.pdf>.

Christian, E.G., 2012. End-of-life management of waste electrical and electronic equipment for sustainable development, Working Paper Series on Legal Empowerment for Sustainable Development, pp. 1−19. Available at: <http://cisdl.org/public/docs/Christian_End-of-Life_Management_of_Waste_Electrical_and_Electronic_Equipment.pdf>.

Davis, J.-M., Garb, Y., 2015. A model for partnering with the informal e-waste industry: rationale, principles and a case study. Res. Conserv. Recycl. 105, 73−83.

Duan, H., Eugster, M., 2007, Employment analysis of WEEE recycling and disposal in China, Internal working paper of EMPA: St. Gallen, Switzerland.

Dwivedi, M., Mittal, R.K., 2013. Willingness of residents to participate in e-waste recycling in India. Environmental Development 6, 48−68.

Dwivedy, M., Suchde, P., Mittal, R., 2015. Modelling and assessment of e-waste take-back strategies in India. Res. Conserv. Recycl. 96, 11−18.

Garide, B., 2014. Innovations for Inclusivity in India's Informal E-Waste Market. International Institute for Environment and Development Briefing (Available at:http://pubs.iied.org/pdfs/17266IIED.pdf).

Gullett, K. Brian, et al., 2007. Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations. J. Mater. Cycles Waste 9 (1), 69−79.

Jacob, S., 2013. For Attero even waste glitters, *Business Standard*, 21 October. Available at: <http://www.business-standard.com/article/companies/for-attero-even-waste-glitters-113102100006_1.html> (accessed 04.15.15.).

Jha, M.K., et al., 2011. Prospective Scenario of e-waste recycling in India, Recycling of electronic waste II, Proceedings of the second symposium, Available at: http://eprintsnmlindia.org/2956/1/28_TMS-2011.pdf

Khattar,V., et al., 2007. E-waste assessment in India: special focus on Delhi. BIRD-GTZ report, 3-66, Available at: http://weeerecycle.in/publications/reports/GTZ_MAIT_E-waste_Assessment_Report.pdf

Kwatra, S., et al., 2014. Understanding public knowledge and awareness on e-waste in an urban setting in India: a case study of Delhi. Manag. Environ. Qual. Int. J. 25 (6), 752−765.

Lundgren, K., 2012. The Global Impact of E-Waste: Addressing the Challenge. International Labour Organization, Programme on Safety and Health at Work and the Environment. Sectoral Activities Department, ILO, Geneva, pp. 5−71, p. 30. Available at: http://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/publication/wcms_196105.pdf.

Osibanjo, O., Nnorom, I.C., 2007. The challenge of electronic waste (e-waste) management in developing countries. Waste Management and Research 25, 489−501.

Pandey, P., Govind, M., 2014. Social repurcussions of e-waste management in India: a study of three informal recycling sites in Delhi. Int. J. Environ. Stud. 71 (3), 241−260.

Pant, D., et al., 2012. Chemical and biological extraction of metals present in e-waste: a hybrid technology. Waste Management 32, 979−990.

Puckett, J., et al., 2002. Exporting harm: the high tech trashing of Asia, The Basel Action Network and Silicon Valley Toxic Coalition: Seattle, Available at: http://ban.org/E-waste/technotrashfinalcomp.pdf.

Raghupaty, L., et al., 2010. “E-waste recycling in India: bridging the formal-informal gap”, *E-Scrap*. Available at: <http://www.weeerecycle.in/publications/research_papers/Article_in_RI_may_2010.pdf>.

Reddy, N.R., 2013. Revitalizing economies of disassembly: informal recyclers development experts and e-waste reforms in Bangalore. Econ. Polit. Wkly. XLVIII (13), 62−70.

Resources-Formalization of Informal Sector. Available at: <http://www.mait.com/formalization.html>.

Rochat, D., et al., 2008. India: including the existing informal sector in a clean e-waste channel. In: Proceedings of the 19th Waste Management Conference of the IWMSA. 6−10 October. Durban, South Africa. Available at: <http://www.ewasteguide.info/files/Rochat_2008_WasteCon.pdf>.

Saritha, V., et al., 2015. Consumer attitude and perception on e-waste: an assessment. Pollution. 1 (1), 31−43.

Sepulveda, A., et al., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environment Impact Assessment Review 30, 28−41.

Silva, 2012. Indian e-waste: manage, make it profitable, save the world, *BRIC Expansion*. Available at: <http://www.bricexpansion.com/indian-ewaste-manage-profitable-save-world/>.

Sinha, S., Mahesh, P., 2007. Into the future: managing e-waste for protecting lives and livelihoods. *Toxics Link Report*. pp. 1−14. Available at: <http://toxicslink.org/?q = content/future-managing-e-waste-protecting-lives-and-livelihoods>.

Sinha, S., et al., Waste electrical and electronic equipments: EU and India sharing best practices. pp. 1−95. Available at: <http://eeas.europa.eu/delegations/india/documents/eu_india/final_e_waste_book_en.pdf>.

Sohail, S., Vasudev, C., 2013. Life of a licensed e-waste collector. *Down to Earth*. August 29. Available at: <http://www.downtoearth.org.in/news/life-of-a-licenced-ewaste-collector-42033/>

Srivastava, A.K., et al., 2011. Evaluating risks of acquired clinical vulnerability among subjects exposed to e-waste. Rev. Environ. Contamin. Technol. 214, 1−14, p. 6.

Umair, Shakila, et al., 2015. Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. Resources, Conservation and Recycling 95, 46−57.

Venkatraman, T., 2015. Mumbai: 62% not aware of e-waste, reveals survey by students. *Indian Express*. 25 September. Available at: <http://indianexpress.com/article/cities/mumbai/mumbai-62-not-aware-of-e-waste-reveals-survey-by-students/>.

Wang, F., Huisman, J., 2010, Formalization of e-waste collection and recycling in China, Proceedings of CARE Innovation Conference 2010, Vienna: Austria. Available at: http://www.transwaste.eu/file/001440.pdf

Williams, E., et al., 2013. Linking informal and formal electronics recycling via an interface organization. Challenges 4 (2), 136−153.

Wilson, et al., 2006. Role of informal sector in waste management in developing countries, Habit. Int, 30. pp. 797−808.

Yu, J., et al., 2010. Managing e-waste in China: Policies, Pilot Projects and Alternative Approaches. Resources, Conservation and Recycling 54, 991−999. 2010.

Further reading

www.cpcb.nic.in
http://www.weeerecycle.in/formalization_of_informal_sector.htm
http://toxicslink.org/docs/Environment_and_Livelihoo_d-Hand_in_Hand.pdf
http://www.moef.nic.in/

Electrical and electronic waste in Pakistan: the management practices and perspectives

12

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12.1 Introduction

The burgeoning use of electrical and electronic equipment (EEE) and their decreasing service life are generating a significant quantity of obsolete EEE. The discarded obsolete or end-of-life EEE are considered as the E-waste (Pathak et al., 2019). However, there is not a fix definition of E-waste. The EU Directive on Waste Electrical and Electronic Equipment (WEEE) defines E-waste as the obsolete equipment that could work while supplying the electric/electromagnetic currents. It includes the large and small household electrical appliances and equipment for information and communications use (European Commission, 2003; Ilyas and Lee, 2014). The Swedish Environmental Protection Agency defines E-waste as the disposed electrical or electronic items those are no longer able to perform its assigned purpose (Swedish EPA, 2011; Tanskanen, 2013). Whereas, the United Nations Environment Programme (UNEP) defines E-waste as the electronics destined for "*reuse, resale, salvage recycling and disposal*" (UNEP, 2011). Pakistan has not its own definition of E-waste, and hence, by considering the E-waste and WEEE both as the same, the items/goods defined in the aforementioned definitions are taken into account under the E-waste in this chapter. Notably, E-waste contains approximately one thousand substances, including metals, plastics, and glass (Vadoudi et al., 2015; Wang and Xu, 2014; Widmer et al., 2005). Further, the metals components contained in E-waste can be subdivided into several types of ferrous, nonferrous, toxic, hazardous, valuable, and precious metals.

Due to the technology loving era of the current time, a fast rate of discarding EEE has presented E-waste as the fastest growing problematic waste of the globe (Ilyas and Lee, 2014). Mainly in the developed countries, the E-waste is mounting pressure for its sustainable solution; however, yet the full proof environment-

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00007-3

friendly solution could be reached that can also be fitted with the economy. The reason that is why a large amount of E-waste is being dumped from the developed countries to under-developing or developing countries (Puckett et al., 2002; Terazono et al., 2006; Umwelthilfe, 2007; Cobbing, 2008). E-waste is a heterogeneous mixture of several hazardous and toxic chemicals belongs to ceramics, polymers, metals, glass, and others. Legally the transboundary movement of these hazardous substances restricts the shifting of E-waste under the umbrella of the Basal convention. Nevertheless, the waste of developed countries is transferred to elsewhere destination countries in other forms than the E-waste (Pathak et al., 2017). Usually as the used EEE (UEEE) donation for their reuse purpose.

12.2 E-waste generation in Pakistan

Although Pakistan is a signatory of the Basal Convention, the country is one of the largest receivers of E-waste. Pakistan has emerged as a major dump-yard for the large volume of E-waste coming from the United States, EU, Japan, UK, Australia, and Gulf countries (as shown in Fig. 12.1). E-waste gets the entry in the form of donations by charities or second-hand used items for the resale and reuses purposes. On the contrary, only 2% of the total amount of imported goods as the second-hand used item is going for reuses. The rest is directly sent for the dismantling and informal recycling works (BAN, 2002; Sthiannopkao and Wong, 2013).

The import of computers from foreign countries as UEEE has found to be in the following order: US > UK > Canada > UAE > Singapore > Australia > EU > China > Korea. The highest 70% of which is from the United States alone (BAN, 2002; Greenpeace, 2009; Sthiannopkao and Wong, 2013; Today, 2014). This situation is not only serious for the environmental and health hazards associated with E-waste but more serious is that the threat remains unaccounted with the unquantified volume of it. One of the

Figure 12.1 The illegal flow of E-waste to Pakistan in the name of second-hand UEEE.

Table 12.1 The average quantities of the major items imported to Pakistan, mainly in the name of UEEE.

Items' name	Average imported unit (million)	Average imported weight (tons)	Average plastic in imported items (tons)
PCs	1.42	35,522	1174
Laptop	0.25	889	28
Monitors	1.03	14,577	2452
TVs	0.20	6414	508
Printers	0.19	1270	317

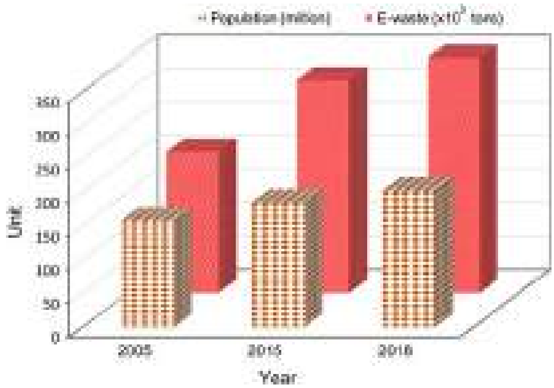

Figure 12.2 The increase in population and E-waste volume in Pakistan as a function of year.

estimations is that more than over 50,000 tons of E-waste dumping by developed countries (Sajid et al., 2019), while other is for 95,400 tons of E-waste per year (Imran et al., 2017). The average quantities of the major items imported to Pakistan (as with the reported data) is summarized in Table 12.1 (Imran et al., 2017).

Moreover, the local generation of E-waste data is also not quantified, which is supposed to be 317,000 tons in 2015. As per the recent report, 72% of the total population of the country has mobile phones which are accounted for over 140 million by the year 2017 (http://pas.org.pk/digital-in-2017-global-overview/). Purchasing of televisions is forecasted to increase at a rate of 12% per annum resulting mainly because of the rapid change in technologies (International, 2015). The sales of personal computers are also increasing at a rate of 5.8% per annum due to increasing demand from individuals, enterprises, and the public sectors (International, 2015). Rapid urbanization and increasing population of the country are overall the major factors driving the EEEs consumption, as newer technologies attract people to buy the products. Further, the local gray market of second-hand items is also contributory, by which the quantification of E-waste generation in the country is a tough task. The large population of the lower middle-income group is a big consumer of this gray market, which is actually the user of refurbished items more than a second time. It eventually leads to generate a higher volume of domestic E-waste (as shown in Fig. 12.2). Lacking proper discard or

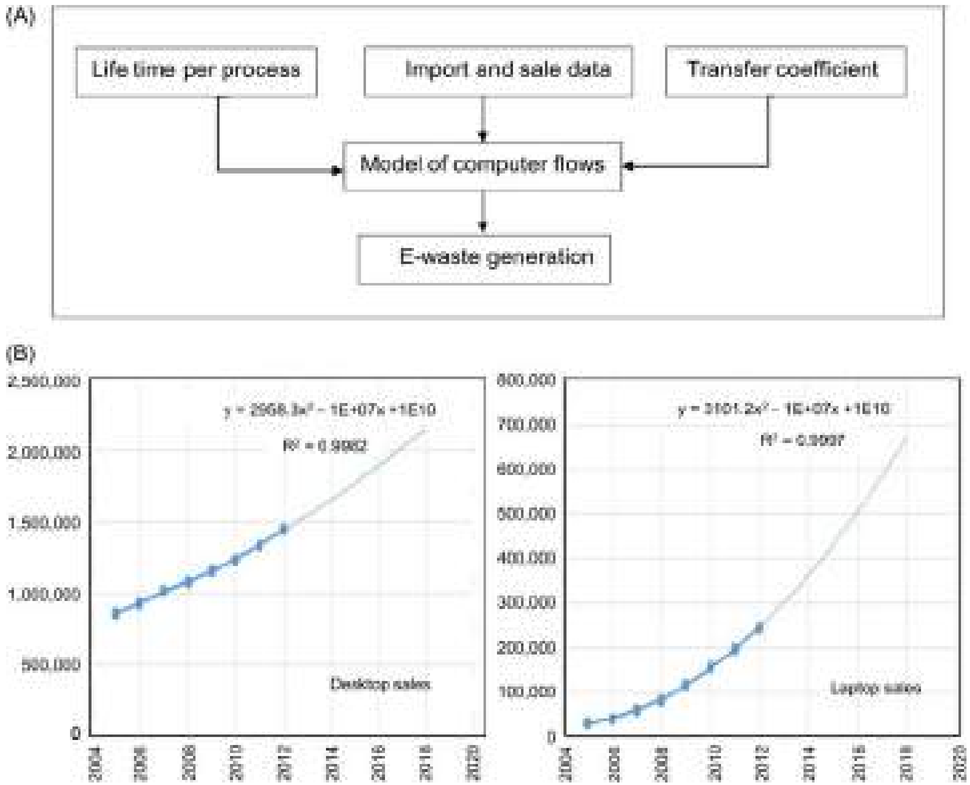

Figure 12.3 A typical assumption for the material flow analysis (A), and sales data of desktops (B) and laptops (C) and its extrapolation for quantifying the volume of E-waste generation after their consumptions in Pakistan.
Source: Adapted from Sajid, M., Syed, J.H., Iqbal, M., Abbas, Z., Hussain, I., Baig, M.A., 2019. Assessing the generation, recycling and disposal practices of electronic/electrical-waste (E-Waste) from major cities in Pakistan. Waste Manag. (in press). Available from: https://doi.org/10.1016/j.wasman.2018.11.026.

Table 12.2 The average quantities of the major items imported to Pakistan, mainly in the name of UEEE (Sajid et al., 2019).

Source from	Source to	Desktop (%)	Laptop (%)	Average (%)
Import/sales	Corporate organizations	25	20	25
	Small businesses	35	35	35
	Households	40	45	40
Corporate and business organizations	Storage after first use	65	53	60
	Reuse	27	34	30
	Disposal	8	13	10
Small businesses	Storage after first use	40	42	40
	Reuse	35	31	30
	Disposal	25	27	30
Households	Storage after first use	38	25	30
	Reuse	32	47	40
	Disposal	30	28	30
Storage after first use	Reuse	50	50	50
	Disposal	50	50	50
Reuse	Storage after first use	50	50	50
	Disposal	50	50	50
Storage after second use	Disposal	100	100	100

collection facility is also responsible for this because people throw the E-waste after running off the working condition of UEEE.

A recent study on the assessment of E-waste generation using the material flow analysis methodology is reported by Sajid et al. (2019). The flow of E-waste in the country is considered to follow the route of material imported as UEEE→distribution→consumption→disposal. Soon after reaching the end-of-life (Fig. 12.3A), they are not supposed to be disposed of and after a time being they are sold to scraper (through the direct sale or donation or auction). A significant part of them eventually ends up and disposed of as E-waste. Using the statistical model, the sales data of the majorly sold items (PCs and laptops) within the periods of 2005–12 are accounted and extrapolated up to the year 2016. Thus fitted polynomial trend line is shown in Fig. 12.3B, based on which the waste generation data for desktop and laptops are projected. Moreover, with some preliminary assumptions, the transfer coefficient is also tabulated (as presented in Table 12.2).

12.3 Policy framework

It is evident from Fig. 12.2 that the generation of E-waste keeps growing, still there is no specific work done on its proper management. In order to ratify the Basel Convention, Pakistan has some indigenous environmental laws; however, effective legislation that explicitly deals with E-waste is required yet.

12.3.1 Legislations dealing the E-waste in Pakistan

The journey toward environmental conservation in the country started with the formation of Pakistan Environmental Protection Council in 1984 following the Pakistan Environmental Protection Ordinance enacted in 1983 (GISW, 2010). Thereafter, the National Conservation Strategy was adopted in 1992 that was also presented in Rio Earth Summit and later endorsed by the United Nation by granting through the International Union for Conservation of Nature for the Sustainable Development Networking Programme. The milestone for the policy on environmental safeguard in the country came with the Pakistan Environmental Protection Act (PEPA) that was enacted in December 1997. Section 11 of which prohibits the discharge/emission of any hazardous chemical into the environment; Section 13 prohibits the import of any hazardous substance; and Section 14 does not allow the handling of hazardous elements in the territory of Pakistan (PEPA, 1997; Abbas, 2010). The National Environment Policy 2005 defines the hazardous materials and their import restriction including those mentioned in the Basal Convention is enacted by the Import Policy Order 2007−08. The recent edition of the Import Policy Order 2016 clearly indicates that air conditioners, refrigerators, monitors, CCTVs, and other home appliances in UEEE or second-hand condition are not allowed to be imported (IPO, 2007, 2016). The aforementioned laws/regulations only guiding the basic constraints on E-waste, but the generalized form of elements involved and principles restricts their implementations. The reason is therefore the flow of E-waste in other forms is to continue and increase as well. It can only be handled by framing specific legislation on E-waste to regulate the E-waste volume, its management, and informal recycling as well. Preparations on the quantitative inventories of EEEs, and E-waste being produced, imported, consumed, recycled, and dumped are the basic need for developing the E-waste specific regulation/law (Iqbal et al., 2015). The collection of E-waste at the local level up to municipal level, and also by implementing the extended producer responsibility (EPR) system, their transportation to the formal recycling centers should be made possible. In that manner only, the best practices can be ensured in the country to deal with this growing problem of the globe. EPR is presently the foremost policy worldwide, intending to provide incentives to EEE manufacturer for integrating the environmental considerations during the product design and have assigned the obligation for environmental impacts throughout the life-cycle of products, including recycling, reuse, and disposal of E-waste (Ongondo et al., 2011). Furthermore, a legislative framework for effective E-waste management in Pakistan can be developed by incorporating the existing tools as shown in Fig. 12.4 (Pathak et al., 2017).

12.3.2 International legislations and status-quo of Pakistan

As with the developed countries, Pakistan needs a national registry system along with a strong collection network and legislative framework (Sthiannopkao and Wong, 2013). Pakistan can learn from the global regulations like the Avoidance of Packaging Waste of Germany to put the financial obligations on manufacturers for

Figure 12.4 The tools for legislative framework on E-waste management.
Source Adapted from Pathak, P., Srivastava, R.R., Ojasvi, 2017. Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India. Renew. Sust. Energ. Rev. 78, 220−232.

the collection and reduction of packaging waste (Ongondo et al., 2011). It has also been adopted by several other European countries (in Norway, Taiwan, Sweden, and Switzerland) and extended to EEE manufacturer. The strong legislative of the EU restricting the use of hazardous substances in EEE (Directive 2002/95/EC, the RoHS Directive), and promotes their recycling. Table 12.3 identifies the important initiatives for managing the E-waste by the international organizations and summarizes their key features as well.

Pakistan can also learn from the legislative gaps remained in the neighboring countries (China and India), where the EPR system has been implemented but they do not have the national registry system to track the produced EEE for the purpose of eventual manufacturer take-back. Therefore the quantification and trace of E-waste generation is still a difficult task. The big gray markets available for the second-hand UEEE in Pakistan are also making the situation vulnerable. The domination of private players, availability of cheap labour, a large rate of E-waste growing volume (by both import and domestic generation), and the costlier technology for its benign disposal, are the factors supposed to keep hurdles despite the enactment of environmental regulations. Henceforth, it is impossible to neglect the informal sector and Pakistan has to make its legislative framework on E-waste management by including the informal sector with the formal and organized practices. In order to make a clear understanding, the status-quo of E-waste management in Pakistan is compared with other relevance countries and presented in Table 12.4.

Table 12.3 Important legislations and initiatives with their key features for the E-waste management (Ilankoon et al., 2018).

Legislation and initiatives	Key features
The Basal Convention	• Reduction of hazardous waste generation and the promotion of sustainable handling techniques at the place of disposal • The restriction of transboundary movements of hazardous wastes • Form legislative frameworks where transboundary movements are permissible
The EU WEEE Directives	• Free take-back schemes for consumers • Reduce WEEE to landfills through collection and recovery targets • WEEE to be collected separately from other wastes • Stimulate "eco-design"—product design that reduces WEEE and increases its ease of recovery • Producer responsibility for end-of-life treatment of their products
Solving the E-waste Problem	• Research and piloting on E-waste treatment • Strategy and goal-setting to eliminate the E-waste problem • Training and development on E-waste issues • Establish communication and awareness among members and throughout the industry
G-8 3Rs Initiative	• Promoting 3Rs: reduce, reuse, recycle • Building a "sound-material-cycle society"
National Strategy for Electronics Stewardship, United States	• Improve design of electronic products • The Federal government leads by example • Enhance the handling and management of used or discarded electronic equipment in the United States • Reduce harm caused by used or discarded electronic equipment in developing countries
Global e-Sustainability Initiative	• Bring together ICT companies, industry associations and non-governmental organizations • One of the key focus area is E-waste • Achieving sustainable objectives and manage risks associated with ICT through innovative technology
International Environmental Technology Centre—UNEP	• Application of environmentally sound technologies (ESTS) in developing countries and countries in transition on waste management

Table 12.4 A brief comparison of the status-quo for E-waste management in Pakistan and some other countries (Imran et al., 2017).

Factors	Australia	Canada	China	EU countries	Ghana	India	Pakistan
E-waste specific rule	Yes	Yes	Yes	Yes	No	Yes	No
Management studies on E-waste	Yes	Yes	Yes	Yes	Average	Yes	No
Import regulation	Well implemented	Well implemented	Well implemented	Strictly implemented	No	Poorly implemented	No
Informal recycling activities	No	No	Very less	Strictly banned	Very high	High (~95%)	Very high (98%)
Implementation of labor law (informal)	Yes	Yes	Yes	No evidence of informal activity	No	Poorly implemented	No
Public awareness	High	Very high	High	Very High	No	Poor	No

12.4 Existing practices for E-waste handling in Pakistan

As mentioned that only 2% of the total amount of imported UEEE is usable material, while all others directly sent for recycling, in most of the ceases by the informal sector. The flow of E-waste in current practices for Pakistan is shown in Fig. 12.5. Only ~2% of formal recycling is being practiced of the total E-waste, including the amount of domestic generation. The practices are vulnerable and unhealthy. From hand-picking/sorting to dismantling are being done without any proper protection to avoid any contact to the hazardous and toxic substances (Ahmed et al., 2018), while burning of the wires, PCBs, and other plastics to detach the metals from polymer substance in the open area (see Fig. 12.6A and B) is causing much pollution to the environment. The practices of this sector are unorganized but pacing with an internal management system in a chain from rag pickers to collectors wherefrom it reaches to scrap collectors and after dismantling and sorting finally reaches to informal recyclers. Earlier the volume reduction by dismantling and sorting was the major part for the informal sector, which was sold to the traders again in an illegal manner to the metal recyclers in China. Slowly, they have also started to strip the metals, targeting copper and gold of the most important in this practice. By providing the heat through torch blowing to melt the plastic substances, metals are subjected to acid bath again in the open environment using the nitric and hydrochloric acids, emitting the hazardous NOx and gaseous chlorine compounds. In the entire practices, not only the workers involved but also the local inhabitants residing in that vicinity are not well-informed of the associated hazards therein. The aforementioned lacking of any specific regulatory to look the occupational exposure and environmental pollution due to the informal recycling practices; make it easy to be continued. Moreover, some of the peoples do understand the associated problems

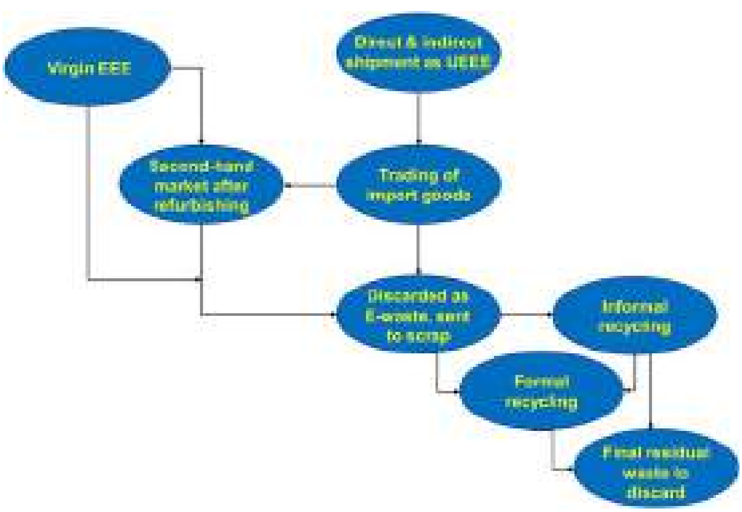

Figure 12.5 Pictorial presentation of the typical E-waste flow in Pakistan.

Figure 12.6 The representative pictures of the E-waste business, showing the vulnerable practices for segregation, manual dismantling, and informal recycling practices without any protective measures.
Source Adapted from Sajid, M., Syed, J.H., Iqbal, M., Abbas, Z., Hussain, I., Baig, M.A., 2019. Assessing the generation, recycling and disposal practices of electronic/electrical-waste (E-Waste) from major cities in Pakistan. Waste Manag. (in press). Available from: https://doi.org/10.1016/j.wasman.2018.11.026.

but as these practices are the only source of their income, they have no option except to ignore the vulnerability with this business.

12.4.1 E-waste receiver and processing sites

In Pakistan, Lahore and Karachi are the main activity centers in terms of E-waste dumping (http://citeseerx.ist.psu.edu). The quantities of major E-waste destination cities in the country by altering the name as UEEE, are summarized in Table 12.5 (Imran et al., 2017). Karachi is the largest economic hub of Pakistan and the end-point of most of the E-waste due to being located at the coastal side of the Arabian Sea (https://www.dawn.com/news/290400; https://www.downtoearth.org). The E-waste from various developed and OECD countries reached in the Karachi port in the name of UEEE. Lyari is the largest recycling site of Karachi along with Sher Shah. The recycling practices herein are informal and with complete disregard, to the grave risks, they pose to human and environmental health. However, the neighbouring countries are also the major destination sites of such E-waste but the legislative development in those countries has somehow diverted the more hazardous

Table 12.5 The major cities receiving the E-waste quantities in the name of UEEE (Imran et al., 2017).

City name	Imported quantity (tons)	Imported quantity (%)
Karachi	85,291	89.4
Lahore	5807	6.1
Rawalpindi	1403	1.5
Islamabad	1155	1.2
Peshawar	1075	1.1
Faisalabad	583	0.6

and toxic materials to the Karachi port. In general, the older the E-waste the higher level of hazardous elements therein. The aforementioned informal recycling practices left significant pollutant in solid, liquid and gaseous forms. The bulk of them is either landfilled or trashed into Lyari River, which falls into the Arabian Sea and disturbing the marine ecosystem. The second largest metro city Lahore is also facing the same challenges due to the informal recycling. Beadon road, Hall road, Hafeez center, Misri shah, and the GT road area near to Mayo Hospital and Pakistan mint are the known areas for E-waste trading. Here the people working inside their small rooms, often without lacking ventilation facility, causes the potential health problems to the workers. Although small in size than Lahore and Karachi, Rawalpindi and Faisalabad is also a hub for E-waste recycling. Time-to-time the district administration drives do penalize and shuts such informal ventures, but this not sufficient when compared to the vulnerabilities of E-waste. Asthma, skin diseases, and nausea are very common in the localities of these areas. The influence of E-waste recycling on the molecular ecological network of soil microbial communities has been studied using the samples collected from Karachi, Multan, and Lahore (Jiang et al., 2017). It is observed that the composition of the microbial community and diversity at the whole and core community levels is significantly affected by the footprints of heavy metals, polybrominated diphenyl ethers, and polycyclic aromatic hydrocarbons. The air quality of Lyari and Sher Shah areas of Karachi have found highly contaminated with the organic flame retardants emitted by the informal recycling practices (Iqbal et al., 2017).

12.5 Research and developments for transitioning towards the formal recycling

The aforementioned only 2% recycling rate practiced by the formal sector is very poor and measurable. Even within the 2% of formal recycling not much information is available and no big recycling company exists that can be a role model in this field. Not only is the lacking of governmental regulatory legislation but in absence of the adequate technical expertise and support also the formal recycling remains un-nurtured. The higher consultation fee, costlier technology, and requirement of expensive set-ups are often a bottleneck for practicing the formal recycling in Pakistan. It indicates for the requirement of the indigenous management and recycling technology. The slow but growing awareness in this field has paid attention to the research communities of the country, and initiative works have been started for exploring the sustainable management of E-waste problem in Pakistan. Several research works have been reported in recent times focusing on the E-waste management system (Iqbal et al., 2015; Imran et al., 2017; Sajid et al., 2019). On the other side, for metal recovery, which has been considered as the integrative part of the sustainable E-waste management, some interesting works have been reported, however, a few in quantity. Interestingly, they are of a wider spectrum using the convention chemical to advance microbial technologies.

Spent lithium-ion batteries (LiBs) are one of the main contributor associated with E-waste and today Pakistan is supposed to consume 7 million units of LiBs. As the spent LiBs contains a significant amount of valuable rare metals like cobalt, nickel, and lithium, its recycling other than dumping as the municipal waste has been proposed by Sattar et al. (2019, 2020). The combined heat treatment−acid

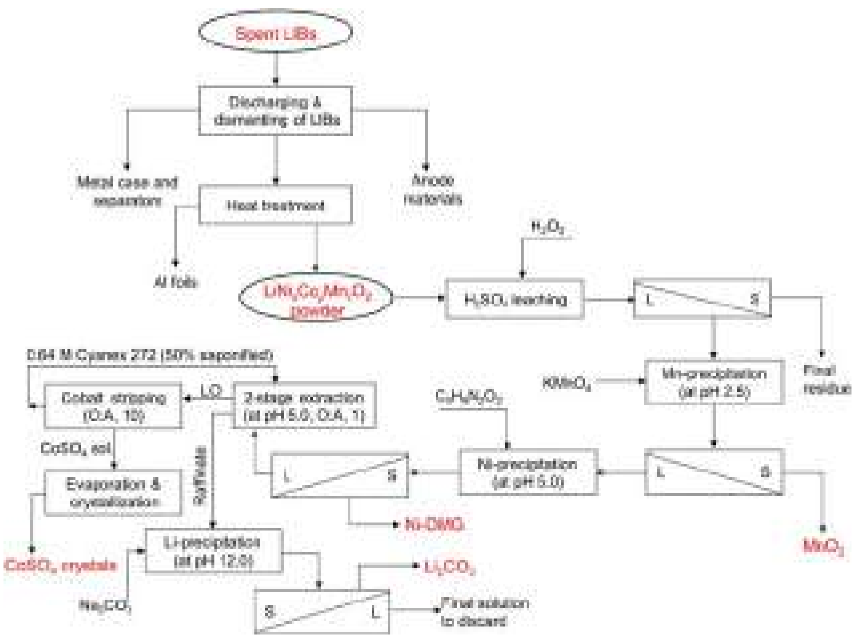

Figure 12.7 An indigenous developed process flow-sheet for the entire recycling of EoL-LiBs at the Mineral and Material Chemistry Lab, University of Agriculture Faisalabad. *Source* Adapted from Sattar, R., Ilyas, S., Bhatti, H.N., Ghaffar, A., 2019. Resource recovery of critically-rare metals by hydrometallurgical recycling of spent lithium ion batteries. Sep. Purif. Technol. 209, 725−733; Sattar, R., Ilyas, S., Kousar,S., Khalid, A., Sajid, M., Bhkhari, S.I., 2020. Recycling of end-of-life LiNix$_{C}$oy$_{M}$nz$_{O}$2 batteries for rare metals recovery. *Environ. Eng. Res.* 25 (1), 88−95. Available from: https://doi.org/10.4491/eer.2018.392.

leaching–precipitation–solvent extraction–crystallization process for the recycling of metals from cathode materials is shown in Fig. 12.7. In presence of H_2O_2 at moderately increased temperature, the enhanced leaching of cobalt that undergoes to solvent extraction for its separation and enrichment of metal concentration, above 99% of metals recovery has been reported. The process advantage is also with the efficient recovery of other rare metals like nickel and lithium (more than 99%) presents the recycling process better than the robust smelting technique, which requires high calorific energy and losing lithium into slag. Moreover, the entire process has been analyzed to be economically viable with a margin of $476 per ton of the cathode powder processing (Sattar et al., 2020). Looking at the need of the time for the recycling of spent LiBs, the University of Agriculture Faisalabad has included the work as the technology for commercialization (101 Innovations Catalogue-UAF, unpublished).

Other than the chemical leaching, Ilyas et al. (2007, 2010) have extensively worked in the bioleaching of E-waste, and certainly, one of the leading work has been carried out. Using the selected moderately thermophilic strains of acidophilic chemolithotrophic and acidophilic heterotrophic bacteria (including the *Sulfobacillus thermosulfidooxidans*), the mixed consortium of the metal adapted culture exhibited the maximum leachability of metals from e-scrap. At the laboratory scale, 81% nickel, 89% copper, 79% aluminum, and 83% zinc recovery has been reported through the bioleaching (Ilyas et al., 2007). This has been further upscaled to column level of study (as the schematic is shown in Fig. 12.8) and the results have been found to be promising (Ilyas et al., 2010, 2018).

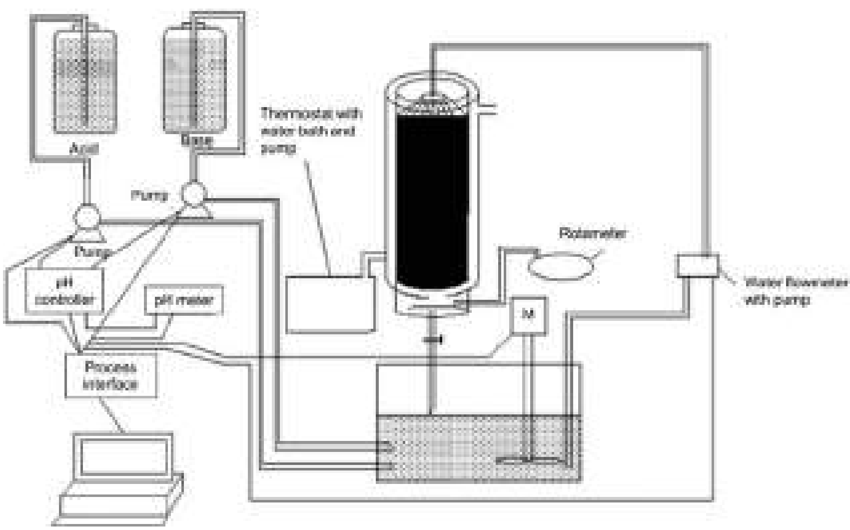

Figure 12.8 A sketch of the column set-up specifically designed for E-waste bioleaching. *Source* Adapted from Ilyas, S., Ruan, C., Bhatti, H.N., Ghauri, M.A., Anwar, M.A., 2010. Column bioleaching of metals from electronic scrap. Hydrometallurgy, 101 (3–4), 135–140.

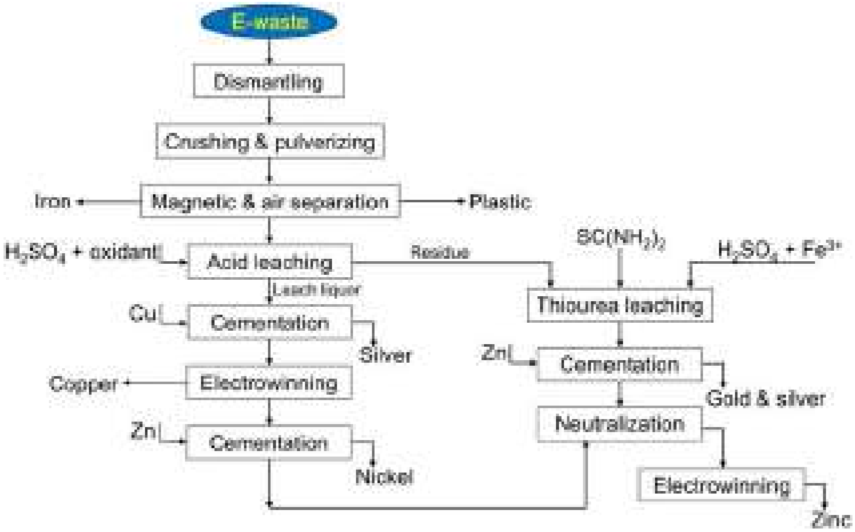

Figure 12.9 A typical recycling of E-waste through the scientific approach for the maximum recovery of base, valuable, and precious metals.

Although a few R&D works have been initiated with encouraging results of metal extraction from E-waste, the government needs to take necessary action to promote the research on E-waste recycling at the higher level to switch from the informal recycling to formal recycling. The government can play a catalytic role by connecting the academic and industrial linkage by providing the market for the recovered value-added products from E-waste recycling. For a country struggling for achieving the self-reliance on the economic front, the recycling of E-waste converting its waste to the wealth can be a leading way toward the circular economy (Ilyas, 2018a,b). Notably, an approximately 146 kg gold of worth 600 million Pakistani Rupee is supposed to be available in the amount of E-waste dumped on yearly basis in Pakistan that contains a total 29,262 tons of metals therein (Imran et al., 2017). One of the possible recycling routes for metals recovery from E-waste is shown in Fig. 12.9.

12.6 Summary and recommendations

In the name of UEEE, Pakistan has become the major destination of E-waste from the exporting countries, which is accounted up to ~94,000 tons per year. Karachi is the largest hub for E-waste trading that receives 89% of total UEEE. The current practices of their handling are totally nonsustainable. In lacking any specific legislation on E-waste management, almost all E-waste is handled by the informal sector. For preparing the specific framework on E-waste management, the government can just follow their neighbouring countries and examples of some developed countries

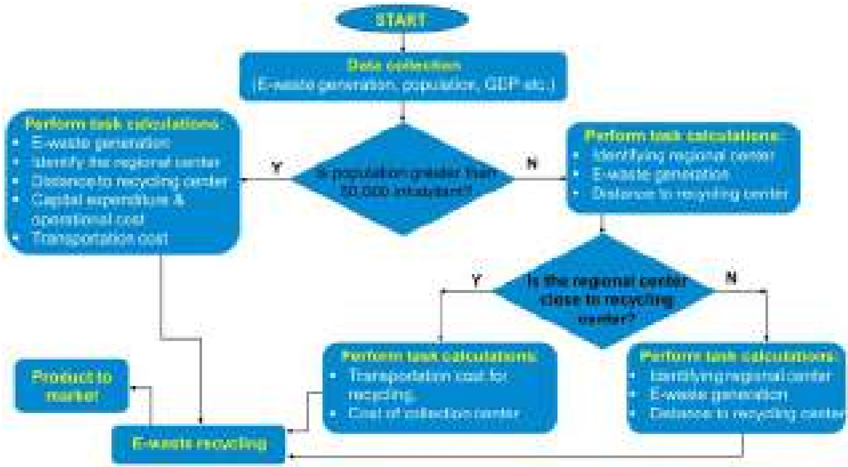

Figure 12.10 An algorithm for the proposed model of E-waste recycling.

like Japan and Sweden. The illegal trade of UEEE in the name of second-hand items and charity work must be controlled by ensuring to obey the Import Policy Order (IPO, 2016) in Pakistan. Legislation like EPR should be imposed on the manufacturers and retailers with obligations of take-back/buy-back of the EoL-EEE/UEEE that can be reused, recycled, and disposed of the residual waste.

At present, only 2% of the total E-waste is being recycled through the formal route, therefore no reliable data are available on E-waste generation and their ways of management. Although a handful of researchers have shown their interests to present solutions of this invited problem of the globe, in absence of governmental direction and encouragements, the benefits of indigenous R&D on E-waste recycling is yet to reach for switching the informal sector toward the formal recycling. The making of coordination between the entities like collectors, scrappers, refurbishers, recyclers, manufacturers, retailers, academia, and governmental bodies, is the need of the hour. They must be educated and well-trained on the collection, handling, and disposal work. For this, time-to-time awareness drive for the common public will be valuable to keep E-waste separate from other municipal solid waste.

The plenty of peoples involved in this business can be benefited more in terms of their good health, sustainable environment, and more earning due to the high yield of valuable metals by adopting scientific practices. Moreover, Pakistan can move forward to the circular economy through the formal recycling of E-waste that can mitigate the major supply risks of several metals recovered from the burgeoning waste volume. To ensure the sustainable management of E-waste, an algorithm is being proposed that can be developed according to the waste generation volume and the provincial population ratio, because it significantly varies from one province to another. In the algorithmic flow shown in Fig. 12.10, a population of 50,000 peoples has been considered for an example that may change. Certainly, this cannot be the only way to handle the E-waste problem but any such initiative can move toward the achievement of all components of the sustainability: societal, economic, and environmental.

Acknowledgments

This work was supported by Brain Pool Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (Project grant number: 2019H1D3A2A02101993). The author S. Ilyas is thankful to the NRF for providing the Brain Pool Scientists award.

References

Abbas, Z., 2010. In: E-waste management in Pakistan. Regional Workshop on E-Waste/WEEE Management, Osaka, Japan, pp. 6–9.

Ahmed, I., Usman, A., Nazir, M.S., Shaukat, M.Z., 2018. Safety practices in informal industrial segment of Pakistan. Saf. Sci. 110, 83–91.

Basel Action Network (BAN), 2002. Exporting harm the high tech trashing of Asia. <http://www.ban.org/E-waste/technotrashfinalcomp.pdf>. Retrieved on August 31, 2018.

Cobbing, M., 2008. Toxic tech: not in our backyard: uncovering the hidden flows of e-waste. Report from Greenpeace International.

EU RoHS Directive, 2002/95/EC. <http://eur-lex.europa.eu/homepage.html>. Retrieved on August 31, 2018.

European Commission, 2003. Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment. Off. J. Eur. Union L3, 24–38.

GISW-Pakistan, 2010. In: Finlay, Alan (Ed.), Global Information Society Watch 2010 Report Focus on ICTs and Environmental Sustainability. APC and Hivos, pp. 187–190. ISBN 92-95049-95-0.

Greenpeace, 2009. Where does e-waste end up? <http://www.greenpeace.org/international/en/campaigns/toxics/electronics/the-e-waste-problem/where-does-e-waste-end-up/>. Retrieved on August 31, 2018.

<http://citeseerx.ist.psu.edu/viewdoc/download?doi = 10.1.1.620.6726&rep = rep1&type = pdf>.

<http://pas.org.pk/digital-in-2017-global-overview/> Retrieved on August 15, 2018.

<https://www.dawn.com/news/290400>. Retrieved on September 6, 2018.

<https://www.downtoearth.org.in/news/pakistan-mulls-ban-on-ewaste-import-651>. Retrieved on September 6, 2018.

Ilankoon, I.M.S.K., Ghorbani, Y., Chong, M.N., Herath, G., Moyo, T., Petersen, J., 2018. E-waste in the international context—a review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manag. 82, 258–275.

Ilyas, S., 2018a. Metal recycling. <https://www.dawn.com/news/1444937>. Retrieved on November 12, 2018.

Ilyas, S., 2018b. Waste management and circular economy. <https://nation.com.pk/16-Nov-2018/waste-management-and-circular-economy>. Retrieved on November 17, 2018.

Ilyas, S., Lee, J.C., 2014. Biometallurgical recovery of metals from waste electrical and electronic equipment: a review. Chem. Bio. Eng. Rev. 1 (4), 148−169.

Ilyas, S., Anwar, M.A., Niazi, S.B., Ghauri, M.A., 2007. Bioleaching of metals from electronic scrap by moderately thermophilic acidophilic bacteria. Hydrometallurgy 88 (1−4), 180−188.

Ilyas, S., Ruan, C., Bhatti, H.N., Ghauri, M.A., Anwar, M.A., 2010. Column bioleaching of metals from electronic scrap. Hydrometallurgy 101 (3−4), 135−140.

Ilyas, S., Kim, M.S., Lee, J.C., 2018. Integration of microbial and chemical processing for a sustainable metallurgy. J. Chem. Technol. Biotechnol. 93 (2), 320−332.

Imran, M., Haydar, S., Kim, J., Awan, M.R., Bhatti, A.A., 2017. E-waste flows, resource recovery and improvement of legal framework in Pakistan. Resour. Conserv. Recycl. 125, 131−138.

International, B. M, 2015. Pakistan Consumer Electronics Report, February 26, 2015, p. 64.

IPO, 2007. In: Import Policy Order, Ministry of Commerce, Government of Pakistan (Ed.), Islamabad, Pakistan.

IPO, 2016. In: Import Policy Order, Ministry of Commerce, Government of Pakistan (Ed.), Islamabad, Pakistan.

Iqbal, M., Breivik, K., Syed, J.H., Malik, R.N., Li, J., Zhang, G., et al., 2015. Emerging issue of e-waste in Pakistan: a review of status, research needs and data gaps. Environ. Pollut. 207, 308−318.

Iqbal, M., Syed, J.H., Breivik, K., Chaudhry, M.J.I., Li, J., Zhang, G., et al., 2017. E-waste driven pollution in Pakistan: the first evidence of environmental and human exposure to flame retardants (FRs) in Karachi City. Environ. Sci. Technol. 51 (23), 13895−13905.

Jiang, L., Cheng, Z., Zhang, D., Song, M., Wang, Y., Luo, C., et al., 2017. The influence of e-waste recycling on the molecular ecological network of soil microbial communities in Pakistan and China. Environ. Pollut. 231, 173−181.

Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manag. 31 (4), 714−730.

Pathak, P., Srivastava, R.R., Ojasvi, 2017. Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India. Renew. Sust. Energ. Rev. 78, 220−232.

Pathak P., Srivastava R.R. and Ojasvi, 2019. Environmental Management of E-waste. In: Electronic Waste Management and Treatment Technology, Prasad M.N.V. and Vithanage M. (Ed.), Elsevier, Oxford, UK, pp. 103−135. Available from: https://doi.org/10.1016/B978-0-12-816190-6.00005-4.

PEPA, 1997. In: Pakistan Environmental Protection Act, Government of Pakistan (Ed.), p. 29. Pakistan.

Puckett, J., Byster, L., Westervelt, S., Gutierrez, R., Davis, S., Hussain, A., et al., 2002. Exporting Harm: The High-Tech Trashing of Asia, Vol. 3. Basel Action Network, Seattle.

Sajid, M., Syed, J.H., Iqbal, M., Abbas, Z., Hussain, I., Baig, M.A., 2019. Assessing the generation, recycling and disposal practices of electronic/electrical-waste (E-Waste) from major cities in Pakistan. Waste Manag. Available from: https://doi.org/10.1016/j.wasman.2018.11.026 (in press).

Sattar, R., Ilyas, S., Bhatti, H.N., Ghaffar, A., 2019. Resource recovery of critically-rare metals by hydrometallurgical recycling of spent lithium ion batteries. Sep. Purif. Technol. 209, 725−733.

Sattar, R., Ilyas, S., Kousar, S., Khalid, A., Sajid, M., Bukhari, S.I., 2020. Recycling of end-of-life LiNix$_C$oy$_M$nz$_O$2 batteries for rare metals recovery. Environ. Eng. Res. 25 (1), 88−95. Available from: https://doi.org/10.4491/eer.2018.392.

Sthiannopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463, 1147−1153.

Swedish EPA, 2011. Recycling and disposal of electronic waste. Health hazards and environmental impacts. Report 6417 of the Swedish Environmental Protection Agency. March 2011.

Tanskanen, P., 2013. Management and recycling of electronic waste. Acta. Mater. 61 (3), 1001−1011.

Terazono, A., Murakami, S., Abe, N., Inanc, B., Moriguchi, Y., Sakai, S.I., et al., 2006. Current status and research on E-waste issues in Asia. J. Mater. Cycles Waste 8 (1), 1−12.

Today, C., 2014. Imports Historical Custom Clearence Data, 2014 Edition.

Umwelthilfe, D.E.U.T.S.C.H.E., 2007. Hamburg: gate to the world for illegal waste exports? Part 1. How Hanseatic City of Hamburg Tries to Get Rid of Its Liability, Berlin.

United Nations Environmental Programme (UNEP), 2011 Recycling e-waste to resources. <http://www.unep.org/pdf/Recycling_From_ewaste_to_resources.pdf>.

Vadoudi, K., Kim, J., Laratte, B., Lee, S.J., Troussier, N., 2015. E-waste management and resources recovery in France. Waste Manag. Res. 33 (10), 919−929.

Wang, R., Xu, Z., 2014. Recycling of non-metallic fractions from waste electrical and electronic equipment (WEEE): a review. Waste Manag. 34 (8), 1455−1469.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Boni, H., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25 (5), 436−458.

Further reading

http://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-6417-4.pdf. Retrieved on August 15, 2018.

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Challenges in E-waste management in Sri Lanka

13

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13.1 Introduction

Safe management of waste of electrical and electronic waste or E-waste is serious issue of many countries. The alarming rate of electrical and electronic waste (E-waste) generation has become a major global concern (Raghupathy et al., 2010). In particular, it is a great challenge for developing countries due to extensive generation, transboundary movement, and lack of technical expertise (Herat and Agamuthu, 2012). It is estimated that the world generates around 20−50 million tons of E-waste annually, most of it from Asian countries. In this connection, management of electronic waste has become a priority concern in most of the developed and developing nations.

Electronic waste, commonly known as E-waste or waste of electrical and electronic equipment (WEEE), or end-of-life (EoL) electronics, denotes electronic and electrical equipment (EEE), including all components, subassemblies, and consumables, supposed to be out of date, or unwanted by the user.

Electrical and electronic equipment are electronic or electrical equipment that have become unwanted, nonfunctional, or obsolete due to technological advancements or that have reached the end of their useful life called as E-waste or WEEE which stands for waste electrical and electronic equipment. E-waste is mainly consisted of computers, mobile phones, printers, and cathode tubes due to their less life cycle.

There is no universally accepted definition of "electronic waste," or "E-waste," which is used as a general term for old, end-of-life, or discarded, electrical and electronic equipment, and which are supposed to be of no further value to their owners (Widmer et al., 2005).

A more comprehensive definition of E-waste can be observed in the European Parliament Directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE). Initially, it defines "electrical and electronic equipment" or "EEE" as "equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields falling under the categories set out in Annex IA and designed for use with a voltage rating not exceeding 1000 Volts for alternating current and 1500 Volts for direct current" (Herat, 2011).

The Waste Electrical and Electronic Equipment Directive (WEEED) of the European Union has identified 10 major categories of WEEE for reporting purpose (Table 13.1).

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00011-5

Table 13.1 Major categories of WEEE according to WEEED.

Category	Examples
Large household appliances	Refrigerators, ovens, washing machines, dishwashing machines, microwaves, electric heating appliances, electric fans, and air conditioners
Small household appliances	Vacuum cleaners, toasters, irons, coffee machines, appliances used for hair cutting, hair drying, tooth brushing, shaving and body care, clocks, and watches
IT and Telecommunication equipment	Personal computers, mouse, screen and keyboard, laptop computers, notebook computers, notepad computers, printers, copying equipment, electric and electronic typewriters, pocket and desk calculators, fax machines, cordless phones, cellular phones, and answering machines
Consumer equipment	Radio sets, television sets, DVD players, video cameras, video recorders, hi-fi recorders, and musical instruments
Lighting equipment	Lamps and bulbs
Electrical and electronic tools	Drills, saws, sewing machines, equipment used for turning, milling, grinding, sawing and cutting, tools used for riveting, nailing and screwing, tools used for welding and soldering, and tools used for garden activities
Toys, leisure, and sports equipment	Game consoles, electric trains, car racing sets, and video games
Medical devices	Radiotherapy equipment, pulmonary ventilators, and dialysis machines
Monitoring and control instruments	Smoke detectors, thermostats, and heating regulators
Automatic dispensers	Drink and money dispensers

13.2 Global scenario

In a new report on E-waste released by the United Nations University, global electronic waste has reached record high levels. 41.8 million tons of E-waste was generated in 2014, fueling concerns about the growing risks to public health, resource conservation and the environment.

According to the Global E-waste Monitor in 2016, the annual E-waste generation of the world is 44.7 million Metric Tons with an equivalent to 6.1 kg/inhabitant. The report also states that only 20% of the total E-waste generated (8.9 million MT) is documented to be collected and recycled through proper streams. From the remaining 80% of E-waste, 4% of E-waste from higher income countries are thrown into residual waste. The fate of the remaining 76% (34.1 million MT) is not known. It has been predicted that global E-waste generation will reach 52.2 million MT in year 2021 with a per capita generation of 6.8 kg/inhabitant.

When considered the regions in the world Asia is the highest generator of E-waste with 18.2 million MT while Europe and America generate 12.3 million MT and 11.3 million MT, respectively. However, Europe has the highest per capita

Table 13.2 The highest generators of E-waste.

Country	Total generation (million MT)	Per capita generation (kg/inhabitant)
China	7.2	5.2
USA	6.3	19.4
Japan	2.1	16.9
India	2.0	1.5
Germany	1.9	22.8
Brazil	1.5	7.4
Russia	1.4	9.7
France	1.4	21.3
Indonesia	1.3	4.9
Italy	1.2	18.9

Source: Blade, C.P., Wang, F., Wong, J., Kuehr, R., Hulsman, J., 2015. The global E-waste monitor United nations University, IAS- SCYCLE, Bonn, Germany (Blade et al., 2015).

generation of E-waste which is 16.6 kg/inhabitant. Africa is the lowest E-waste generator with 2.2 million MT and 1.9 kg/inhabitant.

Table 13.2 shows the 10 countries that generate most E-waste in the world. It should be noted that only 41 countries in the world has official E-waste statistics.

Sustainable Development Goals outlined by the United Nations Organization aims to achieve balance between economic and technological development in parallel to environmental sustainability. E-waste produces a significant challenge in achieving this balance.

SD Goal No. 3: Good health and well-being, tries to ensure healthy and long lives for all, eliminating or reducing major disease such as cancers, malaria and tuberculosis.

SD Goal No. 6: Clean water and sanitation ensure access to safe drinking water and sanitation for all. Millions of people, mostly children die every year from diseases associated with poor quality water and inadequate sanitation.

SD Goal No. 11: Sustainable cities and communities aims to make cities inclusive, safe, resilient, and sustainable to live. The challenge is to maintain clean cities while allowing them to grow.

SD Goal No. 12: Responsible consumption and production ensures sustainable consumption and production patterns. It tries to reduce future economic and social costs of development efforts, by reducing resource use, degradation, and pollution along the whole life cycle of economic activities. It also encourages customers for sustainable consumption and lifestyles.

Management of E-waste is a worldwide challenge in achieving the sustainable development goals. Several conventions and policies have been introduced from time to time in order to manage E-waste.

- The Basel Convention on the Control of Transboundary Movement of Hazardous Waste and their Disposal in 1989 seeks to reduce hazardous waste generation, restrict their transboundary movements, and promote environmentally sound management.

- The Rotterdam Convention in 2004, promotes shared responsibility between E-waste exporting and importing countries. It provides for obtaining and disseminating information to enable E-waste importing countries to decide whether they are willing to receive E-waste from the exporting countries.
- Waste Electrical and Electronic Directive of the European Union in 2012, aims to protect environment and human health by preventing or reducing the adverse impacts of E-waste by laying down regulations for product design and obligations at the end-of-life of the product. It promotes reuse, recycling, and other forms of recovery of E-waste so as to reduce disposal, and all operations involved in the life cycle, especially treatment of E-waste. This makes manufacturer responsible for collecting, recycling, and disposing of E-waste.
- Restriction of Hazardous Substances (RoHS) Directive in 2011, restricts the use of hazardous substances in the production process and promote environmentally sound recovery and disposal. It restricts the use of six hazardous substances including heavy metals such as lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyl, and polybrominated diphenyl ethers in the manufacturing process of new electrical and electronic equipment.

13.3 Environmental and health hazards of E-waste

E-waste is more harmful than other municipal solid waste (MSW) because they contain heavy metals such as lead, cadmium, arsenic, and mercury, persistent organic pollutants (POPs), flame retardants, and other potentially hazardous substances. It has been predicted that E-waste is growing almost three times the rate of MSW in the world. Table 13.3 illustrates health effects of some elements present in E-waste.

Improper handling of E-waste adds toxic matter to environmental cycles through:

- Leachates from dumping sites
- Particulate matter from dismantling activities
- Fly and bottom ash from burning activities
- Waste water from dismantling and shredding facilities

Emissions during burning of E-waste can give rise to greenhouse gases contributing to global warming. Leachates from dumping sites can cause pollution of water bodies and ground water as well as acidification of soil. Hazardous particles contained in E-waste get accumulated in fauna and flora and can enter human bodies through food chains.

13.4 Sri Lankan scenario

Being the country with a highest literacy in the region the government has identified the need to develop country’s capacity in information sector and enhance the

Table 13.3 Negative effects on health by some elements present in E-waste.

Elements	Effects
Arsenic (As)	Carcinogenic substance (skin and lung cancers), cardiovascular disease, and skin lesions
Barium (Ba)	Muscle weakness, damages to heart, liver, and spleen
Cadmium (Cd)	Carcinogenic substance, kidney and lung damage, deficits in learning behaviors, elevated blood pressure, and effects on respiratory system
Chromium (Cr)	Carcinogenic substance, can even cause damages to DNA in cells
Copper (Cu)	Toxic to lungs and mucous membrane, very hazardous if inhaled or contacted with eyes
Lead (Pb)	Causes damage to nervous systems, blood systems, and kidneys, and affects the brain development of children
Mercury (Hg)	Memory loss, sensory impairments, reproductive failure, nausea, vomiting, diarrhea, damages to brain and kidneys, and corrosive to skin and eyes
sulfur (S)	Damages to liver, kidneys, and heart, and suppression of immune system
Silver (Ag)	Damages to eyes through direct contact, repeated exposure may produce general deterioration of health by accumulation in one or many human organs
Zinc (Zn)	Abdominal pain, diarrhea and vomiting, direct contact can cause eye irritation

e-literacy among the citizens. Cumulatively all these reasons lead to boost the generation of E-waste. Like other developing countries in Asia and Africa, Sri Lanka is now confronted with the huge problem of E-waste. Trading of electronic items has become a common practice and the number of sales centers had increased notably within past two decade.

As per the status report on Electronic and Electrical Waste Management in Sri Lanka published by the Central Environmental Authority (CEA) in 2017, total number of EEEs put to the market each year during 2007−15 shown in Table 13.4. As per the said report total number of EEEs put to market increased 22-fold during 2007−15.

13.4.1 Growing demand for electrical and electronic equipment in Sri Lanka

The urbanization rate of Sri Lanka is expected to increase annually by 3%−4% from the current 18.38% of urban population who lives in urban areas and in cities. The urban population contributes for generating MSW which is about 1.0 kg/person/day in Sri Lanka. Although E-waste constitutes about 0.2% of the MSW at present. It is expected to grow with increased urbanization and enhanced quality of life (WRMPP, 2016).

Table 13.4 Summary of total imports in Sri Lanka from 2007 to 2015.

Equipment	Sum of net units (nos.)									Grand Total
	2007	2008	2009	2010	2011	2012	2013	2014	2015	
Air conditioners	**35,555**	**90,582**	**35,378**	**139,768**	**118,455**	**83,639**	**62,450**	**79,496**	**79,529**	**724,852**
Refrigerators	1849	3909	63,606	18,561	49,724	193,413	110,503	130,214	166,566	738,345
Photocopier/Fax		17,372	133,867	146,274	166,194	170,028	139,445	150,841	165,917	1,089,938
Washing machines	20,190	59,216	24,805	42,827	64,822	77,485	28,539	27,587	33,700	379,171
Computers		33,119	202,777	297,192	474,833	519,610	504,848	422,869	401,449	2,856,697
Electric ovens	57,168	82,066	58,226	103,618	142,197	227,357	170,745	138,150	182,960	1,162,487
Mobile phones		225,915	777,143	1,485,248	3,455,947	3,846,712	4,046,694	4,710,247	5,855,551	24,403,457
Televisions	111,950	311,115	163,655	323,689	1,004,838	515,429	442,760	472,529	740,249	4,086,214
Electronic toys	139,377	38,411	2,843,912	3,287,374	3,926,464	3,657,662	419,406	417,566	373,830	15,104,002
Equipment	**Sum of net mass (kg)**									**Grand Total**
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	
Air conditioners	**5,548,690**	**2,747,642**	**1,807,416**	**3,397,114**	**3,977,590**	**2,877,346**	**3,111,185**	**3,375,921**	**4,282,547**	**31,125,451**
Refrigerators	67,185	219,185	558,925	855,541	2,049,982	6,378,340	4,173,688	4,228,004	6,956,737	25,487,587
Photocopier/Fax		171,275	1,074,835	1,321,872	1,749,705	1,502,970	1,837,318	1,745,852	2,018,322	11,422,149
Washing machines	520,829	1,261,824	766,911	1,229,140	1,731,084	1,639,460	952,895	813,729	1,170,295	10,086,167
Computers		404,336	1,863,687	2,765,118	3,320,947	3,361,109	3,027,080	2,697,920	2,435,755	19,875,952
Electric ovens	420,382	582,770	428,897	806,406	1,126,874	1,132,496	1,070,703	1,066,402	1,373,720	8,008,650
Mobile phones		177,067	442,676	493,764	982,936	13,552,995	1,061,712	1,255,062	1,501,295	19,467,507
Televisions	2,249,845	6,109,928	3,160,094	5,405,772	5,761,944	4,543,958	3,158,345	2,925,134	4,180,156	37,495,176
Electronic toys	95,649	36,678	2,551,423	3,127,996	3,548,467	2,909,016	363,286	334,067	354,289	13,320,871

Source: Sri Lanka Customs.

A noticeable increase was shown in the EEE use in Sri Lanka during the past two decades and with the economic growth of the country EEE use is predicted to grow further in the coming decade. Sri Lanka's EEE manufacturing sector is small and it largely relies on imports to meet the country's demand.

Sri Lanka ratified the Basel Convention on the Control of Transboundary movement of Hazardous Waste and their disposal in 1992. In line with the decision taken at the sixth Conference of the Parties of Basel Convention, a National Implementation Plan and the and the preliminary inventory of electronic waste management was prepared in 2008. The implementation plan recognized the Electronic waste management as a priority issue which needs urgent attention.

Since the adoption of "Free market economy" in Sri Lanka demand for electrical and electronic equipment (EEE) is continuously in the increasing trend. EEE such as mobile phones, computers, televisions, washing machines, and refrigerators has become necessities because of the convenience they give in handling the daily tasks, and the comfort they provide. Among other electronic devices a significant increase in the usage of computers and mobile phones has been observed during the past few years. Table 13.5 shows the growth of telephone penetration per 100 citizens in Sri Lanka from 2013 to 2016.

According to the Telecommunication Regulatory Authority of Sri Lanka, it shows 61.06% of overall mobile connectivity index score. Which means almost 27.38 million mobile connections exists in Sri Lanka, where population of approximately 21 million. Mobile penetration has risen from 126% in 2017 to 131% in 2018 which has been increased by several folds. This indicates that the Sri Lank is with the highest mobile penetration in the South Asian Region.

The records of Department of Census and Statistics of Sri Lanka shows that the percentage of computer owned households has also increased from 22.5% in 2016 to 23.5% in 2017. It is predicted that the demand for EEE, especially mobile phones and computers will be increased at a faster rate in the coming years due to technological advancements that add more attractive features to the items day by day as well as competitive prices and promotional campaigns among importers that operate within the country.

The EEE market in Sri Lanka is dominated by imported items. Imported EEE is responsible for approximately 95% of the market and that importation has been increased during the past few years. However, there are few local producers of

Table 13.5 Telephone usage in Sri Lanka.

Year	No. of cellular phones	Telephone penetration (per 100 citizens)
2013	20,315,150	111.87
2014	22,123,000	119.56
2015	24,384,544	128.71
2016	26,227,631	135.73

Source: Annual Report, 2016. Central Bank of Sri Lanka.

Table 13.6 Local production of EEE.

Year	No. of units	
	Washing machines	Refrigerators
2011	78,000	38,000
2012	86,500	46,000
2013	78,500	43,500
2014	99,000	53,000
2015	130,000	90,000

Source: Ranasinghe (2017).

Table 13.7 Contributors to E-waste in Sri Lanka.

Component	Average lifespan (years)
Personal computers	3–8
Printers	1–8
Televisions	15–20
Mobile phones	2
Refrigerators	15–20
Air-conditioners	5–15
Photocopy machines	5–10
Washing machines	15–20

Source: Development of National Implementation Plan for Electrical and Electronic Waste Management In Sri Lanka Final report, 2008.

equipment such as washing machines and refrigerators, and the local production is also in the increasing trend as shown in Table 13.6.

A survey carried out by the CEA of Sri Lanka in 2008, has revealed that approximately 30% of imported computers are secondhand items. Limited purchasing power of countries such as Sri Lanka has created a growing secondhand market for EEE. There are 140 importers registered with the CEA that import secondhand items. The danger in secondhand or used items and locally assembled equipment is that they possess a shorter lifespan than their original counterparts or reputed brands. Therefore they become unusable within a shorter period and add up to E-waste. It has been estimated that per capita generation of E-waste in Sri Lanka as 4.2 kg/year. Table 13.7 shows electrical and electronic equipment that contribute to E-waste in Sri Lanka and their average life span while Table 13.8 shows the penetration and trend in EEE use in the country.

The census study on computer literacy done in 2015 (DCS, 2015) indicates that at least one computer is available in 25% of households of the country. Overall computer literacy reported in Sri Lanka by 2015 is 26.8% (CEA, 2018). The main contributors to E-waste in Sri Lanka are the households, industries, and the commercial sectors. It has been estimated that per capita generation of E-waste in Sri Lanka as 4.2 kg/year.

Table 13.8 Penetration and trend in EEE use in Sri Lanka.

Census period	Population	Household size	No of estimated households in million	TV (%)	PC (%)	Mobile phones (%)	Washing machines (%)	Refrigerators (%)
2012/2013	20,359,439	3.9	5.22	82.7	18.5	87.6	17.2	46.2
2009/2010	20,675,000	4	5.17	80	12.5	77.1	13.1	39.6
2006/2007	19,773,000	4	4.94	81.3	7	77.3	10.8	35.1
2003/2004	19,232,000	4.31	4.46	70.8	4.1	24,5	7.6	29.7
1996/1997	18,336,000	4.61	3.98	50.61	0.4	4.5	N/A	16.8
1986/1987	15,628,000	5.1	3.06	19.6	N/A	1.4	N/A	8.1
1981/1982	14,846,750	5.2	2.86	1.8	N/A	0.9	N/A	2,9

13.4.2 National electrical and electronic waste management policy in Sri Lanka

Policy on E-waste management was drafted and called for public comments in 2008. As stated in the E-waste policy it is a timely action that has to be taken in managing electrical and electronic equipment in a manner which is sustainable throughout its life cycle and it is also necessary to honor and comply with the provisions of the Basel Convention and other related Conventions ratified by the country in managing E-waste.

The key policy objectives of the National Electrical and Electronic Waste management policy were identified as follows:

- Prevent/minimize negative impacts to the environment and health of the people due to haphazard use of e-products and disposal of E-waste.
- Promote integrated E-waste management by looking at all phases of the life cycle of the product and take action where it is most effective to prevent disposal of E-waste in scattered locations and ensure maximum resource recovery.
- Secure social responsibility toward sustainable production and consumption of e-products.
- Ensure waste treatment and final disposal of E-waste in an environmentally sound manner.

13.5 Analysis of electronic and electrical equipment market in Sri Lanka

Electrical and electronic equipment market of Sri Lanka mainly depends on the imported goods. However, there are few locally manufactured electrical and electronic items available. E-vendors evident that there is a tendency in consumers moving toward locally manufactured products as well.

13.5.1 Electronic and electrical Items manufacturers/assemblers

At present only washing machine, refrigerators, and computers are manufactured and assembled in Sri Lanka. There are only three large scale electronic and electrical assembling industries engaged in manufacturing equipments under brand names. One industry is engaged in assembling computers ranging from tablet PC, laptops, and desktop computers and other two companies are engaged in assembling washing machines and refrigerators. These are vendors who assemble computers mislead by providing rough figures on their manufacturing items to avoid the tax payment. However, the estimates show that local production of refrigerators demonstrated remarkable growth within 2014−15. The production has increased in nearly threefold within last 5 years.

Except in 2013 there is nearly twofold growth in local production of washing machines in 2015 comparing with 2011.

13.5.2 Computer assembling

As per the interviews carried out with the computer assemblers, a prominent tendency of dominating branded products in the market is showed between 2005 and 2014 with respect to 1995 and 2004, where the demand for assembled products were very high as at that time there was a big gap in the cost of assembled and branded products.

13.6 Electronic item importers

Imported electronic and electrical goods are account for nearly 95% of the market share. Table 13.9 shows that import data of other types of EEE 2008−14. When looking through the custom data on importations there is a significant growth in importation of electronic goods.

13.6.1 Secondhand electronic item importers

There are nearly 140 secondhand electronic item importers that have been registered at the CEA as they have to obtain no objection and clearance from the CEA upon importation of used electronic items mainly for used computers, washing machines, and televisions. However, cathode ray tube (CRT) monitors are banned to be imported. These used EE goods generally coming from South Korea, Australia, Singapore, and Japan. This registration mechanism only started in 2014.

These imported computers and washing machines are sold at retail shops in island wide. These vendors directly import used e-items as per the demand.

Inadequacy of import-export regulations allows importation of secondhand equipment with relatively low lifespan, which makes Sri Lanka a dumping yard for low quality and used EEE.

Table 13.10 shows the number of secondhand computers and washing machines which were imported to Sri Lanka in year 2016.

It is inevitable that these computers add into E-waste within 2−3 years. The process becomes more rapid due to high humidity level and high temperature in Sri Lanka. There are huge amounts of unusable electronic items gathered at household level, due to lack of proper island wide efficient collection system. The number of sellers that provide take back offers is also very low.

However, after 2016, government restricted importation of used computers and some other e-items were not allowed. However, importers are tricky enough to import the computers as “knocked down” goods and get those assembled locally as there are no any kind of controls over used parts in the legislation.

Table 13.9 Import data of other types of electronic and electrical equipment 2008−14.

S. No.	EEE Category	2008	2009	2010	2011	2012	2013	2014
		Qty (units)	Qty (units)	Qty (units)	Qty (units)	Qty (units)	Qty (units)	Qty (units)
1	Electric heater	72,783	26,470	52,433	55,739	50,719	37,487	185,931
2	Iron	698,376	358,219	89,012	841,576	683,227	736,822	511,803
3	Kettle	243,484	395,202	556,494	1,228,965	1,105,606	1,021,725	1,028,268
4	Microwave oven	16,387	13,686	20,249	32,280	28,660	26,731	15,640
5	Hair dryer	15,480	11,243	33,323	50,833	34,450	31,139	52,510
6	Vacuum cleaner	12,560	39,800	1732	28,718	35,195	38,570	39,125
7	Rice cooker	275,647	135,679	301,881	1,064,624	882,387	681,832	603,670
8	Electric hay mower	33,342	13,083	15,856	16,354	41,397	8430	19,916
9	CD, DVD, and blue ray player	189,697	149,589	248,647	648,322	614,110	383,352	326,951
10	Camera	49,538	34,816	106,336	239,521	277,758	280,010	266,082

Table 13.10 Importation data of second hand computers and washing machines 2016.

Month	Computers	Laptops	LCD monitors	CPU	Washing machines
January	3491	1076	6313	1913	3361
February	3321	749	6554	3791	4231
March	5347	1603	8470	2314	3953
April	31,738	17,754	57,767	34,027	37,355
May	2407	2537	6157	2640	4880
June	7628	2987	12,459	3724	4366
July	8419	3058	9914	4821	8827
August	5492	1954	15,069	10,943	8360
September	3776	4101	8037	8569	8021
October	2482	2606	6806	2640	4880
November	5103	2331	7253	1811	1327
December	7498	3269	4432	1030	4924
Total	**86,702**	**44,025**	**149,231**	**78,223**	**94,485**

Source: Central Environmental Authority.

13.7 Usage of electronic items in household level: desktop or laptop computers

Table 13.11 shows the percentage distribution of computer owned households by Sector/Province levels. In 2014, at least one computer is available in 22% of households of the country. That is one out of every five households is having a computer. This percentage is about 36% in Urban Sector and Rural and Estate Sector show 20.4% and 4.6%, respectively. The highest availability is in Western province (33.0%) while the lowest availability is reported from North Central province. Over the survey periods from 2004 to 2014 overall percentage has increased sharply from 3.8% to 16.6%.

Table 13.12 illustrates computer owned households in Sri Lanka. By the year of first acquisition of a computer—2014. Accordingly, 65% of the households have acquired the first computer during the last 5 years (2010−14) and the Rural sector shows a higher recent acquisition (68%) than the urban sector (55%).

13.8 Mobile-cellular penetration in Sri Lanka

In 2011, Sri Lanka had an estimated 18,003,447 mobile phone subscribers. By the end of December 2012 the number was 20.3 million. This is for 20.8 million people (International Telecommunication Union, 2015).

Sri Lanka has a relatively high mobile-cellular penetration when compared to the Asia-pacific region. Fig. 13.1 illustrates the worldwide mobile-cellular penetration. By beginning 2012, the country's mobile penetration level was higher than the world and regional averages, which has more than doubled from around 27% in

Table 13.11 Percentage of computer owned households in 2004, 2006/2007, 2009, and 2014.

Sector/Province	Desktop (%)				Desktop or laptop (%)	
	2004	2006/2007	2009	2014	2009	2014
Sri Lanka	3.8	8.2	10.6	16.6	11.4	22.4
Urban	10.5	17.8	23.6	25.8	26.3	35.8
Rural	3.1	6.9	9.2	15.3	9.8	20.4
Estate	0.3	1.1	3.1	2.7	3.3	4.6
Province						
Western	8.4	16.4	19.0	24.5	20.7	33.0
Central	3.3	6.7	9.7	18.0	10.4	23.5
Southern	2.2	4.9	6.6	16.0	7.2	21.0
Northern	NA	NA.	NA	10.8	NA	19.5
Eastern	1.2	3.7	5.8	9.6	5.9	14.7
North-western	3.1	4.8	6.9	14.5	7.1	20.1
North-central	1.4	2.7	6.1	7.4	6.8	10.1
UVA	0.4	2.7	4.6	9.2	4.9	11.1
Sabaragamuwa	2.0	3.3	7.3	13.7	7.5	16.6

NA, not available.

Table 13.12 Computer owned households by the year of first acquisition of a computer—2014.

Sector	Total	Before 2001	2001–04	2005–09	2010–14
Sri Lanka	100.0	5.0	6.6	23.7	64.7
Urban	100.0	6.8	9.8	28.0	55.5
Rural	100.0	4.3	5.5	22.3	67.8

Source: Ranasinghe, A.R.M.W.W.K., 2017. Assessing E-waste management system in Sri Lanka and suggesting mechanism to streamline the existing system. Master Thesis of Environmental Science, The Open University of Sri Lanka.

2006 to over 87% by end 2011. The large majority (around 90%) of mobile cellular subscriptions in the country are prepaid. The percentage of the population covered by a mobile cellular signal stood at 98% by beginning 2011, with virtually by 2019 all Sri Lankans covered by a mobile cellular signal.

13.9 Overview of electronic and electrical waste generation and management in Sri Lanka

According to past evidences, the WEEE management establishments had informally started their operations nearly a decade before. This was done through scrap

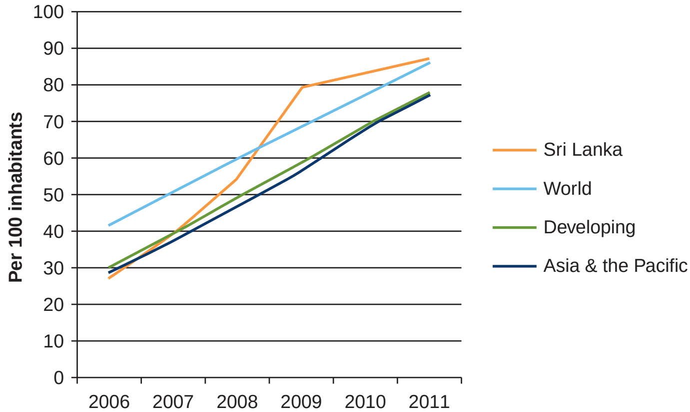

Figure 13.1 Worldwide mobile-cellular penetration from 2006 to 2011. *Source: Ranasinghe, A.R.M.W.W.K., 2017. Assessing E-waste management system in Sri Lanka and suggesting mechanism to streamline the existing system. Master Thesis of Environmental Science, The Open University of Sri Lanka.*

collectors and collecting end-of-life EEEs obtained from corporate sector in bulk when they remove the stock piled E-waste. At the beginning, only two or three E-waste collectors were operated in Colombo distict in Western province, where generation of WEEE was considerably high.

In 2008, certain types of WEEEs had been subjected to regulate under the National Environmental Act by mandating the Scheduled Waste Management license for all E-waste management activities carry out in industrial scale. In parallel to the internal legal framework, government has adopted Basel Conventions' notification procedure for exportation of WEEEs. Currently, it is being strictly implemented and on importing country's consent, exportations are not allowed. Through these procedures, a legal barrier had been set up to control informal exportations.

13.9.1 The stakeholders contribution on waste of electrical and electronic equipment collection

As per the interviews carried out with the "formal E-waste collectors" it was noted that after 2010, formal sector collectors expanded their operations in a more organized way with business agreements with corporate sector. Also they started expanding the collection mechanism throughout the country with their own door-to-door collection. Currently there are 11 E-waste mamagement facilities in operation and all most all are localized to Colombo District.

In 2010, CEA came into a "Memorandum of Understanding" with a telecommunication service provider to establish an island wide collection mechanism for M-waste (waste mobile phone). Through this program, all franchise shops and sales arcades had been converted as collection centers. Under this program there were 47 collection points established to collect waste mobile phones. According to the records this was not very successful as only a very less amount of mobile phones were collected island wide.

In 2011, CEA launched "National Corporate E-Waste Management Program" under a common logo and theme of "ensuring an E-waste free environment." Through this 14 private and public sector partner organizations had signed a "Memorandum of Understanding" with the CEA. Telecommunication service providers, electronic venders, E-waste management companies, and software companies were participated as stakeholders in the national level. The objectives of this program was to establish an island wide collection mechanism, organized drop off events and raising awareness among citizens. This program is still in progress and in 2014 partner organizations have been increased up to 21. Awareness created through this program has boosted the people to enter in to the WEEE business. Even though the main objective of the National Corporate E-Waste Management Program was to establish island wide collection network and it was not sucessfully achieved yet.

When analyzing collection network it was clearly noted that the formal sector collection and storages had been expanded nearly twofold within past 4 years and they do their collection, storage and dismantling practices in more organized way. However currently, only seven formal sector collectors are in operation.

There is a significant tendency for mandating the "Scheduled Waste Management License" as a primary requirement in many public sector and business establishments when they calling tenders to handover their obsolete EEEs. This has induced the informal sector to obtain the license and operate in a formal way.

A recycling facility has been established in the Katunayake export processing zone in 2017 filling the gap of unavailability of a recycling facility in the country. As the current practise only the plastic and metallic components are sold to downstream vendors; recycled internally while all the printed circuit boards are exported. At present, one E-waste management company is in the process of establishing recycling facility (having the processes of metal refining) aimig to cater the entire downstream management of WEEE.

There is a significant expansion of informal sector operations all over the country starting from door-to-door collection and ending up with rudimentary dismantling and metal recovery practices. Mainly scrap collectors are engaged in this business and is operated in domestic level in some localities, which has become a community-based operation.

13.10 Formal sector development in waste of electrical and electronic equipment

Curently there are 10 formal sector collectors bearing "Scheduled Waste Management License" to collect WEEEs are currently in collection operations. Out of these formal sector collectors, all 10 collectors are stationed in Colombo and

Figure 13.2 E-waste collection facilities by mobile phone service providers.

suburbs and five are baring export consents as well. Formal sector development of WEEE is depended on following factors:

1. *Formal sector WEEE management facilities*
   The formal sector collectors ususlly target bulk collections mainly from corporate sector. Modified colletion vehicles with attractive displays are used to collect E-waste in such situations. However the formal sector collectors have stong link with the informal sector as informal sector sell the dismantled parts to the formal sector though there is considrable competition amoung collectors.
2. *E-venders and telecommunication service providers*
   Electronic item venders and Telecommunication service providers who have entered in to a "Memorandum of Understanding" with the CEA had established WEEE collection points in their island wide sales outlets. This mechanism started in 2009 by a telecommunication service provider for the first time. In 2010 and 2014, some other telecommunication service providers and some e-venders joined to the island wide collection network. There are collection centers operate island wide through this mechanism. Normally e-venders collect all most all WEEE devices where as telecommunication service providers collect only mobile phones and batteries. In these sales outlets, a drop-off box had been kept to drop the waste mobile phones. E-waste collection facilities by mobile phone service providers are shown in Fig. 13.2. These collectors having agreements with formal sector WEEE management establishments. CEA monitors this mechanism. However, this sector is not operating in a successful manner as the collection target only their customers. As per the records in some occations, only a very few units have been collected. However, it was noted that state owned mobile service provider has done very significant contribution in raising awareness among citizens and also organizing islandwide drop off events under special programs.
3. *Extended producer responsibility (EPR) of e-vendors*
   E-venders practicing EPR policy also contribute in collection mechanism. Through these mechanisms, consumers can take back waste electronic devices to retail stores that distribute similar electronic items. Because consumers could get back the electronic item at the retail store in reduced price for purchase of a new product. Mainly the refrigerator, TV sets, and air conditioner vendors are engaged in these EPR-based collection mechanism. Basically e-vendor companies practicing this mechanism very active as a very viable strategy to market thier new products. Under this they take the old products

Table 13.13 Exportation of Lexmark torner cartridges.

Year	2013	2014	2015
Number of units exported	5850	11,250	13,840

regardsless of the brand and consessions given to new products. It was revealed that most of these collected WEEE are being directed to the informal collectors.

However, there is a one sucessfull EPR practise being implemented by the local agent of Lex Mark Toner cartridges who collects used cartridges and reexports to the mother company aiming brand protection. Exportation of Lexmark Torner cartridges in 2013–15 are shown in Table 13.13. This is done in complience with the regulatory requirement. Strategies are implemneted for direct taking back from the customers. In addition special drop off events and special promotional programs to collect toners too are carried out.

4. *Nonprofitable agencies/nongovernment organizations (NGOs)*

   Some nonprofitable agencies and NGOs implement collection programs with awareness on WEEE. Currently only one such organization avialble in the country and the amount they collect is very less comparatively. All the collected E-waste are being directed to the licencsed collectors.

5. *Informal sector collectors*

   Informal sector collectors operate their collection activities mainly as door-to-door collection. Their collection mechanisms link with economical mechanism as well. Generally the metal scrap collectors are the key players in this sector. Informal sector collection is distributed throughout the country covering all 25 districts. Unlike the formal sector, informal sector collection operations are distributed within rural areas as well (when comparing with the formal sector, informal sector dominating in rural areas). The collection network of the informal sector may consist of several modes of linkages such as buyers, intermediates, and transporters. This can be considered as the most active collection system in the country. In general small carts and small trucks are used in door-to-door collection. It is extremely difficult to collect the data from informal sector.

6. *E-waste collection through special programs*

Since 2010 the CEA and the partner companies of national E-waste cooperate program held drop off events to collect electronic waste. A drop off event conducted by the CEA is shown in Fig. 13.3. According to the CEA these drop off events mainly aimed to drag the E-waste stagnated in the household level. These drop off events are considered as one of the most sucessfull and effective collection methods.

13.10.1 Sectors engaged in dismantling of waste of electrical and electronic equipments

Dismantling of WEEEs is popular in Sri Lanka as it is required for recycling and recovery as well as for transboundary movements. However, recycling and recovery facilities which operate environmentally unsound manner causing significant environmental and health impacts due to significant amounts of E-waste containing hazardous materials dumped in open-land and waterways (Herat and Agamuthu, 2012). In addition, major environmental and health impacts occur during open burning of E-waste to recover expensive metals. However recycling, dismantling, and recovery

Figure 13.3 E-waste drop off events.

Figure 13.4 Handling E-waste in a formal sector facility.

operations are conducted by mainly informal employment sector in Sri Lanka; however, other sectors where provide significant contribution.

1. *Formal Sector*

   Formal sector dismantling is also carried out by the formal sector collectors which is also an activity covered under the "Scheduled Waste Management License" (hazardous waste management license). General practice in all these formal sector dismantling facilities is manual dismantling to separate printed circuit boards, plastics, and other metal components. Normally 2–20 workers are engaged in dismantling operations in these establishments and some had been provided with adequate trainings. Handling E-waste in a formal sector facility and dismantleing are shown in Figs. 13.4 and 13.5. Such facilties are mainly localized to Colombo and suburbs. Currently there are eight formal sector dismantling facilities in operation.
2. *Electronic item repair shops*

   Some electronic item (e-item) repair shops engage in dismantling operations. E-items that cannot be repaired further are dismantled and components are segregated to be sold out. Mainly removed circuit boards are sold to E-waste collectors.
3. *Informal sector dismantlers*

Generally, the urban poor has engaged in the dismantling of E-waste. Informal sector dismantlers spread all over the country and in most cases operations are going-on in domestic level. Mainly in Colombo district, informal sector operations

Figure 13.5 Splitting cables in a formal sector dismantling facility.

Figure 13.6 Informal sector dismantlers.

are widely found in unauthorized settlements in water body reservations and slums. Usually the scrap collectors are engaged in dismantling of WEEEs. In addition, there are some cottage level establishments dedicated only for dismantling WEEEs. Fig. 13.6 shows an dismantelling operation of PC moniors by informal sector dismantlers. Informal sector collectors sell their E-waste to these establishments is a common practice in Sri Lanka.

Most significant observation made was stockpiled cathod ray tube monitors in large numbers. This was common to all most all of the dismantling facilities. In these places dismantlers simply burn the cables to recover coper which has a comparatively higher economical value. Copper components of the cathod ray tubes are recovered and they openly dump the broken cathod ray tubes which is having lead in the glass. This malpractice will create impacts due to leaching lead in to the environment.

13.10.2 Sectors engaged in treatment and disposal of waste of electrical and electronic equipments

Although there are several sectors involved in E-waste collection in Sri Lanka, there is no formalized country-wide collection system for E-waste. The main E-waste collectors identified as:

1. Formal sector: usually target collection from the corporate sector through predetermined agreements.
2. Telecommunication service providers: have established WEEE collection points in their sales outlets.
3. E-vendors who offer take back services: consumers can get a discount when they purchase a new product if they return the used product such as televisions and refrigerators.
4. Informal sector collectors: usually go from door−to-door and mainly collect household items. They are the most dominating E-waste collectors in the island and their network is distributed in urban, semiurban, and rural areas of the country.

There is a significant link between informal sector and the formal sector E-waste collectors and handlers. Informal sector plays an active role through having island wide collection network and door-to-door collection. Formal sector dominates handling bulk quantities and exportations. Even though there is a control for the formal sector under the Scheduled Waste Management License, the government has no sufficient control over the informal sector.

As informal sector establishments have increased rapidly within the past few years and due to difficulties in accessing them policy makers and relevant regulatory bodies could not able to effectively interfere in streamlining this sector. An integration of all stakeholders such as Electronic item importers, consumers, E-waste collectors, and exporters is at a low level due to insufficient awareness and inadequate use of economic instruments in E-waste management.

13.10.3 Sectors engaged in waste of electrical and electronic equipment treatment

At present the CEA has granted approvals to establish an E-waste recycling or treatment plant at Katunayake Export Processing Zone. This facility will start operations in January 2017. According to the industrialist they developed strategic business agreement with precious metal smelters to refine precious metals by paying a processing fee for the service. We trade refined gold, silver, platinum, lead, copper, and cobalt in metal trade platforms globally.

As the current practice the plastic components and the metallic parts recovered out of WEEE are being recycled locally. Plastic components recovered from WEEEs are crushed in recycling facilities. These recycling facilities are mostly operated as small and medium scale enterprises (SMEs). Recycled plastics are being generally used to manufacture electric switches, plugs, shoe soles and heals. The recovered metal parts are sold to smelters. Out of these recycling/treatment facilities, only few recycling establishments are operated as formal sector.

During the last decade business establishments which are engaged in electronic waste management totally rely on exportation market of electronic waste. At present some large scale electronic waste collectors in informal sector tend to invest on recycling and metal refining facilities. However, there are a considerable amount of E-waste continues to be recycled by the informal sector. All most all of these processes are rudimentary in nature and could be dangerous some processes involve burning, breaking of CRTs and physical processes to recover materials. These result in release of toxic materials to the environment through emissions and effluents. In addition, there is a great potential to cause health impacts to the workers. Fig. 13.7 shows the typical informal sector operations.

Generally the urban poor, localized within Western province has engaged in the trade of waste and recycling which is a most unsafe and polluting livelihood opportunities for survival. Dismantling of electronic items or E-waste is also dominated by the informal sector. Most of the workers involved in such works lives in unauthorized settlements close to marshes and river banks are the urban poor who are unaware or do not bother of the hazards associated with these practices. This makes the situation worse as they do not have the skills and knowledge required in E-waste handling.

13.11 Waste of electrical and electronic equipment disposal and environmental concerns due to heavy metals

In Sri Lanka secured landfill facility is not available to dispose hazardous waste. The only disposal activity that could be observed in relation to E-waste is, open dumping by the informal sector. Fig. 13.8 shows a typical haphazard disposal of E-waste by informal sector. Once they recover the parts, which are having economical value while the rest are dumping in haphazard manner creating several environmental issues.

Figure 13.7 Informal sector operations.

Figure 13.8 Haphazard disposal of E-waste by informal sector.

At present in several municipal dump yards electronic waste are observed. There is a very big possibility of leaching heavy metals contained in these E-waste in to the soil and the ground and the surface water. Several studies done in MSW dump yards indicated metal pollutants in the leachate. Joseph et al. (2018) reported that leachate of active dump site at Karadiyana shows higher concentrations than the stipulated levels of selected trace metals, such as Fe, As, Cu, Ni, Cd, Zn, Pb, and Mn while Wimalasuriya et al. (2011) made similar observation at Gohagoda dumpsite. The both occasions the recorded values are higher than the reported values of Sewwandi et al. (2013). Table 13.14 shows that the heavy metals in leachate of the various dumpsites indicated the presence of metals in higher concentrations which exceeds tolerance limits (Sewwandi et al., 2013).

13.12 Electronic waste exporters

Transboundary movements are taken place by electronic waste exporters. Currently there are seven electronic waste exporters engaged in exportation bearing approvals as per the Basel Convention. Mainly printed circuit boards, batteries and CRTs are exported for the recycling facilities in South Korea, United Kingdom, Singapore, Hong Kong, Japan, the Netherlands, Belgium, and Germany. However, only one company has obtained approvals to export CRT to the Netherland where the cathode ray processing facility is available. Details of formal sector E-waste exporters data following data are shown in Table 13.15.

Although E-waste exporting has become a profitable business, Sri Lanka is yet to tap the E-waste exporting market. There are few companies that export E-waste such as circuit boards and batteries to other countries. But this E-waste is exported without any value addition. The receiving countries are Japan, Singapore, South Korea, Germany, and Belgium.

Table 13.14 Heavy metals in leachate of municipal dump yards.

Sample location	Heavy metals in leachate (ppb)								
	Cr	**Fe**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Cd**	**Pb**
Bandaragama	329	7167	912	227	5362	722	2607	90	479
Gampola	220	5546	335	734	462	164	461	4	34
Gohagoda	470	77,000	1900	190	6600	170	220	20	500
Rathnapura	439	56,343	1311	627	1685	1551	4922	52	168
Kolonnawa	1968	346,930	4473	55	11,759	705	2443	15	421
Galle	486	15,477	673	564	593	1796	5947	52	169
Wennappuwa	363	2501	399	431	409	939	2812	53	87
Negombo	330	20,111	666	535	2062	846	2184	51	333
Matale	345	60,762	115	573	6876	522	1935	100	1777
Hambanthota	80	5341	226	166	19,909	678	2522	172	492
Kataragama	11	1117	89	58	638	106	400	50	123
Max permissible level	100	3000	3000	3000	5000	200	500	100	100

Source: Sewwandi, B.G.N., Takahiro, K., Kawamoto, K., Hamamoto, S., Asamoto, S., 2013. Evaluation of leachate contamination potential of municipal solid waste dumpsites in Sri Lanka using leachate pollution index. <http://www.sjp.ac.lk/wcup/doc/Kawamoto_MoFA_presentation_041214[1].pdf>.

Table 13.15 E-waste exportations.

Company	Exporting country	E-waste type	Year of commencement	Exported quantity (tons)				
				2011	2012	2013	2014	2015
A	Germany, the Netherland Belgium, UK	Printed circuit boards, cathode ray tubes, batteries, ICT equipment	2010	–	25.6	38.5	73.5	95.5
B	Japan, UK, Hong Kong,	Printed circuit boards, batteries and accumulators	2008		160	120	140	110
C	Japan, Singapore	Printed circuit boards, batteries and accumulators	2007	20		30	20	30
D	South Korea	Printed circuit boards, batteries and accumulators	2011		60	80	110	90
E	Netherlands	Printed circuit boards, batteries and accumulators, telecommunication equipment	2014				50	
F	South Korea	Printed circuit boards, batteries and accumulators	2015					140
G	Japan	Printed circuit boards batteries and accumulators	2015					25
Total exportations				*20*	*245.6*	*268.5*	*393.5*	*490.5*

13.13 Operational system flow diagrams of entire electronic and electrical waste management

Figs. 13.9 and 13.10 show the E-waste management and operational systems in Sri Lanka. Fig. 13.9 illustrates the electronic and electrical waste operational flow in sector wise while Fig. 13.10 illustrates the flow of E-waste which were plotted based on the identifications done through field survey and secondary data of E-waste management.

Flow diagram illustrates in Fig. 13.10 explains the entire downstream flow of electronic and electrical waste. Places where the environmental pollution taken place also identified and marked in the diagram.

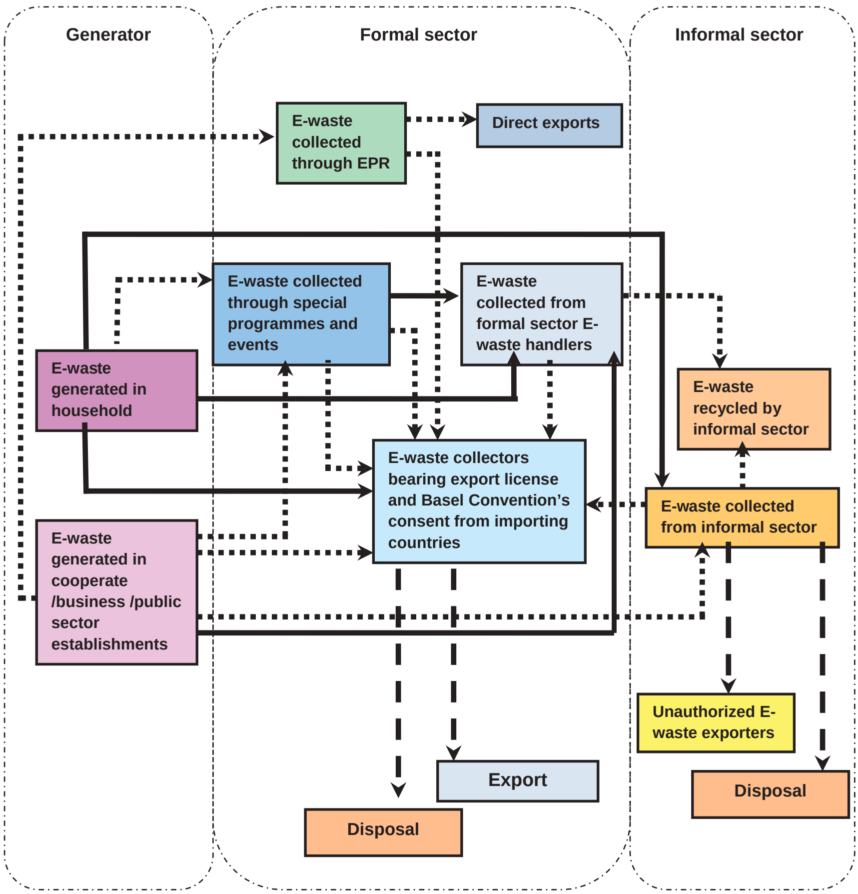

Figure 13.9 Electronic and electrical waste operational flow in sector wise.
Source: Ranasinghe, A.R.M.W.W.K., 2017. Assessing E-waste management system in Sri Lanka and suggesting mechanism to streamline the existing system. Master Thesis of Environmental Science, The Open University of Sri Lanka (Ranasinghe, 2017).

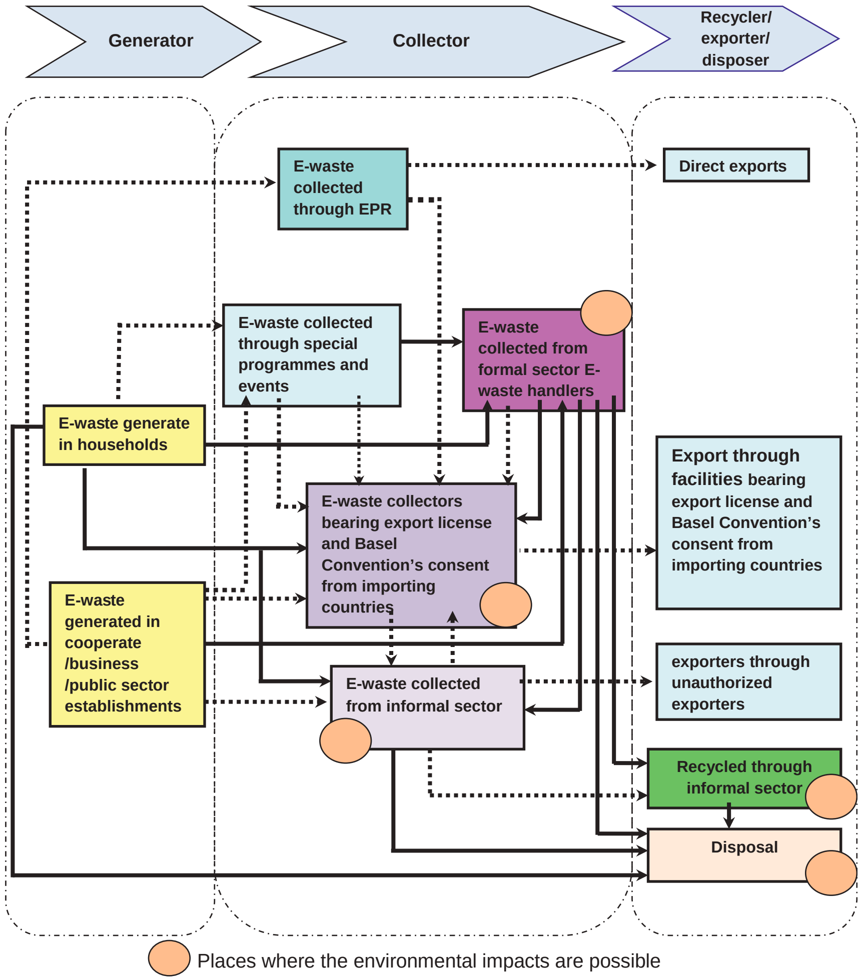

Figure 13.10 Flow of electrical and electronic waste.
Source: Ranasinghe, A.R.M.W.W.K., 2017. Assessing E-waste management system in Sri Lanka and suggesting mechanism to streamline the existing system. Master Thesis of Environmental Science, The Open University of Sri Lanka.

13.14 E-waste management operational system

It can be seen a strong linkage between informal sector stakeholders and informal sector stakeholders. Most of the electronic waste collect from large scale electronic item venders in their promotional take back mechanisms. Generally, E-waste collected through drop-off events and special programs from formal sector follow proper channel to the informal sector for recover valuable parts. These recovery processes involve some risky activities such as breaking glass and burning or it generates considerable amount of waste or invaluable parts from recovery process. However, there are some illegal exporters in operation. In general, informal sector handles large amount of quantity when compared to the formal sector. Most of the WEEE is passing through informal sector in the downstream management process of E-waste, while some of the formal sector operators engaged in undeclared informal operations as well.

Only a very small quantity of electronic waste is being managed through EPR. Stakeholders involvement and the knowledge on EPR is very low. Most of the electronic wastes generated in household level are managed by the informal sector. E-waste generated from the corporate sector are being managed by the both sectors equally. After recovering valuable parts, haphazard dumping of electronic waste is mainly done by the informal sector through rudimentary operations.

13.15 Identified issues in the downstream management of hazardous waste

The major challenge in E-waste management in Sri Lanka is insufficient awareness among all stakeholders on health and environmental hazards caused by E-waste. This leads to improper handling of E-waste, contributing to severe damages. In addition, there are many drawbacks in legislations and collecting and disposal facilities.

1. *Insufficient legislative framework*

   At present legal provisions are in place only to manage waste mobile phones and computers and accessories under the scheduled waste management license. In addition all types of batteries are also included in this regulation. When considering the generation of electronic and electrical waste other types of E-waste such as washing machines, photo copiers, and fax machines must also be taken in to the regulatory mechanism.

   As the existing regulations and policies are not sufficient to address entire lifecycle management of E-waste and entering of secondhand e-devices in to the country, appropriate legal provisions must introduced to control each and every type of E-waste both locally generated and imported.

   At present only categories types of WEEE including batteries and accumulators addressed under the scheduled waste (hazardous waste) management regulations. All type of WEE should be covered and should be addressed under a separate regulation specifically stipulated for electronic and electronic waste. Ideally the regulation must address the management strategies such as EPR.

   Due to the fact that policies and the legal frameworks are not sufficient to effectively implement the E-waste management system in the country, prioritized attention should be given to develop appropriate policies and legislations specifically to deal with E-waste. In addition to that a well-defined regulatory procedure and adequate measures should be taken to control illegal imports of E-waste and to ensure the environmentally sound management practices in place. Further to this some of the major issues and challenges faced in the implementation process can be attributed to the gaps and overlaps in the system. First and foremost, the gaps in the legal framework need to be clearly identified and closed.

2. *Inadequate awareness among citizens*

During this study it was clearly noted that awareness among citizens on hazardous nature of the E-waste and its management is extremely poor even among professionals and the educated people. As per these interviews carried out and questionnaires done with the citizens it was clearly noted that the awareness on the electronic waste, legal background, and disposal methods is not satisfactory at all. Even today, though the CEA has mandated that E-waste be given only to authorized collectors, most of the E-wastes are being disposed-off through informal channel in order to earn some quick money. Therefore it is essential that every citizen shall understand that E-waste is hazardous, and it is their responsibility to get it managed in an environmentally sound manner.

Educating the citizens and other stakeholders including public and private sector on the toxicity or hazardous nature of E-waste and importance of directing E-waste in to proper management mechanism must be recognized as prioritized action. Awareness could be implemented regularly and continuously through mass media and as community-based awareness campaigns. Further to that an intensified awareness and training is also provided for the people involved in informal recycling.

3. *Implementing extended producer responsibility (EPR)*

EPR is recognized as one of the most effective ways of dealing with the E-waste issue. Implementing EPR in Sri Lanka has been identified as a big challenge as there is no any legal provision to implement.

Creating financial mechanism to practice EPR is another challenge as some of the e-items are not coming through appropriate paths into the country and the small sop-assembled products also have a considerable share of the market.

Other main issue on implementing EPR is identified as the competition between the formal and informal sectors to gain access to E-waste.

As the actions to be taken to overcome this challenges it is extremely important to identify and specifically address the obstacles related to implementing EPR and develop strategies and introduction of legal framework to effective implementation of EPR mandating producers, importers, retailers with cost of collecting, recycling, and disposal of E-waste.

4. *Unavailability of efficient island wide collection system*

CEA has established an Island wide collection network via partner organizations of the National Cooperate E-Waste Management Program 5 years before. Under this program nearly 300 collection points were established in electronic vendor sales outlets and franchise shops and arcades of mobile network service providers. At present this collection mechanism is not implementing in a satisfactory manner. However, this collection mechanism can be considered as one of the most effective mechanism as it has a widely spread collection points all over the country.

Most of the electronic item vender companies do not provide take back offers through their distributors and channel partners. This also leads to improper dumping through local scrap dealers. Thus, despite having national level management mechanisms, collection of E-waste poses a big challenge, and a synergy and cohesiveness between systems has become the need of the hour.

In order to overcome these issues it is essential to establish infrastructures which sufficiently address collection, storage, transportation, recovery, treatment, and disposal of E-waste at regional and national levels coupled with creating sufficient awareness among citizens enabling them to handover their E-waste to the nearest collection point.

5. *Stagnating E-waste in household level*

   Electronic waste is lying in household backyards as Sri Lankans tend not to throw away their old electronic items even after those become unusable. This is kind of an emotional attachment to used electronic means that most of them are stored. Most of these items were purchased at a high price and hence people are reluctant to dispose of them even after their useful lifetime is over.

   In order to create an effective influx mechanism in to the E-waste management stream, it is an essential action to introduce a financial incentive system to specially for the household electronic waste.

6. *Ad hoc E-waste management system in informal sector collectors and dismantlers*

   In Sri Lanka a considerable amount of E-waste continues to be collected and dismantled through informal sector. Generally, the urban poor, located in unauthorized settlements engaged in collection and dismantling E-waste. Many of these dismantling practices are rudimentary in nature which is a most unsafe and polluting livelihood opportunities for survival. Some processes involve burning, breaking of CRTs, and physical processes to recover materials. These result in release of toxic materials to the environment through emissions and effluents and there is a great potential to cause health impacts to the workers. It is common to see open burning of plastics to reduce the E-waste volumes and copper wires to salvage valuable metals. Such operations have resulted in severe environmental pollution.

   E-waste collection and recycling enables rapid access to cash money. For many collectors and recyclers this rapid-cash-flow is an important reason to engage in this sector, despite unfavorable working condition.

   Role of the informal sector in the value chain of E-waste cannot be neglected due to its potential of generating income to the nonskilled low-income groups. Responsible agencies may pay prioritized attention to integrate the activities of the informal sector into the mainstream management of E-waste through coupling activities of informal and formal sector. Initiating cluster system by entangling formal and informal sector would be an ideal set-up to drive the informal sector in to formalization.

   The process of integrating the informal sector with the formal sector is a significant challenge. On one hand, diversity and the operational mode of the networking of informal sector is not well known. On the other hand, the informal sector operations are extremely diversified with the involvement of multiple stakeholders who are dealing with number of uncertain variables. Such grounds will require a multilevel approaches for streaming informal sector to formal sector.

   Further to that an intensified awareness on hazardous nature of the E-waste, environmental friendly management and safe technical method also be provided to the people who are engaged in the informal sector operations.

7. *Strengthening formal sector*

   There are few formal sector E-waste management facilities are in operation within the country and currently they are in the process of developing their business. Even though these establishments have been recognized as formal sector there are some technical areas yet to be improved. It is a fare argument that these formal sectors would be able to manage E-waste in an environmentally sound manner by using best available technologies (BAT), better working standards leading to better environmental management and enhanced resource recovery. Adequate capacity building, technology transfer, and funding sources based on low interest loan schemes should be available in order to achieve the expected development in the formal sector.

Relevant governmental agencies may take this matter in to a serious note and actions must be taken to introduce policies and market-based mechanisms to support the well-functioning and sustainability of formal sector.

8. *Issue of CRT disposal*

As the recycle value of the CRT tubes are very low. In global scenario the demand for the CRTs are very low. Recycling of leaded glass component in the CRTs is the main issue. Only three facility providers are available and engaged in recycling CRTs which is inadequate. Currently there is only one collector having export approvals for CRTs. The collection is done at a cost. Generally, it costs 2.5$ per kg and due to this reason, there is a big trend of streaming CRT tubes in the informal sector. However, the tubes are simply broken and recover only the copper coil and lead plates while remaining part including leaded glass are subjected to haphazard dumping.

Majority of the informal sector E-waste collection yards are accounted for CRT televisions.

Popular electronic item vendor companies in Sri Lanka implement take back mechanisms as a marketing strategy to attract customers. In this mechanism prize is subsidized when returning an old television regardless of the brand. As these vendors must bear to disposal cost when give out CRTs to the informal sector as an economically favorable alternative they choose informal sector who undertakes the disposal job for "no cost." Recovery process that is practiced by the informal sector is rudimentary in nature and adversely affects the health of the people engaged and to the environment. To divert this mechanism to a formal and environmentally sound way, a kind of an economical mechanism should be introduced to the vendors to cover the disposal cost such as extended producer responsibility system.

9. *Inadequacy of data available on electronic waste and lack of facilities for the research activities*

At present Sri Lanka does not have a comprehensive data base for the generation and lifecycle management of electronic waste. Unavailability of such a data base is a major drawback that could be negatively affected in the planning processes of E-waste management systems and also for the setting up of electronic waste management facilities. Further to that no proper facilities to perform research activities related to electronic waste.

Improving country's ability to gather data and inventory on E-waste generation and lifecycle management and need on the availability of research facilities must be recognized as extremely crucial requirements. To achieve this, necessary funds, infrastructure, expertise, and adequate human resources could be mobilized to setting up research facilities and to create and updating inventories.

10. *Inadequate knowledge among stakeholders*

Knowledge among stakeholders who are actively engaged in E-waste management is not adequate. Hence capacity building of these groups are highly important. Knowledge sharing among neighboring countries is also identified as an important aspect.

11. *Unavailability of financial mechanism to assure the sustainability of downstream management of E-waste*

It has been envisaged that a national level intervention is crucial to achieve the sustainability of downstream management of electronic and electrical waste. However, the unavailability of financial resources for successful implementation of needful actions is the main issue currently confronted with the stakeholder agencies.

Hence it is crucial to introduce some financial mechanisms to assure a *cradle to cradle* approach for responsibly addressing the increasing volumes of e-product scrap.

Ideally the beneficiaries of this mechanism would be the stakeholders who are engaged in the lifecycle management of electronic products starting from the consumer.

12. *Unavailability of a control mechanism for informal sector*

As the Scheduled Waste Management License is issued upon verifying the destination of the E-waste. For this either the collector should bear the approval to export or to have an agreement with an exporter. However, formal sector companies reluctant to come in to agreements with the informal sector due to the competition in the market. Under this ground formal sector is having monopoly and they have opportunity to demand due to having license.

Because of this mechanism informal sector operating freely without any control mechanism. Regulatory institutions should take this situation in to a serious note and take actions to subject the informal sector to a control mechanism.

13. *Unavailability of a proper recycling facility in the country*

Currently all the E-waste collected are exported. Country will be benefitted positively making contributions to strengthen the country's economy as E-waste recycling has been recognized as a lucrative business. Not only that it provides opportunities for the informal sector to get streamline.

13.16 Challenges in E-waste management in Sri Lanka

According to the status report on electronic waste management in Sri Lanka prepared by the CEA, 2016, current annual E-waste generation is estimated at 20,000 MT. Out of which more than 50% is white goods such as refrigerators and air conditioners. Fig. 13.11 illustrates the annual E-waste generation from 2010 to 2030. Accordingly, the annual E-waste release is expected to increase by more than four times from 10,000 MT per year in 2010 to 43,000 MT per year in 2030. In 2014, white goods (6460 MT) continued more than 50% of the total E-waste releases in that year (12,349). Refrigerator E-wastes release show a rapid growth and by 2013 it forms 48% of the white goods (11,648 MT), followed by air conditioners (6122 MT, 25%), and washing machines (3664 MT, 15%) In 2014, in the nonwhite goods segment (5889 MT), TV dominated the composition (81%) followed by computers (8%). However, computer E-waste releases show a gradual increase and eventually becoming the dominant waste component (6067 MT) in 2030. On the other hand, TV shows a decreasing growth due to already saturated Sri Lankan Market, generating 5732 MT in 2030.

According to Fig. 13.11, the profile of accumulated E-waste stock estimated during 2010−16 was 92,000 MT. Readily recyclable white goods continued 53% (48,600 MT) while the rest was nonwhite goods. 38,000 MT (48%) of the total E-waste releases during this period were TVs and computers. Although large in numbers, in terms of weight, mobile phones formed only 3% (2576 MT) of the accumulated E-waste stock for the period 2010−16.

When consider the value of the recyclables the report says that the potential value of the recovered metals from the TV and PC E-waste stocks accumulated during 2010−16 is estimated at USD 31 million. Current annual E-waste generation is estimated at 20,000 MT of which more than 50% is white goods such as

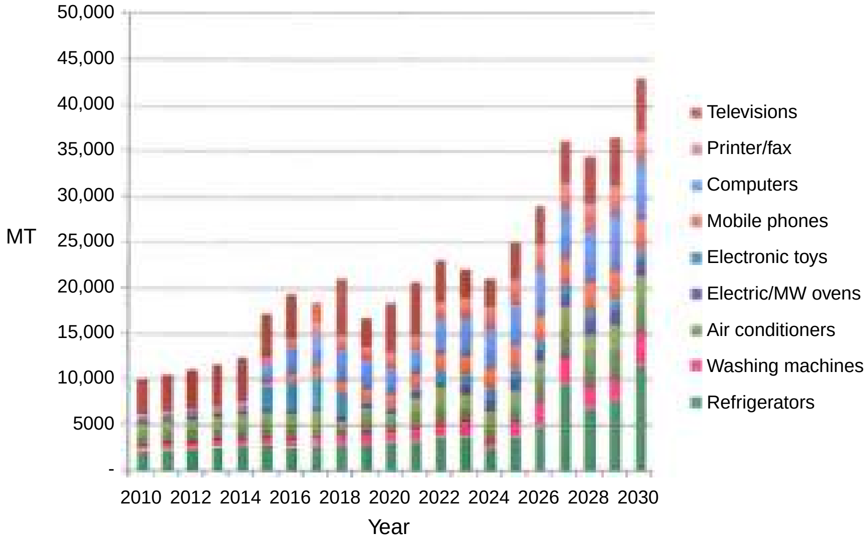

Figure 13.11 E-waste generation in MT per year during 2010−30.

refrigerators and air conditioners. Collection and recycling of white goods is presently being carried out mainly by the informal sector network. Although a few registered recyclers exist to collect and process these wastes, the total amount exported by the registered recyclers accounts for at the most 8% of the nonwhite goods generated per year.

With the increasing knowledge on the importance of E-waste management there is a growing tendency of adopting E-waste legislations in the world. By the end of 2017, the number of countries that have adopted E-waste legislations has been increased to 66, covering 66% of the world population.

However, many countries in the world, especially those are with low or middle-income level status, do not have proper E-waste management regulations. Even if they have E-waste management laws at national level, those are not properly enforced due to inadequate E-waste management infrastructure.

Under the National Waste Management Policy, E-waste management is discussed and yet to be adopted and enforced. As stated in the policy it was designed to provide more detailed focused directions for policy makers and implementers covering vertical and horizontal levels in the administrative and management structures of the country. The multiple challenges faced in the past, facing at present, and also likely to be faced in the future were considered in its design. The time span proposed is up to 2030 under the specific policy statements following statements have been included with respect to the management of electronic waste management.

1. E-waste management shall be considered as part of the integrated solid waste management of the country taking into consideration of the inheriting hazardous characteristics of E-waste.

2. Quantitative and qualitative targets shall be set to promote e-literacy integrating the possible environmental impacts of mismanagement of e-products.
3. Importation of usable used (secondhand) electrical and electronic equipment shall be regulated to prevent and minimize generation of E-waste.
4. Mechanisms shall be developed to prevent outdated/used products reaching Sri Lanka through the mechanisms of gifts, donations, and any other means.
5. A mechanism shall be established to formalize and upgrade the capacities of the informal sector involved in repair and maintenance sector.
6. E-waste collection networks shall be established island wide to prevent haphazard disposal of E-waste and mixed with other waste streams.
7. Infrastructure facilities shall be made available to dispose nonrecyclable E-waste.
8. Resource mobilization strategies shall be developed to ensure efficient E-waste management systems at Provincial and Local Authority Levels covering life cycle management.
9. Importer/producer/agent shall be held responsible for the final disposal of obsolete electronic items.

13.17 Requirements for better E-waste management strategies

At present there is no proper national wide data system on E-waste generated within the country. It is necessary to have access to data such as the amount and nature of E-waste in order to design proper management programs.

13.17.1 Policies, regulations, and legislations

Sri Lanka needs immediate formulation and implementation of proper policies, regulations, and legislations to manage E-waste in the country. The policies and regulations should be sufficient to cover entire life cycle of electrical and electronic equipments that enter Sri Lanka. With special consideration to secondhand items, regulations on importation of secondhand electronic items should address wide range of electronic items including dissembled parts.

As per the current existing legislation only few types of E-waste, for example, waste mobile phones and computers and accessories have been prescribed as hazardous waste. Hence other types of E-waste also be addressed under the legal framework.

The government can provide subsidies for importations environmentally friendly products and increase tax for importation of secondhand products to the country. Importers can be encouraged to abide with the regulations through "business continuation certificates" to ensure importation of high quality products. Simultaneously legislations should enforce to prevent illegal importation of E-waste to the country.

Shared responsibility in E-waste management should be encouraged by the government as an integrated management system for E-waste. Home Appliance Recycling Law (HARL) implemented by Japan in 2001 can be taken as an example in this aspect. The HARL requires producers to replace toxic substances in their products and increase recyclability, while the consumer pays a fee to recycle the product with government being responsible for collection. At the same time the producer is responsible for recycling of materials and proper dismissal of toxic components.

At least Sri Lanka can promote "eco-design principle" by providing subsidies to industry that adopt waste minimization strategies in their manufacturing process. It requires production and process modification through careful selection of inputs and efficient use of inputs, volume reduction by reducing the volume of waste disposed while removing hazardous portion of waste, and recovery and reuse of waste. It brings several benefits to the industry itself such as elimination of waste disposal cost, reduction of raw materials cost while generating income through waste.

So far Sri Lanka has not fully used economic instruments to manage E-waste. Economic instruments are more effective in influencing people's behavior than the command and control instruments such as policies and standards. Introduction of "Extended Producer Responsibility (EPR)" covering local producers of electrical and electronic equipment, importers, and retailers to take responsibility of total life span management of their items, involving collection and recycle or disposal should be done through relevant legislations. Introduction of deposit refunds and take back offers can be worthwhile practices in this regard.

The government can encourage take back offers by introducing tax incentives for companies that provide the service. Most of the households in Sri Lanka have piles of dispensable EEE due to the reasons that they do not know what to do with them, and also some emotional attachments to these items because they had purchased them at a high price. If take back offers are popularized among the citizens, it will become beneficial to people as well as the vendors because the customers will get a discount for the new product they purchase and the companies will have increased sales. The same incentives can be given to encourage "extended producer responsibility" with local producers as well as importers.

The producers or distributors of EEE can add an "advanced recycling fee" to the product price and charge from the buyer to cover the cost of collecting and recycling the product after its valuable life span. The advanced recycling fee can be used as an indicator of quality and durability of the product.

"Polluter pay" principle can be used to make the polluters be responsible for the pollution they create. It is expected that it will influence stakeholders to choose the less expensive behavior. The government can introduce a fine for citizens who do not properly dispose their E-waste. But this requires proper monitoring also.

It is easy to implement "consumer purchasing policies" for government establishments to go for environmentally friendly products when they purchase EEE such as computers, printers, and photocopying machines.

13.17.2 E-waste collection, storage, and transportation

It is necessary to establish proper infrastructure for collection, storage, transportation, treatment, and disposal of E-waste at regional and national level. It will be more effective to have E-waste management as an integral component of solid waste management. These activities could be delegated to provincial councils with a central monitoring unit such as the CEA.

Integration of formal sector and informal sector is necessary as the formal sector alone cannot cover the whole island. There should be a proper mechanism to integrate with the informal sector which dominates the collection and dismantling of E-waste. National level information system to monitor and evaluate E-waste management in the country is a major requirement.

13.17.3 Awareness creation

Creating awareness on hazardous nature of E-waste should be given more attention by the relevant authorities as the citizens and especially those who are involved in E-waste collection and dismantling activities do not have sufficient knowledge. Target oriented programs for waste generators (households, industries, and commercial sectors), waste collectors, and the citizens is essential. Mass media has a responsible role to play in this as it can take the message across the country. NGOs and community-based organizations (CBO) can be used to create awareness at community level. School level programs should be organized to create awareness among the younger generation.

Importers of EEE can amalgamate awareness creation on proper disposal of E-waste with their product promotion campaigns and consumer meetings as part of their corporate social responsibility (CSR) programs.

It should be taken into consideration that lack of trained manpower to handle E-waste is an issue in E-waste management, and most of them involved in these activities are from the urban poor and most likely to be uneducated. Therefore it is mandatory to train them in collecting and dismantling of E-waste as most of them do not possess any knowledge on harmful effects and safety precautions. Educating and training of these workers can be done through NGO or CBOs with the support from the government.

13.17.4 Research and development

Capacity development for management of E-waste through research and development should be considered as a priority by research institutes. Development of research facilities and adequate funding to encourage research and development in E-waste management is necessary to develop low-cost, efficient waste treatment methods, technology transfer, and also to establish recycling facilities in Sri Lanka. The government can implement a special funding program through institutions such as National Science Foundation, National Research Council, and the National Institute of Fundamental Studies. Companies who are willing to establish recycling facilities or to adopt modern technologies for E-waste management should be encouraged by providing them loans at low interest rates. Research and surveys relevant to E-waste and development of a national inventory on E-waste are necessary requirements in E-waste management.

13.17.5 Economic aspects of E-waste management

Promotion of "circular economy concept" in E-waste management offers economic development and employment generation rather than the "take-make-disposal" cycle. It aims to redesign products in such a way to ensure minimized input use, waste generation, and to have extended future use. While in use service should be provided to maintain, repair, and upgrade the products to maximize their lifetime. This system can build long-term resilience, generate business, and employment opportunities while providing environmental and social benefits.

E-waste management and exportation is an economically profitable industry; e-wastes contain both hazardous as well as valuable substances and the total value of all raw materials in globally generated E-waste in 2017 has been calculated as Euros 55 billion.

Materials extracted such as glass, plastic, and metal can be inputs to other industries. Important elements in E-waste such as mercury, silver, and phosphorus can be exported to other countries. Asian countries are the recipients of most of the WEEE generated in other countries and China being the largest importer of E-waste in the world. However, Sri Lanka is not yet exporting E-waste to China. There should be a mechanism to encourage value addition to E-waste that are exported by Sri Lanka. It would fetch more foreign revenue to the country while generating more job opportunities.

All stakeholders, the government, mass scale E-waste generators such as industries, mass media, researchers, and the citizens have their own role to play to face and overcome challenges in E-waste management in Sri Lanka.

13.17.6 Integration of the informal and formal sector

In Sri Lanka a considerable amount of E-waste is collected and dismantled through informal sector. As per the Status Report on E-Waste Management (CEA, 2106) there are about 2000 informal sector establishments operate in Sri Lanka. In general, informal sector operators are localized to a particular area and operate as clusters. Mainly the urban low-income groups are engaged in informal collection and dismantling E-waste. Many of these dismantling practices are rudimentary in nature. These practices are very unsafe and create severe environmental pollution. Some processes involve burning, breaking of CRTs, and physical processes to recover materials. These result in release of toxic materials to the environment through emissions and effluents and there is a great potential to cause health impacts to the workers. It is common to see open burning of plastics and cables to reduce the E-waste volumes and to recover valuable metals.

As the informal sector plays a very active role of the electronic waste management system in the country the informal sector is generating income to the unskilled groups. In order to streamline the informal sector proper integration of informal and formal sector is essential but it is very challenging. This could be done through entangling informal with formal sector, formal sector enabling informal sector to operate as a cluster with the formal sector.

13.17.7 Strengthening formal sector

There are few formal sector E-waste management facilities are in operation within the country and currently they are in the process of developing their business. Even though these establishments have been recognized as formal sector there are some technical areas yet to be improved. It is a fare argument that these formal sectors would be able to manage E-waste in an environmentally sound manner by using best available technologies (BAT), better working standards leading to better environmental management and enhanced resource recovery.

Adequate capacity building, technology transfer, and funding sources based on low interest loan schemes should be available to achieve the expected development in the formal sector.

Relevant governmental agencies may take this matter in to a serious note and actions must be taken to introduce policies and market-based mechanisms to support the well-functioning and sustainability of formal sector.

13.18 Conclusion

The rapid increase and changing need of consumers for electrical devices and information technology on a global scale has resulted in a significant rise in electronic and electrical products. In line with the global scenario there is a significant growth and consumption of e-products and thereby generation of E-waste which shows an exponential growth in Sri Lanka.

Current annual E-waste generation is estimated at 20,000 MT, of which more than 50% is white goods such as refrigerators and air conditioners. The balance 50% of nonwhite goods dominated by television (5000 MT/year), specifically TVs and PCs with CRT monitors which are out of markets. With the significant growth in investments, consumption, and exports, the generation of E-waste from general consumption of the techno-products such as personal computers and mobile phones has been drastically increased within Sri Lanka. Although a few registered recyclers exist to collect and process these wastes, the total amount exported by the registered recyclers accounts for at the most 8% of the nonwhite goods generated per year.

E-waste is of concern largely due to the toxicity of the constituent substances if not managed properly. It has been scientifically proven that these substances have a potential of creating both health hazards and environmental impacts. Despite of the toxic nature of the electronic and electrical waste recycling has identified as a lucrative business all over the world. Like other developing countries in Asia and Africa, Sri Lanka is now confronted with the huge problem of E-waste both locally generated and internationally imported.

In such grounds, E-waste management sectors in Sri Lanka have started their business activities both formally and informally. There is a clear evident that the rate of growth in informal sector is moving ahead than formal sector. Formal sector operations generally confined only to the capital city Colombo and the suburbs while informal sector spread throughout the country and their operational system is far more complicated and creating adverse impacts on the environment and the human health. Hence prioritized attention must be given to identify the system and responsible authorities may mobilize required resources and disseminate appropriate technologies to streamline the informal sector and integrate them with the formal sector. Formal sector operations also yet to be developed; currently it is confined only to collection and dismantling and it was noted that the business ventures have not been made attractive and investments are not sufficient to meet the high-level operations. Even today, most of the E-waste are being disposed-off through informal channel for earning some quick money. Therefore it is essential to aware the people that E-waste is hazardous, and it is their responsibility to get it managed in an environmentally sound manner.

Even though some of the nonwhite goods are collected by the informal network and dismantled to recover components that have economic value, a large percentage of the items, such as CRTs, which cost money to dispose, are left at the site of collection or dumped haphazardly in open dump yards. Cheap, safe, and simple processing methods for introduction into the informal sector are currently lacking. Further there is no single secured landfill to accommodate all hazardous waste including E-waste in Sri Lanka. Therefore it is utmost need to establish a secure landfill for hazardous waste including for E-waste disposal.

When the management of E-waste to be taken on a more serious note, there is a need for dedicated policy and legislative mechanism which should be able to offer clear guidelines for collection, transportation, storage, dismantling, material recovery, preprocessing, and end-processing for final metal recovery. This is important as emerging and developing economies will continuously generate more E-waste in the next 20 years. Even though there are some regulations in place to address the management of electronic waste, some aspects are not sufficiently and effectively addressed and therefore introducing adequate legal provisions are required.

References

Blade, C.P., Wang, F., Wong, J., Kuehr, R., Hulsman, J., 2015. The global e-waste monitor United nations University, IAS- SCYCLE, Bonn, Germany.

Herat, S., 2011. Review on challenges and issues in environmentally sound management of e-waste in Asian countries. Background Paper prepared for the National e-Waste Forum, Colombo, Sri Lanka.

Herat, S., Agamuthu, P., 2012. E-waste: a problem or an opportunity? Review of issues, challenges and solutions in Asian countries. Waste Manag. Res. 30 (11), 1113−1129. Available from: https://doi.org/10.1177/0734242X12453378.

Joseph, S.M.R., Dilsharan, B., Punchihewa, N.D., Athapattu, B.C.L., Vithanage, M., Jayawardhana, Y., Wijerathne, D.M., Kulkarni, J., et al., 2018. Design and development of bio-reactors and leachate barricades for landfill leachate treatment. Transactions of the Annual Sessions of IESL. The Institution of Engineers, Sri Lanka, pp. 145−133. <http://digital.lib.ou.ac.lk/docs/bitstream/701300122/1603/1/Joseph%20et%20al%20_%20IESL_2018_%20Landfil%20leachate.pdf>.

Raghupathy, L., Chaturvedi, A., Mehta, V., Killguss, U., 2010. e-waste recycling in India integrating informal and formal sectors. In: *Proceedings NASEW*, NML Jamshedpur, India, p. 38.
Ranasinghe, A.R.M.W.W.K., 2017. Assessing e-waste management system in Sri Lanka and suggesting mechanism to streamline the existing system. Master Thesis of Environmental Science, The Open University of Sri Lanka.
Sewwandi, B.G.N., Takahiro, K., Kawamoto, K., Hamamoto, S., Asamoto, S., 2013. Evaluation of leachate contamination potential of municipal solid waste dumpsites in Sri Lanka using leachate pollution index. <http://www.sjp.ac.lk/wcup/doc/Kawamoto_MoFA_presentation_041214[1].pdf>.
WRMPP, 2016. The megapolis, western region master plan—2030, Sri Lanka: from island to continent, western region megapolis planning project. Ministry of Megapolis and Western Development, 2016.
Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., et al., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25, 436−458.
Wimalasuriya, K.M.D.D.C., Chandrathilake, T.H.R. C., Liyanage, B.C., Gunatilake, J., 2011. In-situ water quality and economical leachate treatment system for Gohagoda dumping site, Sri Lanka. Soc. Manag. Syst. Internet J. Available from: http://kutarr.lib.kochi-tech.ac.jp/dspace/bitstream/10173/853/1/sms11-7165.pdf.

Further reading

Development of a National Implementation Plan for Electrical and Electronic Waste Management in Sri Lanka, 2008. Final report, component 1. Ministry of Environmental and Natural Resources, Central Environmental Authority, Sri Lanka.
Ministry of Environment and Natural Resources, Sri Lanka, 2006. Development of a National Implementation Plan (NIP) for E-Waste Management in Sri Lanka.
Status report on Electronic Waste management In Sri Lanka, 2016. Central Environmental Authority, Ministry of Mahaweli Development and Environment.
<http://www.statistics.gov.lk/HIES/HIES20122012_13Finalreportpdf/International> Monitory Fund, World Economic Outlook Database, April 2015.

Electronic waste management practices in Nigeria

14

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14.1 Introduction

E-waste is a term used to cover items of all types of electrical and electronic equipment (EEE) and its parts that have been discarded by the owner as waste without the intention of reuse (StEP, 2014). In different regions it is also named WEEE (waste electrical and electronic equipment) or e-scrap. Various definitions for electronic waste in literature accept that E-waste includes both the whole device and all its component parts that have been discarded by the owner as waste without the intention of reuse, whether functional or not. Electrical and electronic equipment (EEE) includes a wide range of products—almost any household and business item with power or battery supply. The past 2−3 decades have witnessed the discarding of huge quantities of electronic waste and it is obvious that this and its environmentally sound management represent no doubt one of the foremost environmental challenges of the 21st century. This is a globalized problem affecting both developed and developing countries (Osibanjo et al., 2016).

Literature in the past 1−2 decades has proven that E-waste is one of the fastest growing waste types in the world (Widmer et al., 2005; Lundgren, 2012). The exponential increase in the total amount of E-waste generation could be associated to many factors, which include consumer demand for upgraded designs and options, high obsolescence rate due to low quality of EEE products and unnecessary purchases of EEE—for example the purchase of a new mobile phone considering that new mobile phone models are released at highly regular intervals among others. Meanwhile new designs, models, or upgrades of mobile phones come with new accessories, such as chargers, headsets thereby forcing the early retirement of functional accessories. These short innovation cycles, increasing affordability of electronic devices especially in developing countries, coupled with low recycling rates contribute to rapidly rising quantities of E-waste. Even hand-held devices like mobile phones that appear very small in size or weight contribute hugely to the cumulative waste generation by this sector (Osibanjo et al., 2008). The past two

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00014-0

decades have witnessed a steady decline in the average lifespan of most electronic products ranging from computers to mobile phones, causing significant addition to E-waste. For some electronics, such as computers, the average lifespan has been reported to have dropped in recent years by about 50% from 4 to 2 years (BAN/SVTC, 2002). E-waste has become a global, interregional and domestic problem, and significant quantities collected for recycling in the developed countries are moved across international boundaries toward developing countries. Baldé et al. (2017) observed that about 44.7 million metric tons (Mt) of WEEE were generated all over the world in 2016 and the amount of WEEE is expected to increase to 52.2 million metric tons by 2021. Of about 44.7 million metric tons generated yearly, it is estimated that vast majority of the generated WEEE is shipped to countries in Asia and Africa for reuse or recovery. This trade is consequent on the composition of UEEE—reusable equipment which even when un-reusable could be salvaged for their valuable parts/components/modules and used in repairs of salvaged for the materials contents that can be used as secondary raw material. E-waste is unique as it contains both hazardous substances (e.g., cadmium, lead, mercury, and persistent organic pollutants) as well as precious metals (e.g., gold, silver, and rare earth metals) which could cause some irreversible health and environmental damages if treated and discarded improperly. The dumping of UEEE and E-waste in developing countries worsen the challenges faced in E-waste management in these countries. The management practices adopted in Nigeria, the challenges, and the way out are discussed in this chapter.

14.2 UEEE/E-waste flows into developing countries

One key factor that drives the flows of UEEE into developing countries is the high demand for electronic devices by low income earners—either by those that do not have access or those that desire to upgrade to newer models/brands that have better features—sound quality, camera, and memory size. Consumer electrical and electronic products have been instrumental to the revolution witnessed in the communication, entertainment, transport, education, and healthcare sectors around the world (Osibanjo and Nnorom, 2007). Most developing countries have need for ICT wares to facilitate the following: technology transfer; technical assistance; capacity building; warning systems; information, resource management systems; monitoring and assessment mechanisms; communication; education; awareness-raising; promoting and facilitating the exchange of information on best practices; knowledge sharing; dissemination of scientific or technical knowledge; and the wider application of techniques and assessment methodologies, among others (Lall and Garai, 2005). The effective application of ICT has the potential to benefit all aspects of human life. While there are many factors contributing to the digital divide, the high price of information technology hardware is no doubt a significant one (Williams, 2003). Due to lack of financial resources to most people in developing countries like Nigeria, much of the growth in the ICT sector rely on second-hand equipment imported from rich, developed countries (Nnorom, 2012). Presently, large quantities of UEEE mixed with E-waste are imported into Nigeria annually. Majority of the imported devices are nonfunctional (E-waste) and are posing serious management challenges (Nnorom and Osibanjo, 2008). E-waste generation and management is one of the most obvious global environmental problems, and unfortunately the infrastructure to manage it properly is still poorly developed and scarce in most developing countries. Globally, the recycling of E-waste (especially some categories such as CRTs) poses huge technical challenge because it is not feasible economically, while the recovered materials hardly find ready applications. Meanwhile most developing countries lack the appropriate physical infrastructure which require huge investments to acquire. In some developing countries, the obvious challenges are provision of food, shelter, and roads such that E-waste management is least considered for investment. Some of the factors driving the flows of UEEE/E-waste into Nigeria are as follows:

- The digital divide—the high demand for electronics.
- Low cost of UEEE which meets the purchasing power of most low income earners.
- General acceptance that UEEE are of higher quality compared to some new EEE imported from Asia.
- The profit margin of the importers.
- Durability of certain UEEE compared to some new devices.
- Lax laws.

14.2.1 Bridging the ICT digital divide in Nigeria: merits and demerits

Studies have shown that access to ICT is a key indicator of a country's economic and social situation (Nnorom, 2012). The "*unequal access to ICT to people relative to their geographical location, living standard, level of education, and sex*" have been defined as digital divide (Ya'u, 2002; Marine and Blanchard, 2004). This refers to the gap that exists in the opportunities to access and use advanced information and communication technologies (ICTs) between countries or geographic regions or by individuals at different socio-economic levels (Monge and Chacón, 2002). Indices of the Digital Divide include PC penetration, Internet usage, bandwidth consumption, content creation, and online representation. In Nigeria, as in many other developing countries, digital divide is so glaring—only a small number of wealthy people have access to certain ICT-wares especially the branded new equipment (Nnorom, 2012). As a result, most low-income earners rely on used ICT-wares as new devices are relatively expensive for ordinary people. Digital divide would not have attracted so much attention but for its impact on development within a global economy, which is increasingly based on the exchange of information and knowledge (Marine and Blanchard, 2004). Some of the effects of the digital divide on countries and individuals are presented in Table 14.1.

Donations by nonprofit organizations and individuals in developed countries have facilitated access to used computers in developing countries. Such computers

Table 14.1 The effects of the digital divide on countries and individuals.

Issue	Notes
Unfair competition	Disadvantaged countries are unable to compete with their counterparts in the developed countries due to lack of access to information and knowledge (e.g., access to funding for research and scholarships)
Cost of access to ICT	Worsening/deepening poverty as the digitally disadvantaged spends more to access the technology (higher costs of access to the Internet and phone calls)
Unfair playing field	The digital divide reduces the possibility of a global "level field" in trade, investment, and relations
Maintaining the divide	Higher costs of "maintaining" the digital divide or even attempting to bridge it has negative effects on economic stability

Source: *From* Nnorom, I.C., 2012. Bridging the digital divide and creating an ICT dump: an overview of the unsustainability of exporting used and end-of-life ICT-wares to developing. In: E-Waste: Management, Types and Challenges. Editors: Yuan Chun Li and Banci Lian Wang. Series: Computer Science, Technology and Applications; Environmental Remediation Technologies, Regulations and Safety. ISBN: 978-1-61942-217-9s, Nova Science Publishers, Inc. New York, NY, pp. 67−88.

are received, stored, refurbished, packed, and shipped by volunteers who donate their time and expertise. Some of these programs are aimed at assisting the educational institutions in the developing countries with low cost new computers, second hand, and refurbished computers. These programs have been in the forefront of assisting the developing countries with ICT wares. ICT diffusion stands to assist developing countries in achieving the improvements that are so desperately needed, especially in the areas of economic and social changes, education, and technological advancement. In Nigeria, so much has been achieved in Internet penetration and access to ICT-wares in the last decade and significant proportion of the ICT-wares are imported and used. Nigeria achieved a teledensity of 100% as at January 2015 from 0.4 per cent in 2001 (NCC, 2018). Since then, the telecoms sector has maintained a steady teledensity growth reaching 114.66 per cent in April 2018 with telecoms subscribers number reaching 160,524,590 (This Day, 2018a). There have been improvements since then (Fig. 14.1).

Mobile internet subscription in Nigeria also maintained a steady growth, increasing from 91.4 million in July 2017 to 98.4 million in December 2017. Consequently, Google ranked Nigeria highest in online presence in Africa, above South Africa and Kenya (This Day, 2018b). The Google research study also ranked Nigeria among the top three countries of the world that spend quality time online in search of various goods and services. The increased access to ICT-ware and Internet in Nigeria in the last decade has seen a leap in access to knowledge, citizen's participation in socioeconomic activities and effective use of ICT in key sectors such as governance and commerce, education, and healthcare. Presently, electronic commerce is flourishing including Internet banking, because online money transfers/payments, ATM services, and use of POS (point of sale) are readily

Figure 14.1 Teledensity in Nigeria.
Source: From National Communications Commission (https://www.ncc.gov.ng/stakeholder/statistics-reports/industry-overview) (accessed 20.11.18.).

accepted or used. Online hotel reservations, flight bookings, and flight management that we now enjoy from our homes and offices are delivered by telecommunication (NCC, 2018). Some other benefits of access to EEE are presented in Table 14.2.

Though export and donation of used electronics have been recognized as important means for bridging the digital divide, it however presents some demerits. Huge amounts of nonfunctional used electronics are imported and sold by individuals and registered businesses. Studies have identified Lagos as a hub for trade in UEEEs (Ogungbuyi et al., 2012; Odeyingbo et al., 2017). Thus, the export of used electronics has been used as a channel to dump un-reusable electronics in the developing countries. The adoption of crude technology in the management of end-of-life electronics poses substantial risks. Literature abounds on the negative impacts of material extraction of valuable from E-waste using crude technologies in the developing countries.

14.2.2 Quantity and quality of UEEE imports into Nigeria

Every year, Nigerian ports at Lagos receive millions of units of various types of UEEE which are imported from different countries including United State, Europe, Japan, China, and South Korea (Odeyingbo et al., 2017). Many developing countries including Nigeria rely on these imported second-hand ICT equipment from developed countries, primarily from Europe and North America to meet their digital gadget and electronic equipment needs (Odeyingbo et al., 2017). Low income earners in Nigeria depend on such imports of used EEE as a means to seek and stay abreast of technological developments in an increasingly globalized world. The domestic need of UEEE stimulates the international trade and transboundary

Table 14.2 Some benefits of access to EEE.

Sector	Notes on benefits
Cost	The new ICTs is less expensive and more powerful as they bring greater access to information and knowledge
Governance	The new ICT have been supporting e-governance around the globe. Increasing use of ICTs to provide information on election, voters' registration, and candidates in national elections. For example, SMS (short text messages) are sent to potential voters as part of the campaign strategy
Business	Drastic revolutions in the way people in developing countries communicate and conduct business. ICTs allow businesses to make more informed and strategic decisions as well as electronic commerce (e-commerce)
Education	ICT is opening educational opportunities for many including distance education. It also plays an important role as a tool in public education, and in pressing for changes in government policies
Poverty eradication	Payment of government stipends to unemployed youths
Environment	Dissemination of information on oil spills
Healthcare	Cheaper and better telecommunication services are also carrying telemedicine. ICT have assisted in rescue operations and in providing information to doctors in remote areas on life-saving operations/surgeries
Agriculture	Distribution of government subsidized agro-chemicals such as fertilizers to farmers

movement of used EEE/WEEE into Nigeria. Studies have monitored UEEE and E-waste importation into Nigeria. Presented in Table 14.3 is a summary of information on amounts, quantity, and origin of UEEE imports into Nigeria.

The recently published report of the "person-in-the-port" (PiP) presented more reliable information about quantities and qualities of the UEEE imports into Nigeria. An overview of the PiP is presented in the section below.

14.2.3 Overview of the "person in port" project

The PiP observed that many electronic devices that fall under the WEEE Directive categories were imported to Nigeria. Most of the UEEE were imported from Europe, United State, and Asia. The PiP further revealed that, the majority of imported used LCD TV was from United Kingdom origin and other parts of Europe, while majority of CRT TVs were imported from China. The quantity of UEEE imported into Nigeria via the two relevant ports in Lagos for UEEE imports into Nigeria in 2015 and 2016 was calculated to be around 60,000 t annually (Odeyingbo et al., 2017). The importation of UEEE with (roll-on/roll-off) RoRo-imported vehicles was estimated to be around 41,500 t or 69% of UEEE import per

Table 14.3 Summary of import figures of UEEE into Nigeria.

Source	**Estimated quantities and qualities of imported UEEE**	**Year of study**
Basel Action Net-work (BAN)—The digital dump, exporting reuse and abuse to Africa (BAN, 2005) www.ban.org	500 containers of computer scrap of various age enter Nigeria every month	2005
ÖKOPOL—Institute for Environmental Strategies Transboundary shipment of waste electrical and electronic equipment/electronic-scrap—optimization of material flows and control (2010) http://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/3933.pdf	• Total import to Nigeria in year 2006 was estimated at 2,885,999 tons (authors calculation) • 536,475 tons were imported from Germany in year 2006. (authors calculation)	2010
E-waste country assessment Nigeria (Ogungbuyi et al. (2012) http://www.basel.int/Portals/4/Basel%20Convention/docs/eWaste/EwasteAfrica_Nigeria-Assessment.pdf	600,000 tons	2010
Waste crimes, waste risks: gaps and challenges in the waste sector (UNEP, 2014) http://www.unep.org/newscentre/default.aspx?DocumentID = 26816&ArticleID = 35021#sthash.9J7R9wSr.dpuf	About 60%–90% of waste is illegally traded or dumped	2015
Person in port (PiP) project (Odeyingbo et al., 2017)	60,000 t/y	2015–2016

year, representing the largest share and the commonly used importing route for UEEE import. Annual import of UEEE import via container was estimated to be about 18,300 tons in total, with 8,800 t being imported in containers with vehicles and 9,500 t in containers without vehicles per year.

The UEEE imported into Nigeria could be categorized as follows:

- Functional for reuse as a product.
- Nonfunctional but serviceable for reuse.
- E-waste/scrap (nonfunctional and un-serviceable)—in some cases these can be cannibalized and some components may be retrieved for use as replacement parts.

The study observed that UEEE and E-waste are imported in 20 feet (67 m^3 of inner in volume) or 40 (33 m^3 of inner in volume) feet shipping containers, with and without vehicles and UEEE stuffed inside RoRo imported used vehicles, that is, trucks, lorries, and cars (Fig. 14.2).

The PiP presents the approach and results of the inspection of containers and vehicles and the review of import documents for UEEE imports via the Tin Can Island Port Complex (TCIPC) and the Lagos Port Complex Apapa (LPCA), the two hubs for UEEE imports in Nigeria, in 2015 and 2016. The person in the port (PiP) inspected 201 containers and 2,184 (RoRo vehicles with used electrical and electronic equipment (UEEE), and reviewed 3,622 import documents of UEEE in containers. The containers with imported UEEE represent around 0.7% of all containers with goods imported via the LPCA and the TCIPC in 2015 and 2016. Thus, on the average one out of 143 imported containers was found to contain UEEE.

It was observed that UEEE of virtually all categories (except automatic dispensers) are imported into Nigeria, often mixed with other goods such as sewing machines, bicycles, kitchen wares, sports equipment, and other household items/furnishings. UEEE are imported in containers with and without vehicles and stuffed inside RoRo imported used vehicles.

Figure 14.2 UEEE importation into Nigeria in containers: (A) with vehicles; (B) without vehicles; and (C) in RoRo imported vehicles.

The major sources of UEEE imports in containers based on the number of containers imported during the PiP are China (23%) followed by United States (21%), Spain (11%), United Kingdom (9%), UAE and Morocco (4%), Malaysia, Germany, Belgium, and Hong Kong with around 3% each. These 10 countries accounted for around 80% of the total imports observed during this study. Around 30% of the exports by number originated from ports located in the EU and Norway (Fig. 14.3).

Generally, the condition of the imported UEEE is not known to the Nigerian Port Authorities and goods are imported without prior functional test at the country of origin. An evaluation of the condition of UEEE by the PiP is presented in Table 14.4. Further, the value of individual UEEE is classified by marketers and retailers based on the age, make and model, size and cosmetic appearance of the UEEE at the selling point. Functionality condition is not always known at the time of entry.

UEEE import is motivated by the financial gain made by the various operators in the UEEE flow network in Nigeria. This trade generates considerable profits when sold for reuse. The profitability is driving individuals and companies that are not registered with the regulatory agency, NESREA (National Environmental Standard and Regulation Enforcement Agency) to import UEEE to be most active in the business. The Person in Port report observed that importers registered formally for the importation of UEEE accounted for just 3.5% of all UEEE importations for 2015 and 2016 (Odeyingbo et al., 2017). This may be one of the reasons why most declarations of imported UEEE in the import documents were found to be wrong, vague, or incomplete (Fig. 14.4). For instance the record might just indicate importation of a vehicle(s) and used sewing machines, whereas the container actually contained huge amounts of UEEE. Containers with goods imported into

Figure 14.3 Countries of origin of UEEE imports in containers into Nigeria 2016−2017 (number of exports) (Odeyingbo et al., 2017).

Table 14.4 Condition of the various categories of UEEE imports according to country of origin.

EEE category	Examples of UEE imported	Major country of origin	Average age	Condition at entry
Large household appliances	Refrigerators, freezers, washing machines, and air conditioner	Mostly from Europe	5–10 years	Nontested
Small household appliances	Coffee machine, bread toaster, pressing iron, microwave oven, and electric blenders	UK and Germany	5–10 years	Nontested
IT and telecommunication equipment	Computers, CPU, monitors, and mobile phones	USA, China	5–8 years	Nontested
Consumer equipment	Television (CRT and LCD), radio, DVD, and Hi-Fi	China, USA, Europe (mostly UK and Spain)	5–15 years	Nontested

Source: From Odeyingbo, O., Nnorom, I.C., Deubzer, O.K., 2019. Used and waste electronics flows into Nigeria: assessment of the quantities, types, sources, and functionality status. Sci. Total Environ (accepted for publication).

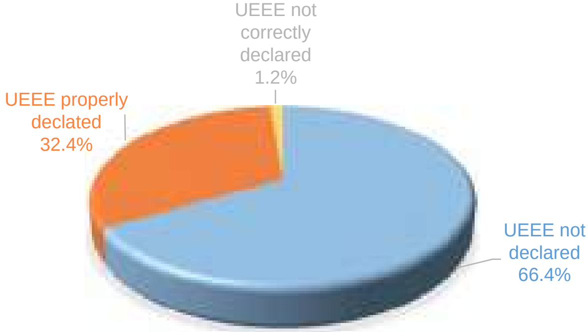

Figure 14.4 Comparison of import declarations in shipping manifests with physical inspection.

Nigeria could be declared as “a car and some personal effects” on the shipping manifest, whereas physical examination would reveal—a vehicle, 25 CRT TVs, 40 electric cookers, and 5 radio sets.

Importers also register the content of their containers as “used electronics” without indicating the type of used equipment loaded in the container. This could be a strategy adopted to divert suspicions which would attract search by the regulatory agency. The comparison of import declarations and inspection results show that almost 70% of imports in containers are not properly declared, especially when the UEEE is imported in a containerized vehicle.

Although some values could be obtained from imported nonfunctioning equipment, resulting from reuse of component parts in refurbishments and repairs, the value is however lower compared to that when there is direct reuse of the product/equipment. The effective refurbishing sector in Nigeria also contributes to the motivation of importers to import both functioning and nonfunctioning equipment. The refurbishing sector can fix and replace many damaged equipment hence it encourages importer to import such class of equipment and consumers to buy equipment sold at nontested status. The main factor driving the flow of UEEE into Nigeria is the profit margin of the importers and the demand for cheap UEEE of perceived good quality and durability. Behind the scene, the issues are as follows:

- Unfavorable economic conditions in the country which creates a demand for cheap UEEE compared to new ones, thereby creating a flourishing market for UEEE.
- A flourishing refurbishing sector dominated by active technicians that have the ability to fix many technical defects in UEEE at a reasonable cost. This motivates the importer to import both functioning and nonfunctioning UEEE. Again, the activities and competence of the refurbishing sector motivate many buyers to engage in such transactions. Very high percentages of nonfunctioning imported UEEE are fixed successfully. Spare parts are also readily available from nonrepairable devices which are cannibalized. The cost of repairing the same equipment in the country of origin (developed country) is far higher and spare parts may only be sourced from new parts. These factors altogether, very often make it uneconomical to repair UEEE in many developed countries; hence such devices enter the waste steam.

14.3 E-waste management in Nigeria

In an ideal case, optimum resource efficiency and low environmental impacts can be reached when E-waste is collected and treated in state-of-the art facilities. However, imperfect disposal scenarios exist in Nigeria and this is the cause of the E-waste problems. The challenges facing E-waste management in Nigeria have been by discussed by Osibanjo and Nnorom. (2007) as well as Odeyingbo et al. (2017). These include:

1. Influx of UEEE with reduced life often mixed with E-waste.
2. Low collection rates of EoL EEE, because the final owners either stores EEE in drawers and cabinets and disposes at will.

3. Ignorance of the toxicity or hazardous nature of E-waste by the general population.
4. Sale of E-waste to scavengers by consumers rather than paying recycling fee.
5. Dearth of recycling infrastructure for the appropriate management of E-waste.
6. Disposal of E-waste through the normal household bins, often times getting to the open dumps before any scavenging can take place.
7. Flows of E-waste through the informal recyclers than through the few existing formal recyclers.
8. Difficulty in sourcing for funding to invest profitable E-waste recycling. The crude techniques adopted results loss of resources, energy wastages, and environmental pollution/human exposure to toxins.
9. Lax enforcement of E-waste legislation.
10. Nonimplementation of the EPR components of the E-waste regulation.

Given that Nigeria does not possess appropriate facilities and infrastructures to fully process the WEEE using state-of-the-art facilities, crude techniques are adopted in the informal sectors which cause avoidable risks to human health and the environment (Nnorom and Osibanjo, 2008). Furthermore, valuable resources including gold and copper are lost due to lack of infrastructure and inefficient processing methods while the recovered valuables are of low quality/purity.

14.3.1 E-waste management in the informal sector in Nigeria

In Nigeria, like in most developing countries, it is the informal sector that dominates the waste collection services, especially in areas where formal waste collection systems are nonexistent (Scheinberg, 2001). Besides buying from private households, activities of the scavengers are characterized by collecting EoL materials from dumpsites and backyards free of charge. Considering the financial benefits, some consumers collect and store large quantities of E-waste and sell to scavengers. The size, type, quantity, and quality of the EoL devices all influence the price paid by the scavengers. Generally, most scavengers look out for certain E-waste categories or components—due to the material composition and recoverable resources.

E-waste management components are a combination of steps and actions taken in the management and treatment of E-waste. This includes activities such as collection, sorting, reuse, refurbishing, repairing, and recycling and these can be broken down into three thematic steps:

- Collection
- Preprocessing (including sorting, dismantling, and mechanical treatment)
- End-processing (including refining and disposal)

Generally, each of these steps are managed by specialized operators. The efficiency of each of the steps has great influence on the entire recycling output.

14.3.1.1 Collection

The collection of EoL WEEE is a key aspect of an E-waste management component. Collection procedures also involve sorting and transporting the collected materials. The efficiency of a collection mechanism determines the amount of material that is available for recovery and that are channeled toward recycling, and the amount that is lost in the process of storage and/or uncontrolled disposal.

At the moment, organized scrap collection point for E-waste is rare in Nigeria; however, effective and organized informal collectors exist. E-waste collection in many developing countries and emerging economies is organized in an informal door-to-door collection system, where collectors pay money to consumers to be allowed to pick up used and obsolete electronic devices, mostly metals-containing waste fractions (Odeyingbo, 2011). Such door-to-door collection systems, however, can only be, operated at low wages for the waste pickers or with subsidies from public or private sources (Manhart et al., 2011). Personnel moving round to pick such waste are called scrap collectors. The scrap collectors earn their daily livelihood from picking and collection of valuable waste which includes scrap metals, obsolete electrical electronic devices, and old cans. The nonvaluable E-waste components are dumped on the dumpsite, or simply burnt.

14.3.1.2 Sorting/dismantling

The collected EoL materials are transported to the various E-wastes dismantling cluster for the onward dismantling and sorting into various component parts by the E-waste workers based on material composition and the value attached to them. For instance, computer screens and TVs are manually dismantled, to recover metals such as iron, steel, copper, and aluminum. Recyclable and reusable components such as the printed wiring board (PWB) are removed while the remaining components especially plastics are destroyed by burning. Little or no attention is given to component parts containing hazardous materials such as batteries, condensers, and cathode ray tubes. Since there is no provision for the management of hazardous components, such are often disposed at open dumps. In a sustainable management scheme hazardous substances have to be removed and stored or treated safely while valuable components/materials need to be taken out for reuse or to be directed to efficient recovery processes. The conservation of resource especially in the area of reuse before recycling and proper recycling in itself could play a key role in environmental protection by avoiding the hazardous waste flow into the open dumps thereby reducing the risks associated with disposal.

14.3.1.3 End-processing

Formal recycling centers are rare in Nigeria. Informal preprocessors collect materials from scrap collectors and local refurbishers. Some preprocessors at the same time are active as scavengers. The preprocessors disassemble E-waste and other wastes to extract valuable materials like copper, steel, entire printed wiring boards and other valuable components, and sell them directly to the end-processors, such as blacksmiths and aluminum smelters. The PWB and some other components are often sold to middle-men that export them to end processing units mostly in Asia.

There is no regard for safety or environmental protection in these activities and personal protective equipment are rarely used. The preprocessors work locally in the residential neighbourhoods and their activities result in environmental pollution that pose health hazards. They engage, for example, in the open incineration of cables and other plastic parts in order to retrieve copper and other metals. There is lax enforcement of existing legislation, which makes this an open business—encouraging the operators to do everything possible to obtain valuable materials and earn income.

A summary of the activities of informal E-waste management in Nigeria are presented in Table 14.5.

In Nigeria, E-waste materials are treated using primitive mechanical tools such as hammers, chisels, screwdrivers, and bare hands to separate metallic materials from other materials such as plastics and glass. The common metals of interest include steel, aluminum, and copper. The printed wiring boards (PWBs) in of particular interest because of the larger amounts of precious metals they contain. Cables and wires are incinerated to liberate copper and other metals in open-air; PWBs are separated, collected, and sold to scrap traders, while other unsalvageable

Table 14.5 Activities of informal E-waste management.

Activities and conditions	Strength	Weakness
Preconditions of access	Low initial investment, no particular qualification required; entry and exit in the WEEE business are easy	No control or regulatory enforcement, unfair trading practices No data are kept and quantification is difficult
Jobs	Labor intensive, employment of local people Support for the local economic	It comes with exposure to health hazards
Dismantling	Manual operations, cost saving profitable business may be generated Effective manual dismantling of WEEE components	Lack of effective technology to prevent pollution. Loss of resources during treatment of more complex components such as PWBs
Skilled in identifying waste with high economic value	Sorting, effective collection with high collection rate, cleaning and altering physical shape to facilitate transport, highly skilled in upgrade and repair, dismantling and recovering material	Income is low, poor wages, no access to health services, and dependence on scrap dealers

Source: From Manhart, A., Osibanjo, O., Aderinto, A., Prakash, S., 2011. Informal e-waste management in Lagos, Nigeria—socio-economic impacts and feasibility of international recycling co-operations, Freiburg/Germany & Ibadan/Nigeria 2011; Scheinberg, A., 2001. Financial and economic issues in integrated sustainable waste management. Tools for decision-makers. Experiences from the Urban Waste Programme. The Netherlands: Waste http://www.waste.nl/page/525; Yoshida, A., Terazono, A., Ballesteros, F.C., Nguyen, D.-Q., Sukandar, S., Kojima, M., et al., 2016. E-waste recycling processes in Indonesia, the Philippines, and Vietnam: a case study of cathode ray tube TVs and monitors. Resour. Conserv. Recycl. 106, 48–58.

or invaluable fractions such as plastic and opened-up cable, are discarded by open-air burning or disposed at dumpsites and riverbanks. Field observation reveals that environmental protection is not usually considered nor enforced at any of the activities. These activities impact negatively on the ecology—affecting both the informal recyclers, persons working or living nearby, and the entire ecosystem. A summary of the impact of current management practices for E-waste in Nigeria are presented in Table 14.6.

The common E-waste recycling activities adopted in the Nigerian informal sector involves the dismantling of E-waste, the recovery of valuable components/parts (often sold to dealers that export same for processing) and the use of crude techniques in the recovery of precious metals. These activities of the informal E-waste handlers can be improved on especially in the following areas:

- Methods/techniques adopted—adopting eco-efficient methods that results in good recoveries with minimal impact on health and environment.
- The recoveries achieved with respect to quantities recovered and the purity.
- Protection of health and environment.
- Income of the operators.

When recycling of E-waste is maximized, it could serve as an incentive and source of revenue for the recycling business considering that E-waste contains only about 2.70% of pollutants and over 60% of valuable metals (Widmer et al., 2005) including steel, aluminum, and copper (EMPA, 2005) as well as precious metals (e.g. silver, gold, and palladium). The value of the materials recoverable from E-waste makes recycling activities economically interesting. This is an indication that there is great benefit and potential when E-waste is channeled toward routes that adopts best practices.

Table 14.7 sums up the strengths, weaknesses, opportunities, and threats (SWOT) related to E-waste management in Nigeria

14.3.2 Formal E-waste sector in Nigeria

Unlike the informal sector, operators in the formal E-waste sectors are legally registered EoL collection and processing/recycling service providers. Such organization must have permission from the relevant authority to collect, dismantle, and process E-waste following standards stipulated by the industry regulator after obtaining relevant operational licences. Formal E-waste recycling facilities are expected to adopt environmentally sound management options. Formal E-waste recyclers are expected to follow all practicable steps to ensure that all collected WEEE are managed in a manner which will protect human health and the environment.

Until recently, there was no formal E-waste recycling in Nigeria. The initiation and promulgation of an E-waste regulation instigated series of positive developments in the management of E-waste in Nigeria culminating in the establishment of the first E-waste recycling facility in Lagos, Nigeria.

The creation of a right balance of legislative driver and positive long-term business condition is essential for the sustenance of recycling business. These are the

Table 14.6 Impact of current E-waste management.

Impact	Action	Positive impact	Adverse impact
Social	• Picking, buying and selling of E-waste and other recyclable waste materials	• Provides jobs for scavengers • Contributes to social development through tax	• These activities can expose scavengers to toxic chemicals and microorganisms • They burn certain E-waste components, for example, cables to recover valuables thereby exposing themselves and the environment to a cocktail of toxins
Economic	• Money exchange for picking E-waste and selling E-waste component	• Source of income for families • Generates 62 Million Naira in tax annually	• Low income earning for scavengers • Risks from hauling the collected recyclables along the road using carts
Environment	• E-waste is disposed of with the household waste that goes to open dumps • Very low chance of separation	• EoL recyclable materials are collected and channeled into the recycling system thereby ensuring resource conservation • Veritable source of input for the informal sector	• Burning of cable component releases hazardous gases into the atmosphere while broken CRTs tubes will release lead and these are released into the air, water, and soil and may enter the food chain • Uncollected recyclables results in loss of of E-waste component for recyclers.
Health and safety	• A typical recovery method in informal sector for recovering copper from cables is to burn polyvinyl chloride in open air • Harmful chemicals are used to leach PWB to obtain precious metals	• None	• Cuts and infections from sharp waste fractions • Injuries from handling heavy devices • Exposure to hazardous substances during recycling operations, for example, dioxins and furans during burning operations, and heavy metals during CRT crushing operations • Chemicals released at waste dumpsites and during waste burning have negative effects on the environment and ecosystem

Source: From Heacock, M., Kelly, C.B., Asante, K.A., Birnbaum, L.S., Bergman, Å.L., Bruné, M.-N., et al., 2015. E-waste and harm to vulnerable populations: a growing global problem. Environ. Health Perspect. 124 (5), 550−555, https://doi.org/10.1289/ehp.1509699; Manhart, A., Osibanjo, O., Aderinto, A., Prakash, S., 2011. Informal e-waste management in Lagos, Nigeria—socio-economic impacts and feasibility of international recycling co-operations, Freiburg/Germany & Ibadan/Nigeria 2011; Velis, C., Mavropoulos, A., 2016. Unsound waste management and public health: the neglected link? Waste Manag. Res. 34 (4), 277−279.

Table 14.7 SWOT analysis of E-waste management in Nigeria.

Strength • Readily available skilled refurbishers with high potential for improved technological task to extend functional life of nonfunctional equipment • EoL devices and disposed E-waste can be refurbished or cannibalized and reused as parts. This creates more access to cheap UEEE	**Weakness** • Lack of awareness of the human and environmental impact of the activities of operators in the informal sector • Poor enforcement of legislation on E-waste management and implementation of EPR • Absence of infrastructure for the formal collection, storage, dismantling, and processing of E-waste • Absence of infrastructure (e.g., engineered landfills) for the disposal of the hazardous fraction from E-waste • Uncontrolled operation of informal sector resulting in deleterious effect to humans and the environment
Opportunity • Reform in the sector can result in green employment opportunities • Viable business opportunities for investors to finance sound recycling via emission reduction, trading scheme, that is, the clean development mechanism (CDM)	**Threat** • Toxic when discarded improperly • Informal activities result in the exposure of man and the environment to toxic and hazardous materials • High prices offered for E-waste diverted into reuse or cannibalization for recovery of parts for use in repairs could divert E-waste meant for recycling into the reuse route—thereby threatening the sustenance of a recycling business

Source: Adapted from Odeyingbo, O., 2011. Assessment of the flow and driving forces of used electrical and electronic equipment into and within Nigeria. Master Thesis. Environmental and Resource Management. BTU.

main discouraging limitation to business operation in developing countries, especially private business operators. For example, in Nigeria, the nonfunctional status of existing regulation is the major driver of the unsustainable E-waste management system by the informal sector. The continued uncontrolled or streamlined operation of the informal recycling activities could create competition for recycling between the formal and informal sector. The existence of formal E-waste recycling in Nigeria will result in a reduction of carbon footprint of waste management and assure effective recycling of E-waste. The activities of the first and only E-waste recycling facility in Nigeria is reviewed.

14.3.3 Hinckley E-waste management activities

Hinckley Recycling is a subsidiary of Hinckley Group, an established business with over seventeen (17) years of business in the ICT market in Nigeria. The company has two facilities dealing with EoL electronics: (i) Ikeja Dedicated IT Refurbishing Unit—established in 2015 and dedicated to refurbishment, value recovery, and data destruction, and (ii) Hinckley Recycling—started recycling operations in 2017 for the safe and responsible collection and recycling of all E-waste streams.

The company facility in Ojota, Lagos, is the first government approved E-waste recycling facility in Nigeria. It took the company 5 years of rigorous environmental tests, assessments, clearance, and accreditation stages, locally and internationally to acquire all necessary certifications to assure that the company is equipped to responsibly treat all E-waste streams capturing the 10 waste electrical and electronic equipment (WEEE) categories from the Nigerian environment. The company complies with National and International regulations for the recycling and disposal of E-waste. All E-waste processed by Hinckley is issued with a certificate of destruction recognized by NESREA and Lagos States Environmental Protection Agency (LASEPA), ensuring its business is legally compliant with the Harmful Waste (Special Criminal Provisions) Act Cap HI, 2004 & the National Environmental (Electrical/Electronic Sector) Regulations S.I No 23 of 2011. All the Company's operations are conducted in an environmental friendly manner, with adherence to the Basel Convention and ensuring that its business is contributing to reducing carbon footprint as well as recycling E-waste responsibly.

The collect and recycle services (CARS) of the company is targeted at organizations that have obsolete or unwanted equipment and expect an efficient and economical solution that delivers compliance to data security and environmental legislation. Under the CARS, Hinckley recovers redundant electronic items, securely destroying all confidential and protected data and manages the recycling of WEEE—in most cases exceeding the reuse, recycling, and recovery of targets. The company policy requires that all EoL equipment delivered to them are tracked and reported, to guarantee the clients that EoL devices are treated in a legally compliant manner and through a quality assured safe and environmentally responsible process (http://www.hinckley.com.ng/recycling/).

14.3.3.1 Refurbishment activities

Hinckley has an operational facility at Ikeja for refurbishment, value recovery, and data destruction, which is a separate entity from the recycling operations. In 2010, Hinckley exceeded 10% by weight of items reclaimed for reuse from what was previously classified as waste electrical and electronic equipment (WEEE)—exceeding targets in the draft Recast WEEE Directive (http://www.hinckley.com.ng/recycling/). Additionally in 2012, Hinckley processed over 2,000 items, refurbishing and selling the majority for reuse. Hinckley's Recycling Services Department also recovers repairable items and components from the waste items for refurbishment and reuse. Hinckley is Nigeria's leading repair and remarketing of used ICT products and they repair over 1000 items per month.

The company considers this service as a desirable route that many organizations can choose for equipment that merely requires a "refresh" in the product life cycle: refurbish existing equipment and redeploy such back into the organization.

Hinckley provides a range of solutions that enable an organization to have equipment collected from one location, refurbished, upgraded if required, reconfigured, and then redeployed to the same or another designated site.

14.3.3.2 Recycling operations

Hinckley accepts and recycles devices within the 10 WEEE categories. The Hinckley Recycling facility at Ojota is a multi-E-waste stream processing facility with capacity for 20,000 tons of E-waste per annum. The company's newly acquired facility has been inspected and approved for recycling by the regulatory bodies. The Ojota facility receives both hazardous and nonhazardous waste streams. Presented in Table 14.8 is the company's classification of fractions/components from E-waste.

Hinckley's process is transparent and is audited as material are tracked through the entire company processing from collection to the destination of the secondary material. (Company report). Some of the machines used in the processing are shown in Fig. 14.5.

Being a semiindustrialized processing facility, Hinckley ensures that all E-waste are processed into minute material fractions for further processing by the downstream sector. All hazardous components are treated safely and processed at state-of-the-art facilities worldwide. Hazardous components such as refrigerants are collected using the machine shown in Fig. 14.6. The approach adopted in processing specific components/materials of E-waste are presented in Table 14.9.

Formalizing the informal E-waste sector via training is essential in bringing the much needed change to assure protection of human health and the eco-system. In 2018, Hinckley commenced series of training programs for operators in the informal E-waste sector in Nigeria to update them on better E-waste management practices and keep then abreast of the environmental and health implications of their operations. The firm commenced the series with a week-long training of members of the

Table 14.8 Hinckley recycle classification of hazardous and nonhazardous E-waste components.

Nonhazardous fractions	Hazardous fractions
Aluminum	Lithium ion batteries
Iron/steel	Capacitors
Copper	Lead-acid batteries
Bronze/Brass	Nickel-cadmium batteries
Stainless steel	Other batteries
Mixed ferrous metals	LCD screens
Mixed nonferrous metals	CFL (e.g., scanner bulbs)
Mixed plastic	Toner cartridges
ABS plastic	CRT leaded glass
Glass	Phosphorous powder
Printed circuit boards (PCB)	Brominated plastic

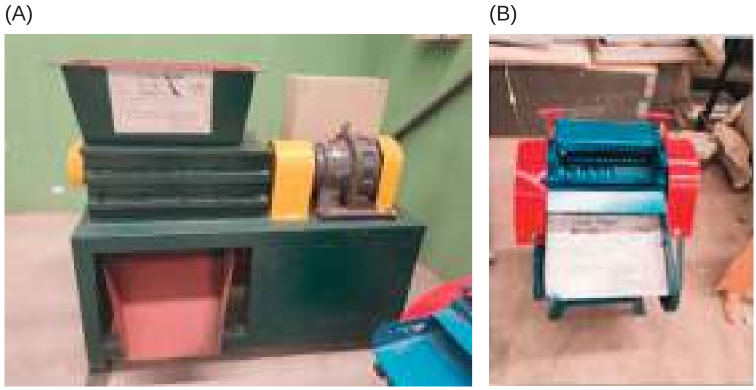

Figure 14.5 E-waste processing machines: (A) two-drum shredder and (B) cable striper.

Figure 14.6 Refrigerant recovery machine.

Association of Vendors of Used Computers and Allied Products, which is a body of the informal operators that have about 500 active members within Lagos. The training was followed by physical examination and laboratory testing of some of the scavengers for exposure to harmful chemicals from E-waste processing (Punch, 2018).

14.3.3.3 Challenges

In Nigeria, it is common to find scavengers, waste collectors, and smelters posing as "recyclers" by going house-to-house collecting E-waste for a fee. Such collectors divert E-waste into the informal recycling since they do not have facilities to recover precious elements and manage the hazardous fractions in an environmentally sound manner. These individual constitute a challenge to the proper management of E-waste rerouting E-waste into the informal sector while acting as the "new recyclers in town." This and the nonimplementation of extended producer responsibility constitute huge challenges to formal recycling in Nigeria.

Table 14.9 E-waste processing approach for specific components/materials.

Components	Material	Classification	Recycling process	End product (downstream)
Refrigerant	Gas	Gas is hazardous	Gas will be safely extracted using RRM-650. The gas will be stored and reused	Recycled gas for reuse
Compressor	Copper, steel, motor, and oil (lubricant)	Used oil is hazardous	Copper will be extracted and transferred locally at approved smelters. Oil is extracted and stored for reuse	Copper ingots
Condenser	Steel and copper	Nonhazardous	Metals and plastics will be extracted and transferred locally at approved smelters	Steel and copper ingots
Condenser fan	Plastic, steel, and motor	Nonhazardous	Metals and plastics will be extracted and transferred locally at approved facilities	Copper and plastic
Evaporator	Copper/steel/aluminum	Nonhazardous	Metals and plastics will be extracted and transferred locally at approved smelters	Copper/steel/aluminum ingots
Filter/Dryer	Iron and silica gel	Nonhazardous	Silica gel is processed from KDF (Copper and Zinc)	KDF
Accumulator	Iron and gas	Gas is hazardous	Gas will be safely extracted using RRM-650. The gas will be stored and reused	Iron ingots
Body	Foam and plastic	Hazardous	Dismantled and bailed for local downstream production purpose	Mixed foam and plastic; use in building material
Divider	Iron, glass, and plastic	Nonhazardous	Material will be extracted and transferred locally at approved facilities	Recycled glass, iron ingots, plastic furniture

Hinckley has to deal with the low E-waste awareness as well as inadequate finance. There is no level playing field in this sector as Hinckley is unable to offer households or organizations same or comparable amounts as they receive from the scavengers due to the processing and treatment costs incurred for responsible recycling. Unfortunately, the situation is so bad that companies with environmental ISO standards, who uphold global sustainability, HSE, and environmental policies are unable to look away from the financial gains the informal sector avails them. This value system is one Hinckley battles with on a day-to-day basis.

14.4 Comparative analysis of E-waste treatment in developed versus developing countries

Today in industrialized countries, E-waste is processed separately from other waste streams owing to its material composition and appliance size (Krauchi et al., 2005). Many OECD (Organization for Economic Co-operation and Development) countries have developed management systems based on realities of the system boundary and legislation (OECD, 2014). The European Union WEEE (2002/96/EC) and RoHS (2002/95/EC) Directives, revolutionized E-waste management by setting collection, and recycling/recovery targets and restricting the use of hazardous materials in the manufacture of electronic products. In Europe, both the new and old WEEE directives set targets for collection, recycling, and recovery rates. The old WEEE Directive set a target collection rate of four kilograms per capita from 2006 to 2016, whereas WEEE 11 (effective from 2016) has set a 45% collection rate of the average weight of electrical and electronic devices that were placed on the market in the previous 3 years. Such ambitious legal framework does however not exist in Nigeria at the moment.

Switzerland has a legislation in force that ensures WEEE are managed effectively. The management is based on EPR with a clear definition, roles, and responsibilities of all the stakeholders involved (Sinha-Khetriwal et al., 2005). The Swiss Foundation for Waste Management (S.EN.S) is a nonprofit organization assigned to recover selected WEEE on behalf of manufacturers, importers, and retailers. It commenced its operation in 1990 with the responsibility of recycling refrigerators and freezers. In addition to the activities of Swiss foundation for waste management (S.EN.S), the Swiss Association for Information, Communication and Organisation Technology (SWICO) recycling guarantee was created by the association of manufacturers and importers of office electronics and IT equipment in Switzerland in 1993. SWISCO was initially collecting office electronics and IT equipment. It operational coverage however expanded to include other WEEE such as mobile phones, consumer electronics, telephone switchboard systems, as well as dental equipment (Hischier et al., 2005; Streicher-Porte et al., 2005). Both systems are well established, offering complete take back and recycling systems financed by an advanced recycling fee (ARF) (Hischier et al., 2005). These fees are paid by the distributors, the retailers, and finally to the consumers, who pay an ARF with the purchase of any EEE (Streicher-Porte et al., 2005).

However, this is not the case in the developing countries. The backlog demand of EEE in developing countries as well as the lack of national regulation on management of E-waste and/or lax enforcement of existing laws promotes the growth of informal economy that deals with E-waste (Osibanjo and Nnorom, 2007; Ni and Zeng, 2009).

It is difficult to have an effective and sustainable formal E-waste collection system without an effective financial mechanism combined with legislation. In Nigeria, the informal collectors in most cases buy E-waste from the consumers while only a few consumers hand over their E-waste free of charge. It is rare for a consumer to pay for the disposal of E-waste.

Inappropriate methods are used in the management of E-waste in the developing countries, including disposal with municipal waste, disposal into surface water bodies and the use of "unsound" techniques in the "crude recycling" of selected components of E-waste to recover valuable materials such as copper, silver, and gold (BAN, 2002; 2005). The crude techniques adopted in material recovery from E-waste include open burning, cathode ray tube cracking and dumping, circuit board recycling, plastic fragmentation and melting, and dumping various waste residues (Ni and Zeng, 2009). These activities are wrecking environmental havoc in the developing countries and various studies have reported severe environmental and health implications of such activities (Fu et al., 2008; Wong et al., 2007). The conventional waste management approach is that waste generation, collection and disposal systems are planned independently. However, experience has shown that all these are very closely interlinked and each component can influence the other. This situation also corroborates the situation in E-waste flow network, where active interaction exists between the various components in the flow network.

The complexity of E- waste management in Nigeria could be demonstrated by the amount of interconnections between the various components which affects each other. The reality of the interaction of the component is represented by the interaction between the operators in the flow network which includes actors involved in retail, refurbishment, consumption, repair, disposal, dismantle, export of dismantled scraps, or local recycle. For instance, the E-waste collection and recycling activities in Lagos are carried out by informal waste collectors (commonly referred to as "scavengers") who move round the city collecting E-waste together with other metal-containing wastes. Mostly, these collectors buy such obsolete devices for small amounts of money from individuals, businesses, or private households. There are also collectors who cannot afford to buy these obsolete devices because of financial constraint hence they focus on what is freely available, for example, at open dumps. Dismantled and assorted E-wastes are sold to traders while nonvaluable fractions are thrown back on the dumpsite. The E-waste recyclers disassemble obsolete electrical and electronic equipment in order to liberate metals that can be sold for economic gain. Some metals of interest include steel, aluminum, and copper. Cable wires are incinerated to liberate copper, printed wiring boards (PWBs) are separated, collected, and sold to traders. Invaluable fractions are discarded mostly by burning and discarding on dumpsites. The various stages are closely related and executed.

This trend in the management of end of life materials of E-waste in Nigeria leads to a high accumulation of residual materials which are difficult to manage due to lack of appropriate management scheme that can take care of both valuable E-waste component and the nonvaluable ones. It is evident that an appropriate E-waste management system would require a financial scheme to sustain the system. The nonexistence of an appropriate management scheme that integrates E-waste finance still creates a research gap necessary for empirical studies.

At the moment, enterprises and individuals engaging in E-waste management cannot effectively manage the collected EoL materials in environmentally sound methods without the availability of additional financing systems and/or other safeguard mechanisms that ensure a proper handling of all fractions of EoL WEEE especially the CRTs containing device. The work of Manhart et al. (2011) revealed that an average E-waste collector and recycler in Nigeria earns between US$ 0.22 and US$ 3.36 per day. This earned income is below the internationally defined poverty line of US$ 1.25 for majority of these operators especially those with dependants. These financial returns cannot secure the operators a decent living. The quantity and quality of the collected WEEE under consideration determines the overall management approach adopted because of the different monetary values attached to the various components and also the competition between informal business and formal system.

An ideal management system, within the formal sector, is expected to observe all the environmental and occupational regulations attached to their activities while taking care of both valuable and nonvaluable components. This is expected to increase the operational cost of activities, whereas the informal sector generally does not obey many of the set rules which give them cost advantage over the formal operators. The nonenforcement of the existing E-waste regulation is assumed to be one of the major drivers of the unsustainable E-waste management system in Nigeria.

14.5 Proposing a sound E-waste management strategy in Nigeria

Studies have shown that pollution from E-waste processing using crude methods has the potential to cause damage both to the environment and human health through the contamination of air, soil, water, and sediment. Studies of blood, breast milk, and hair of workers and people residing within E-waste treatment sites have reported elevated levels of heavy metals levels (Zhao et al., 2007, 2008; Li et al., 2017).

14.5.1 Financing E-waste management

The financing mechanism of E-waste take-back system activities and allocation of economic responsibilities, along the EoL material flow network has proven to be challenging in many developing and developed countries with existing take-back schemes or countries discussing potential take-back scheme (UNEP, 2014; StEP, 2009). An effective financial scheme will involve financial responsibility to the key stakeholders throughout the flow network. An appropriate system would require a financial system which takes care of both valuable and nonvaluable fraction in such a way that the value of recyclables should be able to offset the processing cost with a profit margin after handling the nonvaluable, hazardous components.

The present E-waste management system in Nigeria cannot finance itself. One of the materials of high values in E-waste is gold and its concentration in PCs is estimated to be about 4 g. This value creates an incentive to recover gold from the PC. Unfortunately, when the gold-containing components are sold at lower values for recovery/refining abroad, the monetary benefit is drastically reduced. More so, the other material fraction in E-waste attracts low economic value, e.g., glass and plastics. This condition is responsible for the burning or dumping options in developing countries. The availability of recycling technology in Nigeria will assure enhanced profitability from the E-waste fractions currently exported. Funding is therefore necessary to drive sound management approach to E-waste.

In developing countries house-to-house collection of E-waste by the informal sector is believed to significantly achieve higher collection rates when compared to voluntary take-back systems in Europe (UNEP, 2014). This can be attributed to the fact that such procedures are convenient for the consumers and sometimes the money paid by the collectors is an economic incentive that encourages the consumer to participate (Odeyingbo, 2011).

Various studies have identified the need for a well-functioning local take-back and recycling scheme which involves development of effective collection strategies (not cherry picking), ensuring collection of both valuable and nonvaluable fractions which are channeled into appropriate recycling process and or treatment/disposal routes. To ensure an effective collection and appropriate treatment, an appropriate financial scheme that can achieve a win-win situation for all the stakeholders involved, conservation of resources through recycling, and reducing impact on the environment is crucial. Financing E-waste management system should be a system which aims at establishing institutional frameworks by initiating a suitable process that will accommodate negotiations, regarding responsibilities, and rules amongst relevant stakeholders at local, national, regional, and global level and how such system could be sustained in a long term and fair market condition for all.

14.5.2 Enforcement of E-waste regulation in Nigeria

Sequel to the high incidence and influx of shipments of hazardous waste and E-waste into Nigeria, the Government moved to address this transboundary movement. It is expected that the availability of policy and law could help develop a legal framework centered on the activities of the stakeholders to assure environmentally sound management of E-waste. Due to the documented evidence of E-waste dumping in Nigeria and the return of shipments of E-wastes to country of origin, the government through the regulatory agency, NESREA initiated moves to control the in-flow of E-waste via legislation. In 2011, the government passed the National Environmental (Electrical/Electronic Sector) Regulation which banned the importation of E-waste and provided guidelines on environmentally sound management of E-waste. NESREA has the responsibility to enforce all environmental laws, regulation, guidelines including monitoring and control of E-waste. The agency wants to stop the importation of unserviceable UEEE coming into Nigeria. In recent times, NESREA together with the Nigeria Port Authority sent back some ships suspected to carry E-waste into Nigeria from Europe. The NESREA Regulation stipulates that all UEEE imported into Nigeria shall comply with the following provisions:

1. The item(s) shall be of comparative models of equipment in use.
2. It shall be fit for the purpose it was originally designed for.
3. It shall be fully functional as originally intended.
4. The outward/external appearance of the item shall not show any waste characteristics
5. It shall not be scrap.
6. The items shall be properly package for protection during transport, loading, and unloading.

Some of the regulatory requirements for the importation of UEEE into Nigeria are:

A. Where the holder of the equipment/products indicates intention to ship or is shipping UEEE and not WEEE, the following documentation shall be provided to back up the claim to NESREA:
   I. A copy of the invoice and documentation relating to the sale and or transfer of ownership of the UEEE which states that the equipment is for direct reuse and fully functional.
   II. Evidence of evaluation/testing, such as certificate of testing proof of functional capability on every item in the container/truck.
   III. A declaration made by the holder who arranges the transport of the UEEE that none of the material or equipment within the consignment is waste.
   IV. Evidence of sufficient packaging to protect it from damage during transportation, loading and unloading.

B. Prior to any transboundary movement of UEEE, the importer or the representative shall provide information to the appropriate authorities (NESREA and Nigerian Customs Service) providing compliance with this guidance.

C. For practical reasons of control, every carrier (e.g. shipping container, lorry, and truck) of UEEE shall be accompanied by
   - A Cargo Movement Requirement (CMR) document. The CMR is a proof of evaluation/testing and certificate containing testing information on each item, and
   - A Copy of permit to import.

D. Item that should not be imported into Nigeria.

E. Consequently, UEEE would normally be considered waste if:
   i. The product is not complete and some essential parts are missing.
   ii. Functionality or safety is impaired.
   iii. The appearance is generally worn or damaged.
   iv. The packaging is insufficient.

v. The item has among its constituent parts anything that is required to be discarded including refrigerators or air conditioners containing ozone depleting substances (ODS).
xvi. It is destined for disposal or recycling instead of reuse.
xvii. It is old or outdated destined to be cannibalized to gain spare part.

Despite the regulatory provision of the Basel Convention and the NESREA regulation, huge amounts of UEEEs and E-wastes still flows into Nigeria annually (Odeyingbo et al., 2017). It is therefore necessary to review existing legislations if necessary and ensure strict enforcement to assure sound E-waste management. It may also be necessary to review the type of permits or licenses issued to importers of UEEE to assure compliance to existing regulation—especially on the importation of only functional UEEEs.

14.5.3 Introduction of environmentally sound technology

The role of technology and appropriate skill cannot be over looked in the E-waste management system. The continuous training of personnel working in E-waste management sector and provision of basic infrastructure are crucial. The availability of techniques relating to personal protection, handling of hazardous products, first aid and combating fire and flames are essential for people working in this sector. The provision of appropriate technology would contribute in achieving the aim of an eco-friendly recycling business.

14.5.4 Effective extended producer responsibility implementation

Extended producer responsibility (EPR) is an environmental protection strategy aimed at decreasing total environmental impact from a product and its packaging, by ensuring that the producers of the product take responsibility for the entire life-cycle of their products especially in the take-back, recycling, and final disposal of their products, including its packaging. The primary responsibility of EPR lies with the producer, who makes designs and marketing decisions. In 2013, an EPR system was initiated by NESREA with the introduction and adoption of a draft Guidelines for Implementation of EPR for the Electrical and Electronic Sector (EES). The guidelines create an avenue to achieve a sustainable E-waste management status in Nigeria by implementing and enforcing the EES regulation of 2011. The core stakeholders targeted in the EPR guidelines includes producers/importers, manufacturers, and assemblers of EEE. The guideline incorporates the establishment of collection centers in collaboration with the original equipment manufacturers (OEMs). It further makes provision for the establishment of an EEE Registry, that is, an organization that maintains an inventory of recyclers/E-waste related companies and E-waste stocks nationwide, and this will be operated by third-parties and public−private partnerships, to achieve an effective EPR system in Nigeria. A synergy of both voluntary and mandatory approaches to E-waste should be encouraged and the EPR concept should be reviewed to include other stakeholders, such as the consumers and government. In addition, the following will facilitate effective EPR in Nigeria:

- Establishment of WEEE registry/database.
- Proper regulation of the informal sector.
- Introduction of nonmonetary incentives that will encourage for consumers to return EoL goods for recycling or pay for the disposal of their waste.
- Creation of a financial model to fund environmentally sound recycling.
- Efficient record keeping that is easily retrieved to facilitate rational investment decisions.

One of the challenges to an effective EPR is the overlapping and lack of clarity in the roles and responsibilities of stakeholders—importers, collectors and recyclers, municipalities, consumers, and the producer responsibility organizations (PROs). Maybe, the earlier this is resolved in the Nigerian EPR, the more likely the EPR will impact positively on E-waste management in Nigeria. Also of importance is the illegal importation of UEEE by individuals and businesses that are not registered with the regulatory agencies. Recent findings showed that only 3% of the importers of UEEE are registered with the regulatory agencies in Nigeria (Odeyingbo et al., 2017). This implies that the vast majority of the importers cannot contribute to the EPR scheme and this will result in inadequate levels of finance to handle end-of-life costs.

Monitoring and control by the government agencies will ensure that stipulated conditions and target are met by operators. Monitoring is an important component in the E-waste management system because it ensures continuous improvement and maintaining compliance to the existing regulation and standards. Awareness creation among the stakeholders is necessary to rational investment decisions.

14.6 Conclusion

E-waste management represents the dark side of advances in the information communication technology (ICT) sector, which obviously has been instrumental to the transformation of virtually all aspect of human endeavors. The export of UEEE/WEEE generated in the developed countries to the developing countries may have some benefits but the negative impacts are so evident in the destination countries due to the absence of facilities/infrastructures that would facilitate environmentally sound management of E-waste and assure resource conservation. Low end techniques such as open burning and other crude E-waste management practices are adopted and these result in the emission of pollutants like dioxin, furan, and heavy metals. E-waste is unique as it contains both hazardous and valuable/precious metals.

The factors driving the inflow of UEEE and E-waste into Nigeria, the management approaches adopted as well as the challenges in achieving environmentally sound management of E-waste were discussed. Progress in the formal recycling sectors was reviewed while some of the approaches in achieving sound management practices were presented. The major challenges facing E-waste management in

Nigeria include inflow of E-waste, poor take-back/collection strategies that favors formal processing, and dearth of state-of-art technologies to recover resources from E-waste. Incentive-based policies that protect human health and the environment must be proactive and practical in this sector.

The PiP has shown that physical inspection of containers and vehicles conveying UEEE is critical in UEEE/E-waste inventories. The national adoption of this strategy will unravel the real flows of UEEE/E-waste and this is important in checking illegal E-waste trafficking. The importation of huge quantities of UEEE/E-waste into Nigeria, many of which are nonfunctional, aggravates the already bad situation. Considering the recent discoveries on the modes of importation and the functionality reported, it is pertinent that the existing regulation is enforced to ensure strict monitoring of UEEE and E-waste importations. The observation by the PiP that only 3% of the importers of UEEE are registered with the regulatory agency is worrisome. This shows that about 97% of active UEEE importers are into illegal activities and would most likely make no effort to adopt best practices and implement the NESREA regulation in their action. This could be a reason for the wrong declarations observed by the PiP.

The regulatory agencies should ensure that the existing laws are enforced especially with respect to implementation of EPR. Strict enforcement of the provisions of the E-waste regulation is essential to ensure the adoption of environmentally sound management options that guarantees protection of life and the eco-system. Awareness creation on the toxicity of some E-waste components and the health implications of informal recycling are essential to divert E-waste from the informal sector. Controlling the importation of UEEE to ensure that only tested and functional devices are imported as enshrined in the E-waste regulation will reduce the volumes if E-waste managed.

References

Baldé, C.P., Forti V., Gray, V., Kuehr, R., Paul, S., 2017. The Global E-waste Monitor – 2017, United Nations University (UNU), International Telecommunication Union (ITU) and International Solid Waste Association (ISWA), Bonn/Geneva/Vienna.

BAN, 2005. The Digital Dump: Exporting Re-Use and Abuse to Africa, the Basel Action Network. October 24, 2005. Puckett, J. (Ed.). www.ban.org.

BAN/SVTC, 2002. Exporting harm: the high tech trashing of Asia. The Basel Action Network and Silicon Valley Toxics Coalition. February 25, 2002. Puckett, J., Smith, T. (Eds.).

EMPA, 2005. Swiss e-Waste Guide, a knowledge base for the sustainable recycling of e-waste. Swiss Knowledge Partnerships in e-Waste Recycling. www.e-waste.ch.

Fu, J.J., Zhou, Q.F., Liu, J.M., Liu, W., Wang, T., Zhang, Q.H., et al., 2008. High levels of heavy metals in rice (Oryza sativa L.) from a typical e-waste recycling area in southeast China and its potential risk to human health. Chemosphere 71, 1269–1275.

Heacock, M., Kelly, C.B., Asante, K.A., Birnbaum, L.S., Bergman, Å.L., Bruné, M.-N., et al., 2015. E-waste and harm to vulnerable populations: a growing global problem.

Environ. Health Perspect. 124 (5), 550−555. Available from: https://doi.org/10.1289/ehp.1509699.

Hischier, R., Wager, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ. Impact Assess. Rev. 25, 525−539.

Krauchi, P.H., Wager, P.A., Eugster, M., Grossman, G., Hilty, L., 2005. End-of-life impacts of pervasive computing. IEEE Technol. Soc. Mag Spring 2005, 45−53.

Lall, A., Garai, A., 2005. Capturing grassroots voices in the information society and sustainable development: the policy dialogue in India. In: Willard, T., Andjelkovic, M., Vosloo, S., Mungai, W., Salas, M., Lall, A., Garai, A., de Assumpção, D.A., Sobeih, A. (Eds.), A Developing Connection: Bridging the Policy Gap between the Information Society and Sustainable Development. International Institute for Sustainable Development, <www.iisd.org>.

Li, X., Tian, Y., Zhang, Y., Ben, Y., Lv, Q., 2017. Accumulation of polybrominated diphenyl ethers in breast milk of women from an e-waste recycling center in China. J. Environ. Sci. 52, 305−313.

Lundgren, K., 2012. International Labor Office (ILO). The global impact of ewaste: addressing the challenge. 2012. Available from: http://www.ilo.org/wcmsp5/groups/public/-----ed_dialogue/-----sector/documents/publication/wcms_196105.pdf (accessed 14.10.14.).

Manhart, A., Osibanjo, O., Aderinto, A., Prakash, S., 2011. Informal e-waste management in Lagos, Nigeria—socio-economic impacts and feasibility of international recycling co-operations, Freiburg/Germany & Ibadan/Nigeria 2011.

Marine, S., Blanchard, J.M., 2004. Bridging the digital divide: an opportunity for growth in the 21st century. Alcatel Telecommunications Review-3rd Quarter 2004. Strategy White Paper. Alcatel. pp. 1−8. www.alcatel.com.

Monge, R., Chacón, F., 2002. Bridging the Digital Divide in Costa Rica Access to and Use of Information and Communications Technologies (ICTs). Translation of the original version in Spanish, by: Xinia Rodríguez Castillo. Costa Rican Advisory Commission on High Technology (CAATEC). Digital Costa Rica Series 1. ISBN 9977-911-55-X.

NCC, 2018. Nigeria Has Achieved 100 Percent Teledensity https://www.ncc.gov.ng/thecommunicator/index.php?option = com_content&view = article&id = 888:nigeria-has-achieved-100-percent-teledensity&catid = 25&Itemid = 179 (accessed 20.11.18.).

Ni, H.-G., Zeng, E.Y., 2009. Law Enforcement and Global Collaboration are the Keys to Containing E-Waste Tsunami in China. Environ. Sci. Technol. 43, 3991−3994.

Nnorom, I.C., 2012. Bridging the digital divide and creating an ICT dump: an overview of the unsustainability of exporting used and end-of-life ICT-wares to developing. In: Li, Y.C., Wang, B.L. (Eds.), E-Waste: Management, Types and Challenges. Nova Science Publishers, Inc, New York, NY, pp. 67−88. Series: Computer Science, Technology and Applications; Environmental Remediation Technologies, Regulations and Safety. ISBN: 978-1-61942-217-9s.

Nnorom, I.C., Osibanjo, O., 2008. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Res. Conserv. Recycl. 52, 843−858.

Odeyingbo, O., 2011. Assessment of the flow and driving forces of used electrical and electronic equipment into and within Nigeria. Master Thesis. Environmental and Resource Management. BTU.

Odeyingbo, O., Nnorom, I.C., Deubzer, O.K., 2017. Assessing imports of used electrical and electronic equipment into Nigeria: Person in the Port Project. November, 2017. BMZ/ GIZ and US-EPA; 68 pp. http://collections.unu.edu/eserv/UNU:6349/PiP_Report.pdf.

Odeyingbo, O., Nnorom, I.C., Deubzer, O.K., 2019. Used and Waste Electronics flows into Nigeria: assessment of the quantities, types, sources, and functionality status. Sci Total Environ (accepted for publication).

OECD, 2014. Global Forum on Environment Issues Paper, The Sate of Play on Extended Producer Responsibility (EPR) Opportunities and Challenges, Global Forum on Environment: Promoting Sustainable Materials Management Through Extended Producer Responsibility (EPR) 17−19 June 2014, Tokyo, Japan. Available from: http://www.oecd.org/environment/waste/Global%20Forum%20Tokyo%20Issues%20Paper%2030-5.

Ogungbuyi, O., Nnorom, I.C., Osibanjo, O., Schluep, M., 2012. E-Waste Country Assessment Nigeria. E-waste Africa Project of the Secretariat of the Basel Convention, United Nations Programme (UNEP). Basel Convention Coordinating Centre for Africa (BCCC- A) in Nigeria and Swiss Federal Laboratories for Materials Science and Technology (EMPA), St. Gallen/Switzerland, May, 2012. http://www.ewasteguide.info/Ogungbuyi_2012_BCCC-Empa.

Osibanjo, O., Nnorom, I.C., 2007. The challenge of electronic waste (e-waste) management in developing countries. Waste Manage. Res. 25, 489−501.

Osibanjo, O., Nnorom, I.C., Ogbonna, K.C., 2008. Modeling waste generation by the telecom sector in Nigeria: the grey side of the impressive outing. Waste Manage. Res. 26, 317−326.

Osibanjo, O., Nnorom, I.C., Adie, G.U., Ogundiran, M.B., Oketola-Adeyi, B., 2016. Global management of electronic wastes: challenges facing developing economies in transition countries in the management of electronic waste. In: Izatt, R.M. (Ed.), Metal Sustainability: Global Challenges, Consequences, and Prospects. Wiley Interscience Publishers, pp. 52−84. Chapter 3.

PUNCH Newspaper, 2018. Hinckley begins training on e-waste handling. Published March 5, 2018. Report prepared by Maureen Ihua-Maduenyi, https://punchng.com/hinckley-begins-training-on-e-waste-handling/ https://guardian.ng/property/firm-sets-up-e-waste-recycling-facility-in-lagos/.

Scheinberg, A., 2001. Financial and economic issues in integrated sustainable waste management. Tools for decision-makers. Experiences from the Urban Waste Programme. The Netherlands: Waste http://www.waste.nl/page/525.

Sinha-Khetriwal, D., Kraeuchi, P., Schwaninger, M., 2005. A comparison of electronic waste recycling in Switzerland and in India. Environ. Impact Assess. Rev. 25, 492−504.

StEP Initiative/United Nations University, 2009. E-waste Take-Back System Design and Policy Approaches White paper. Jeremy Gregory, Federico Magalini, Ruediger Kuehr, Jaco Huisman. ISSN: 2071-3576 (Online).

StEP, 2014. Solving the E-Waste Problem (StEP) 14 January 2014 Initiative Differentiating EEE Products and Wastes Recent Developments and future possibilities under the Basel Convention available in http://www.stepinitiative.org/files/step/_documents/StEP_GP_Differentiating%20EEE%20products%20and%20wastes_20140114.pdf (accessed 21.01.16.).

Streicher-Porte, M., Widmer, R., Jain, A., Bader, H.-P., Scheidegger, R., Kytzia, S., 2005. Key drivers of the e-waste recycling systems: assessing and modeling e-waste processing in the informal sector in Delhi. Environ. Impact Assess. Rev. 25 (5), 472−491.

This Day, 2018a. Nigeria Maintains Teledensity Growth for Nine Consecutive Months (Article by Emma Okonji) June 21, 2018. https://www.thisdaylive.com/index.php/2018/06/21/nigeria-maintains-teledensity-growth-for-nine-consecutive-months/ (accessed 20.11.18.).

This Day, 2018b. Nigeria Maintains Steady Growth in Teledensity, Mobile Internet Subscription. ThisDay Newspaper https://www.thisdaylive.com/index.php/2018/02/15/nigeria-maintains-steady-growth-in-teledensity-mobile-internet-subscription/ (accessed 20.11.18.).

UNEP, 2014. Basel convention on the control of transboundary movements of hazardous wastes and their disposal, United Nations Environment Programme/Secretariat of the Basel Convention; 1989. http://www.basel.int/text/documents.html.

Velis, C., Mavropoulos, A., 2016. Unsound waste management and public health: the neglected link? Waste Manage. Res. 34 (4), 277–279.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, A., Scnellmann, M., Boni, H., 2005. Global perspectives on the e-waste. Environ. Impact Assess. Rev. 25, 436–458.

Williams, E.D., 2003. Extending PC lifespan through secondary markets. In: 2003 IEEE International Symposium on Electronics and the Environment. May 19–22, 2003. pp. 255–259.

Wong, C.S.C., Wu, S.C., Duzgoren-Aydin, N.S., Aydin, A., Wong, M.H., 2007. Trace metal contamination of sediments in an e-waste processing village in China. Environ. Pollut. 145 (2), 434–442.

Ya'u, Y.Z., 2002. Confronting the digital divide: an interrogation of the African initiatives at bridging the gap. In: Paper presented at the CODESRIA/TWN Conference on Africa and the Challenges of Development in the New Millennium. Accra, Ghana. Apr. 2002.

Yoshida, A., Terazono, A., Ballesteros, F.C., Nguyen, D.-Q., Sukandar, S., Kojima, M., et al., 2016. E-waste recycling processes in Indonesia, the Philippines, and Vietnam: a case study of cathode ray tube TVs and monitors. Resour. Conserv. Recycl. 106, 48–58.

Zhao, G., Xu, Y., Li, W., Han, G., Ling, B., 2007. PCBs and OCPs in human milk and selected foods from Luqiao and Pingqiao in Zhejiang, China. Sci. Total Environ. 378, 281–292.

Zhao, G., Wang, Z., Dong, M.H., Rao, K., Luo, J., Wang, D., et al., 2008. PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. Sci. Total Environ. 397, 46–57.

Further reading

EC, 2003. European Commission 2003 WEEE Directive WEEE Directive. Directive 2002/96/EC of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE). Brussels, January 2003.

E-waste recycling slum in the heart of Accra, Ghana: the dirty secrets

15

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15.1 Introduction

Accra, Ghana, has many dirty little secrets. First, the country's peaceful transition to democracy after a tension-packed democratic election in 2016 (Bekoe, 2017), years of double-digit growth from 2011 to 2015 (World Bank, 2019), the offshore discovery and mining of oil in commercial quantities since 2010 (Oteng-Ababio, 2018), and its promotion to middle-income status in 2015 (World Bank, 2019) are all refreshing but unfortunately, these are yet to translate into job creation for the teeming youths who enter the labor market annually (Yeebo, 2014; Aryeetey and Kanbur, 2017). The status quo remains: unless you are well educated, wealthy, connected, or able to work for years as a part-time, casual laborer, or apprentice; you are on your own: you need to invent a job, and often a series of them (Cobbinah and Darkwah, 2018). As such a burgeoning informal economy accommodates the majority (68%) of urbanites, and informal settlements house the vast majority of the recent migrant population (Grant and Oteng-Ababio, 2019).

Second, the urban policy terrain accommodates broad-brush universal goals like sustainability and equity (Grant and Oteng-Ababio, 2019). Indeed, the city was ones framed a Millennium City (Afenah, 2012), a Rockefeller 100 Resilient City (Melara et al., 2013), and today plays a core role in supporting the UN Sustainable Development Goals. The above notwithstanding, it is not clear how city authorities deal with or relate to different policy objectives in practice. A dirty little secret is that the authorities pay lip-services to all inclusive governance in local and international fora. They employ popular catchphrases like participatory democracy, lifting people out of poverty, and slum upgrading, but in practice, neoliberalism predominates and obliterates alternative agendas (Obeng-Odoom, 2016; Gillespie, 2016). Despite the government's bizarre claims (MasterCard, 2014, p. 1), a body of scholarly literature today contends that the masses of peoples in Accra are disenfranchised (Gillespie, 2016; Morrison, 2017; Oteng-Ababio, 2018).

Third, we draw on empirical research in Agbogbloshie to uncover the dirty secrets and clash of rationalities that pit neoliberal logic against people-centered approaches. We show that micropolitics is far from straightforward: diverse

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00019-X

strategies are incorporated into neoliberal positioning, and multiple strategies operate within the people-centered framework. Cross-alliances and arrangements arise from time to time, but place-making is a highly contested and negotiated process. Excavating Agbogbloshie dwellers' lived experiences within the informal space economy against the backdrop of neoliberal tendencies, we propose an alternative reading of settlements, where urbanites live, work, and engage in their place-making. Integrating Lefebvre's ideas about the "right to the city" and building upon his foundational notion of "lived space," we seek to reevaluate their potential contribution to the city economy as a whole. We engage in the elucidation of the right to the city frequently acknowledged and discussed but less often studied in depth. As geographers, we stand clearly in the camp that reasons are contingent and agnostic properties of the rights that citizens have with real places, as opposed to imagined places in some utopian future (Pierce et al., 2016). Although Lefebvre was writing from a postwar European context, we believe that his ideas can be extrapolated for engagement with global South slums and the constructive engagement around the Ghanaian urban condition today (Huchzermeyer, 2014). As urban space is produced locally but enmeshed in broader civic and economic processes, we focus on a subscale of rights to a place, in this case, a settlement that situates a slum and a hive of informal economic activities.

The right to inhabit a place comes abruptly into frame when the state opportunistically takes advantage of the urban crisis to engage in revanchist actions justified by eschewing a selective "dire litany of boundless chaos, anarchy, and hopeless disorder in everyday life—and therefore must be fixed" (Murray and Myers, 2006, p. 2). Such a situation masks the search for policy responses that can reconcile the city's social responsibility with its economic goals, while simultaneously managing a loose and disparate network of actors with diverse interests (Obeng-Odoom, 2011; Oteng-Ababio, 2018). This has the effect of limiting the epistemology of normative action, calling for a proscribed remedial intervention to offset the crisis (Murray and Myers, 2006). Suffice however to state that hasty remedies often defeat themselves (i.e., proscribing African "cities without slums") and frequently inflict considerable collateral damage with demolition (Grant, 2015; Stacey, 2018). Afenah (2012) explains that in 2011, the authorities' discursive practices provide only a supporting scaffolding to free lands for motivated private capital, creating what Gillespie (2016) has termed "an urban enclosure" out of dispossessed people's properties. Framing the city through the narrow lens of the conjoined discourses of modernization and development and inviting private capital not only to build the natural fabric but also to remake the social relations compel an alternative focus on the urban poor.

The chapter is structured into five sections. Section 15.2 sketches various days of reckoning, in part, overshadowing the fate of Agbogbloshie and contributing to the construction of negative grand narratives. Section 15.3 outlines the philosophical tenets that underpin the general arguments of the right to the city and sharpens the focus of that right by considering the dimensions of place-making and lived space. The entrepreneurial urbanism which is an informal activity is juxtaposed with the city's entrepreneurial urbanism. Section 15.4 situates Agbogbloshie within the local economy before exploring the trajectory of entrepreneurial urbanism around the settlement. The discussion is organized around the themes of (dis)connecting the plebeian, the "doom, and gloom" shadow, managing increased private sector interests, and (re)claiming the traditional heritage. The final section calls for nuanced understandings of informal settlements and the need to restructure power relations that underlie the production of urban space shifting from (ab)using informality toward (in)formalizing Lefebvre's urban inhabitants.

15.2 Days of reckoning

In recent times, some media outlets and public officials among others opposed to the occupation of Agbogbloshie graphically refer to the settlement as "Sodom and Gomorrah," referencing the biblical city destroyed by God because its inhabitants were sinful. Thus, tropes are selectively employed to denigrate the community: "a graveyard" (New York Times, 2010), "The E-waste Republic" (Ottaviani, 2015), and "one of the sickest places in the world" (Leahy, 2013) are but few examples. Public officials keen to modernize the booming city (Accra) often view the poor making living by sifting through rubbish or hawking on the streets as hindrance, and as usurpers of public spaces meant for formal businesses and wealthy residents. The Accra mayor has even gone as far as labeling Agbogbloshie as "a threat to national security" (Gillespie, 2016, p. 72). Having worked in the settlement for over a decade, we can confirm that Agbogbloshie is a thoroughly polluted place and the people working in the recycling trade are exposed to severe health and safety risks. Clearly, E-waste burning occurs at the farthest end from the shacks at night, creating plumes of toxic smoke and considerable residue that leaches into the ground (Oteng-Ababio and van der Velden, 2019).

Nevertheless, we can also empirically confirmed that the E-waste trade generates much-needed jobs for the youth and contributes to a vital repair and recycling culture in the city (Grant and Oteng-Ababio, 2019). As rightly stated by Oteng-Ababio and van der Velden, (2019, i) "this complexity is lost in the Western media," as most of them only focused almost exclusively on Agbogbloshie as an E-waste dumpsite, drawing on the dramatic imagery of burning cables and tires for the extraction of copper, which forms only part of the activities of the scrap metal yard (Grant, 2006). The fact however remains the settlement today has grown substantially, with a 2009 estimated population of 79,000 from self-built houses (People's Dialogue, 2010), to become the largest E-waste processing site in Ghana, a food market, a timber market, a lorry repair center, and bus and motorcycle transportation depots and sheltered an informal army of workers (see Fig. 15.1).

Administratively, the commercial and public transportation hubs among others, generate levies, rates, and taxes for the city authorities (Stacey and Lund, 2016). At the same time, the informal activities are brimmed with life and pushed up against all of its boundaries (e.g., the Odaw River, the railway line). Legally, much of the settlement appears condemned (Stacey and Lund, 2016). Hence, it was no surprise

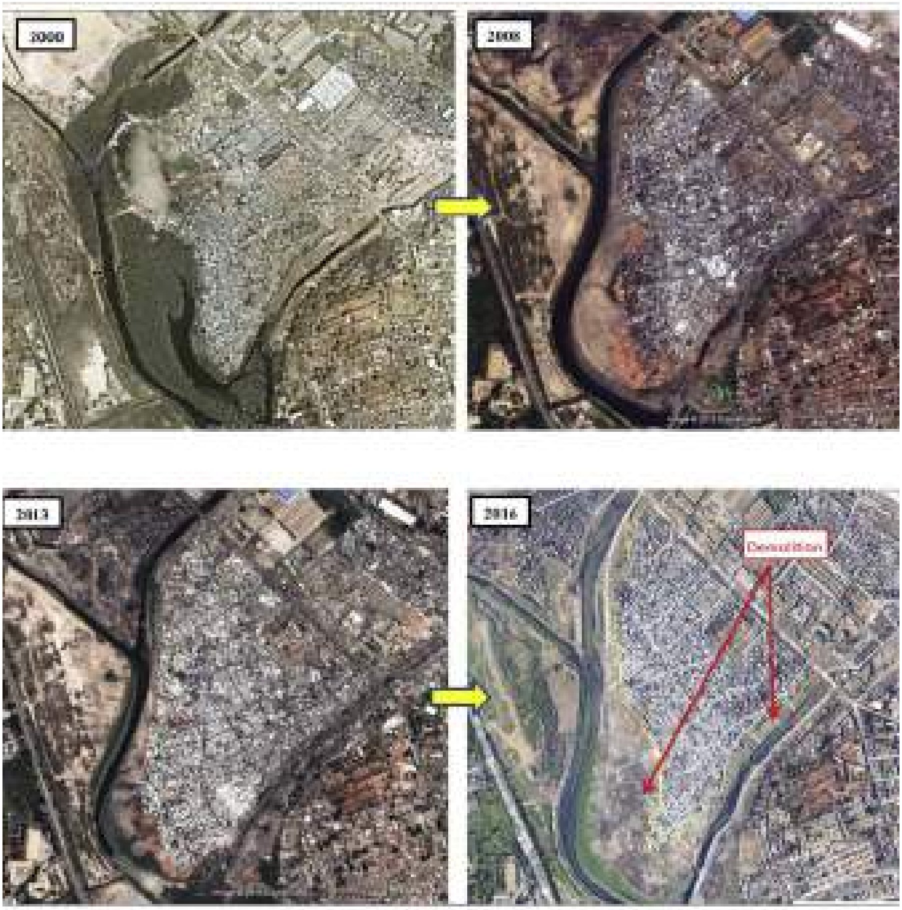

Figure 15.1 A Map showing the changing contours of Agbogbloshie (study area) boundaries. Source: Authors' Own Construct.

when in 2002, an Accra High Court okayed AMA's decision to evict the "illegal occupiers" to pave the way for an internationally funded, large-scale environmental clean-up of the Korle Lagoon (Gillespie, 2016). Though the court ruling triggered the city authority's eviction threat, several counter factors, including an effective community organizing, a proactive international advocacy, and the government's lack of political will led to a stay of execution. The authorities resorted intermittingly undertaken swift and brute bulldozing operations "to clear the waterway and reduce the risks of flooding" (Songsore, 2017, p. 5). Apart from its no-nonsense approach to any (ostensibly in the interest of private capital), the authorities in 2012 attempted to cajole the sprawling agricultural market traders to move to a new site some 35 km away in Adjen Kotoku, in an effort to decongest the central city (Afenah, 2012) at an estimated cost about of GH¢172.2 million (Smith-Asante, 2015, p. 1). Although the plan included fire and police stations, the lack of residences for the market sellers, coupled with the government failure to pay the landowners the requisite compensation spelt the demise of the project (Smith-Asante, 2015).

The latest of demolition exercises on June 19, 2015, sought "to deal decisively with the challenge pose by Agbogbloshie," after a "twin disasters" of June 3, when a floodwater caught fire and disastrously claimed 259 lives (Tornyl, 2015, p. 1). The victims of the said exercise demonstrated against what they deemed was "inhuman" treatment from the city authority. Shouting "we have nowhere to go" apparently referring to the government's humanitarian gesture of sending them to their home region in northern Ghana, the victims picketed around the AMA office and the Parliament House, while even a larger group burned tires to block the main road leading to the Agbogbloshie market (Iddrisu, 2015). Although the actions of the city authorities make a broad statement about the rights of residents in Accra to have a safer environment, it also reflects a more significant situation where the most marginalized poor are always blamed for the woes in the city. This is in spite of the fact that there are many more slums (about 80) in the city as well as enormous metropolitan-scale deficits in housing, sanitation, waste infrastructure, and decent work (Grant and Oteng-Ababio, 2019). We opined that the hegemony of entrepreneurial urbanism has honed officials' appetite for economic growth and radically imbibed a more business-friendly mindset. Further, we argue that the authorities' universalist aspirations and parochial assumptions of modernizing the city through the wholesale adoption of western successful theories, which sees people in Agbogbloshie as "out of place" remain problematic (also see Myers, 2016; Gillespie, 2016).

15.3 Privileged rights to the city: the hegemony of entrepreneurial urbanism

Urban scholars have long grappled with the challenge of mediating the creative or destructive impacts on actors and place. Harvey (2003, p. 939) for example, notes, "the city is the historical site of creative destruction . . .[it] has also proven a remarkably resilient, enduring and innovative social form." Writing to celebrate the anniversary of Marx's Das Kapital, Henri Lefebvre also articulated a new politics of citizenship, residency, and above all the right to urban life, arguing: "[T]he right to the city cannot be conceived of as a simple visiting right or as a return to traditional cities. It is a transformed and renewed right to urban life" (Lefebvre, 1996, p. 158). Central to Lefebvre's thesis, which Harvey (2003) did much to popularize, is the idea that inhabitance itself should confer the right to participate in place-making, or the construction of lived space. This right entails both a more abstract and a more real or concrete dimension.

The abstract dimension is the right to be part of the city as an oeuvre, that is, the right to belong to and the right of city dwellers to coproduce urban spaces, and the right not to be alienated from the areas of everyday life (Mitchell and Villanueva, 2010). This embodies a claim to integrated social, political, and economic rights—the right to education, work, health, leisure, and accommodation in an urban context that contributes to developing people and space rather than destroying or exploiting people and space. The right to the city is "like a cry and a demand" and "can only be formulated as a transformed and renewed right to urban life" (Lefebvre, 1996, p. 158). To Lefebvre, the forces of alienation that are active in urban space continuously need to be challenged and contested (Lefebvre, 1996, p. 158). Harvey (2003, p. 939) surmises: "the right to the city is not merely a right of access to what already exists, but a right to change it after our heart's desire... We need to be sure we can live with our creations; ... the right to remake ourselves by creating a qualitatively different kind of urban sociality is one of the most precious of all human rights."

When there is a myriad of competing interests, the question however is whose rights matter, and in which place(s)? Agbogbloshie is a microcosm of such competing interests. There is a longstanding traditional heritage claim (detailed in Section 15.5.4). Additionally, some international organizations such as Greenpeace have likened the settlement to a poisonous cauldron, and have been advocating for the institution of extended producer responsibility (EPR) to compel the producers of electronics to take full responsibility of any of their devices. Indeed, Pure Earth (2014) initiated a technical solution, while the German development aid in 2017 announced a US$20 million grant to construct a formal recycling plant and a health clinic in Agbogbloshie (Deutsche Welle, 2017). Earlier in 2016, the Ministry of Environment, Science, Technology, and Innovation had also announced the construction of a US$30million state-of-the-art E-waste recycling facility also in Agbogbloshie (Business & Financial Times, 2016). Though commendable, Oteng-Ababio (2018, p. 5) have raised issues with the apparent fragmented nature of foreign intervention. He argues that such localized interventions only displace the risks elsewhere, and recommends addressing inequalities as an effective way to improve health and welfare.

The AMA's crisis framing of Agbogbloshie moves attention away from its constitutional responsibilities to all the citizenry, including the fundamental rights essential for a dignified life, for example, rights to inhabit, decent employment, shelter, food, services, open space, and childcare. Such framings have emboldened the AMA to passively take away power from residents (Gillespie, 2016; Stacey, 2018; Cobbinah and Darkwah, 2018), and this tactic enables them to engage coyly in demolitions exercises (Oteng-Ababio and Grant, 2019). Harvey (2008) takes an even stronger stance, arguing that "between equal rights, force decides." While this chapter grapples with power relations in Accra, it does so in the context of the city's complex processes and outcomes, and how residents are made and remade without knowing why, how, wherefore, and to what end.

The challenge is even daunting in today's neoliberal world, with its heavy emphasis on market-induced policies (Obeng-Odoom, 2016). Entrepreneurial urbanism, which is the new face of city governance, promotes economic growth with place promotion to attract foreign direct investments (Myers, 2016). Its proponents advocate for a more entrepreneurial, business-friendly mindset (Deas and Headlam, 2015). This reorientation is exceptionally alluring to city authorities as it prioritizes international success model that puts more emphasis on the way cities must be governed (Scott, 2001). Examples include the new push for satellite cities in Accra (e.g., Apolonia; Hope City) and throughout Africa (Watson, 2014), where standard rules are suspended in the service of global capitalism (De Boeck, 2011), and as sites engineering social exclusion (Watson, 2014). Deas and Headlam, (2015, p. 130) rightly caution against the unbridled application of external-derived models to stimulate economic growth in different geographical settings. Lovering (2001) sees such policies as unrealistically preoccupied with improving cities' international standing at the expense of the more mundane issues. This portends inter-institutional friction or official hostility to the urban commons (Myers, 2016), and goes against an alternative way of "seeing" and "knowing" Africa's urbanization in general, with increasing informality, where most people "work outside of the formal economy, live in informal housing and conduct business without using banks" (Grant, 2015, p. 135) and where they often evolve their own "governance rules" beyond the purview of state authorities (Paller, 2015).

Our analysis draws on data from three major projects conducted between 2010 and 2016. The first, sponsored by Global Development Network (GDN/Grant/2012-13/023/AMC/UG), was held between 2012 and 2013 and focused on understanding the E-waste stream in Ghana. There were 100 participants in the study: 80 individuals were surveyed using a structured questionnaire administered February 1–April 30, 2010 (60 E-waste recyclers) and 20 individuals in E-waste-related activities (e.g., intermediaries, importers, and scrap dealers), and 20 in-depth interviews were conducted with key stakeholders (e.g., executives at the Scrap Dealers Association, Environmental Protection Agency, the UN Development Programme, and reuse shop owners and their customers). A second 2-year project (URF/7/LMG-006/2013–2014), sponsored by the Office of Research, Innovation and Development (ORID) at University of Ghana, followed and adopted community asset mapping in each of the four leading chains of activity (scavengers, scrapyard workers, refurbishers [repairers], and dismantlers) to better understand how local communities engage and make sense of waste. A third study took place in the aftermath of the demolition of June 2015 and involved interviews with 15 policymakers and stakeholders about the decisions to demolish. This research effort also entailed site visits and analyzing aerial photography to document the changes.

15.4 Accra's governance orthodoxy: managing "public interests" with private assistance

Long before colonialism interlude, history documents how local authorities devised means of decentralizing power (e.g., installation of subchiefs and local representatives) as a way to perfect their local governance system (Acquah, 1958). The devolution of powers began well before Ghana adopted the District Assembly concept in

1988, now guaranteed under the 1992 Constitution as the district's highest political authority with deliberative, legislative, and executive powers (Government of Ghana, 1992: Article 241, 3). Yet, in Agbogbloshie, the governance structure varies as city authorities unrepentantly perceive those who live and work in such "disaffected communities" as people without status, and are virtually excluded from any joint problem-solving trajectory (Melara et al., 2013). Under the circumstances, the governance structure that often emerges ropes in male-dominated bodies, including NGOs, religious and traditional leaders, and opinion leaders (Owusu and Braimah, 2012).

The lack of legal recognition means the community is more likely to extract public services from NGOs and political parties that want to curry favor (Stacey, 2018). Prior studies have detailed Agbogbloshie's reliance on People's Dialogue (PD), a local NGO affiliated with Slum Dwellers International (Paller, 2012) and the Old Fadama Development Association (OFADA) (Stacey and Lund, 2016). Stacey and Lund (2016, p. 15) recount a January 2015 example of a mediation process and outcome when "the constituency NDC-MP agreed to forward several electricity poles, which together, with a transformer and electricity meters [gleaned from good relations with an electricity company] were welcomed by residents. Their installment reduced fire risk and improved residents' sense of security." Although this is a cheap buy-off compared to a proper, longer-term, budgeted upgrade for the entire community, such signaling to residents goes some way to acknowledge their right to inhabit by incremental improvements. It did not, however, foretell that large-scale demolitions and evictions that were to take place 5 months later, when the state (re)affirmed and (re)established its control over land-related development (Stacey and Lund, 2016).

Ironically, some community leaders seem to benefit from insecurity (slumlords who do not have to perform repairs/upgrades). After demolitions, these leaders benefit from controlling the informal land market that individuals have to avail of again to secure rehousing. Some key informants alleged that the leaders receive "tip-offs" before demolition exercise, while some individual tracts in the slum appear "to be untouchable" (PI, October 2015). Besides, the vast array of international organizations (e.g., GIZ, Fairphone) involved in projects in Agbogbloshie is a mixed blessing for governance. On the one hand, it alleviates the state's burden of creating empowerment opportunities. For example, in collaboration with the Ministry for Gender, Children and Social Protection, modest efforts under the "Kayayee" Project (female head-porters) have been undertaken to train some migrant women in soap-making, hairdressing, and to upskill informal workers. This also means that the NGOs have the opportunity to closely monitor the seemingly state-sponsored violations of the rights of marginalized people which then undermines the city's international image. Further, the NGOs tend to be more accountable upwardly to their donors than downwardly to members of the community (Paller, 2012; Stacey and Lund, 2016).

All-in-all, emerging studies amply suggest that the toxic discursive narratives only tell part of the Agbogbloshie story (Morrison, 2017; Grant and Oteng-Ababio, 2019; Paller, 2015). Instead, it appears to a strategy to elicit public outrage and mask the complex recycling activities, involving reuse, repair, and refurbishment as residents attempt to survive the quagmire of poverty and deprivation (Afenah, 2012). To Afenah (2012) the coy portrayal of Agbogbloshie as a "nuisance" or unsanitary toxic zone leads to sustained attempts "to right the wrong" through forced eviction. In Accra, the strategy coincides with a rising private interest in valorizing the land (Gillespie, 2016) and overshadows the myths on Agbogbloshie as the world's biggest and most toxic dump—which it is not! (Minter, 2015; Oteng-Ababio and van der Velden, 2019).

The toxic hazard narrative also enables the government to engage in politics of daily life by aligning its strategies with the emotions of urbanites who see migrants from northern Ghana as "other" and who want a city for Gas and other established residents (Paller, 2015). The authorities' actions epitomize a Janus-faced state wishing to save the residents from being poisoned but leaving them without jobs to go into the unknown and other precarious situations. It portends to different episodes of daily politics whereby at the time of elections, political parties, feeding on "the politics of the belly" and the "politics of rationalism," rely on slum-dwellers as foot-soldiers to spread party messages. At eviction times, however, slum-dwellers are treated as combatants (Paller, 2015). A range of responses, ranging from status quo to eviction threats, to violent repressions and compromised relocation, all reflect the dithering state apparatuses that seem incapable of resolving tussles for land, citizenship, and the right to the city when it comes to the sparse population, but not for the nonpoor (Paller, 2015). Fig. 15.2 presents the timelines of attempted eviction threats since 2000.

15.5 Unpacking Agbogbloshie's inhabitants

15.5.1 (Dis)connecting the plebeian

Visually, Agbogbloshie is a weak and organically developed settlement. However, a critical examination uncovers people's livelihoods and homemaking practice, or what the inhabitants call *New York City*, a land of freedom to pursue an opportunity. The settlement offers one of the cheapest rents not only for those informal workers but also for some formal workers recently transferred to Accra. It operates as a hub of everyday economic activities, though a new trend of a maker ecosystem (e.g., AMP, 2017), which harnesses indigenous knowledge with innovative low and sustainable designs are emerging. Operationally, Agbogbloshie is known for a full continuum of open worlds of work, ranging from low levels of subsistence to middle-income entrepreneurs whose needs are at the apex of business and social networking, to even those who desire for simple life so that they can remit as much as possible back home. There are those whose social capital extends only to friendly relations, while others' networks extend to formal companies and outside investors and money people they front for in day-to-day Agbogbloshie operations.

By and large, Agbogbloshie interconnects informal and formal industries; it leads in city-wide E-waste collecting, arguably providing a municipal service,

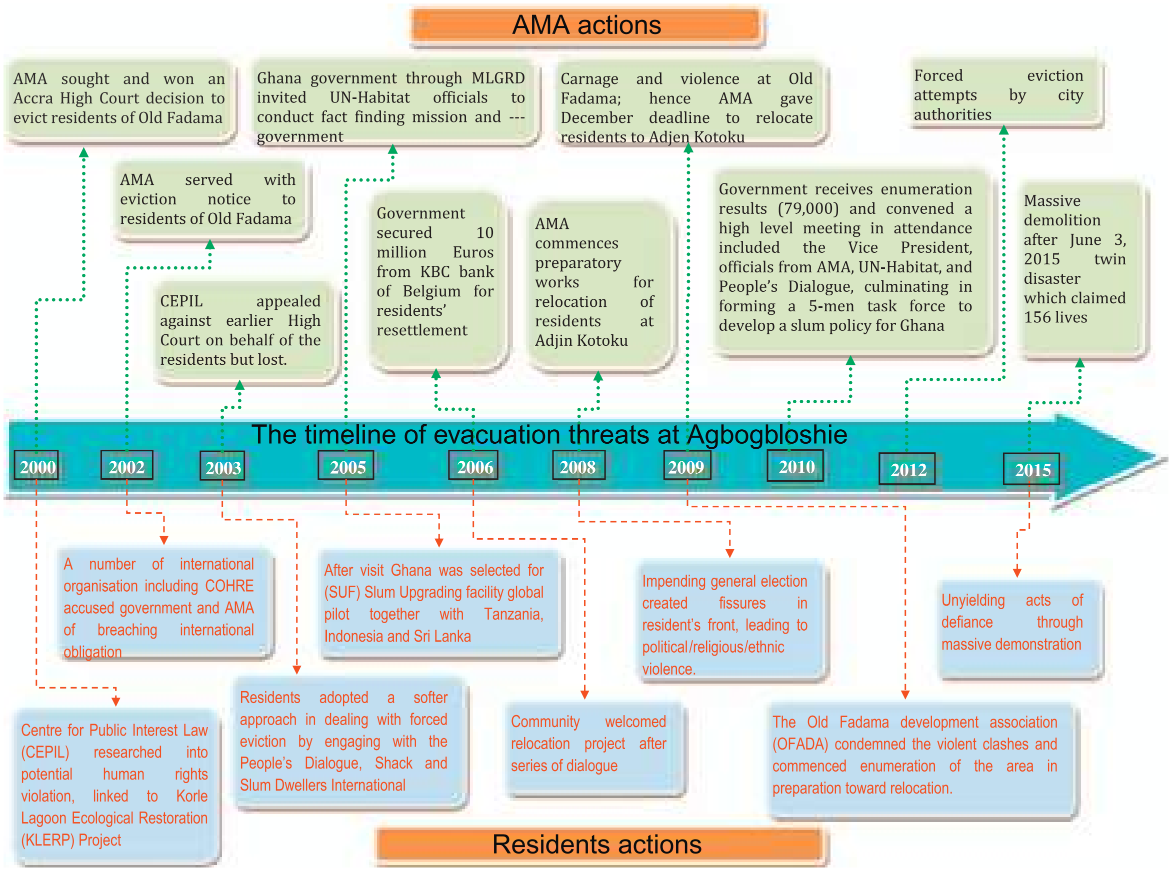

Figure 15.2 Timelines of attempted eviction threats at Agbogbloshie (2000–2015).

recycling valuable metals for local industries (e.g., copper for Tema's smelter), and creating local ancillary "life-saving" and empowering jobs (Grant and Oteng-Ababio, 2016). It provides opportunities for people to escape poverty, and a platform to participate in Accra's economy. Conservatively, 6000 people earn a living directly from the E-waste economy, with at least 30,000 people within its chain of activities (Grant and Oteng-Ababio, 2019) (see Table 15.1). Typically, the recycling activities provide a vertical progression, with some participants moving up the ladder from scavenging into retailing refurbished products, while some women transition horizontally into "more respectable" employment such as trading in agricultural products (Oteng-Ababio, 2018). Economically, the E-waste sector contributes US$105 million−$268 million annually to the Ghanaian economy and sustains the livelihoods of at least 200,000 people nationwide (Grant and Oteng-Ababio, 2016).

Most workers in the E-waste economy originate from the three northern regions (63% of respondents) (Grant and Oteng-Ababio, 2012). One resident whose story is an epitome of most "Agbogbloshians" is Ibrahim, a native landlord who has turned the frontage of his property, bequeathed to him by his parents (migrants from the north in the 1970s) into a meeting place. During our fieldwork, the graffiti on the side of his premises—Accra belongs to Ghanaians—sounded a strong cord. Born and raised in Kokomba (yam) Market, Ibrahim, 32, now works as recycler (middleman), having worked as a collector for over 4 years. Aside from his involvement in the E-waste economy, Ibrahim is a second-year, part-time, Higher National Diploma (HND) student at Accra Polytechnic (now Accra Technical University). Ibrahim had a strong sense of belonging to Accra even though he was acutely aware of his minority status:

> *Yes, I have a northern extraction, but I am a Ga [native of Accra]. I was born and raised here [Accra]. I don't understand the calls on us to go home; where is home? Accra is not for Gas alone. They should ask the big men also to leave. We know Ex-President Rawlings is from Volta [region] but stays in East Legon [a high-income neighborhood]; they should go there too. They should stop these prejudices against the soft targets [minorities].*

Our respondents elaborated on residents/NGO and NGO/NGO tensions, confirming a complex local micropolitics and between the community and city authorities or international sponsoring agencies. Interviewees reiterated discomfort and disconnect with some NGOs that continuously churn out saving or doomsday narratives and do not do enough to show the struggles and successes of everyday lives. To Ibrahim and others, AMA's aggressive, combative, and impulsive stance is all about responding to the "power of private capital," and that the NGO leaders are junior partners in NGO-state relations. Residents interviewed created a "symphony of voices" that feel silenced by AMA's "inhuman behavior" and the tacit support that the city mayor enjoys. Many interviewees feel disempowered as nobody speaks for their interests, with some arguing: "all NGOs have agendas, [...], the leaders seem more motivated to maintain themselves in the NGO world rather than work in the

Table 15.1 Hierarchical (vertical) structure of informal E-waste activities and incomes at Agbogbloshie.

Role in E-waste circuitry	Estimated average monthly income (USD)[a]	Percent of Ghanaian daily minimum wage[a]	Main E-waste activities
Scrap dealer	1500	2747	Commands E-waste operations at the top of the chain of activities; negotiates deals with and link players in the formal with the informal economy.
Middleman	1050	1923	Buys extracted metals and pre-finances activities of both collectors and recyclers. Well-connected individuals who bring recycled collections to end-processing unit condition.
Recycler	175–285	321–522	Picks through E-waste in order to extract metals. Individuals may or may not choose to specialize in a particular type of electronic. Many recyclers partake in open burning as an extraction technique.
Refurbisher	190–250	348–458	Conduit for technology transfer. Repairs nonfunctioning electronic goods to be sold in the Ghanaian secondhand electronics market.
Scrap collector	70–140	128–256	The entry point in E-waste economy normally for new young male (normally in their twenties) economic migrants. Collects obsolete electronics in carts or rentable cars-for-hire. Collectors either buy E-waste from consumers or scavenge for parts at dumpsites.
Female traders/ Kaya Bola	20–60	36.6–109.7	Provide support services such as selling of food, water, and secondhand clothes. Some also trade in E-waste products, recovered metals on behalf of their husbands and relatives as well as collectors' tools such as hammer, wrench, and screwdriver.
Child laborer	≤ 20	≤ 36.6	Males participate in recycling or collecting. Young girls may be found distributing water for consumption and fire control.

[a]Income and wage figures are calculated using the 2016 exchange rate of 1 USD = 0.26 GHC.

dirt and grime and hot, long days of trading [. . .] our community is worked on by NGOs as opposed to working with."

We encountered informal (re)inventing and (re)making livelihoods in response to sustained eviction threats (to a few, E-waste will be formalized and banned soon) and E-waste turf battles as the sector becomes overcrowded. Former scavengers/recyclers are diversifying into motorcycle taxis, locally termed Okada, or tricycle cargo activities, Mahama Camboo. This sector is seen as fast becoming a primary transport mode, notwithstanding the government's landmark legislation (LI 2180) that prohibits motorcycle taxis. During our interviews, the "leader" of the Okada group revealed that the business of motorcycle taxis offers about 150 jobs to former recyclers, while scrap dealers participate by buying the motors and renting them out at GH¢20 a day. Given Okada's maneuverability in severe traffic congestion, compatibility with bad roads, and its demand-responsiveness to serve the sizeable public transit deficit, a thriving informal public service mobility market has been created (see Oteng-Ababio and Agyeman-Opambour, 2015).

Further, there are now extensions of mobile phone refurbishment in Osu's "Oxford Street," and Nkrumah Circle. The repair chains involve a high degree of internal organization, and their outlets are highly profitable, collectively repairing about 1000 mobile phones (screen replacement, water damage, broken casings, and unblocking devices) every month (Oteng-Ababio et al., 2019). These "sophisticated on-site repair facilities," accompanied by readily available replaceable parts, now offer an "informal product warranty." For example, repairs and replacements are free if the problem has ever been attended to by "the group" and the standard business practice is a 48-hour turnaround. Other diversified areas are the food niche-based associations (e.g., Onion, Tomato, Yam, Groundnut Traders Union). These activities epitomize the multidimensional ways urban migrant women in particular innovate, network, and remake themselves from E-waste-related activities to engage in long-distance trade that, in turn, catalyzes spin-off activities that deepen the ties between the south and north of Ghana.

15.5.2 The "doom and gloom" shadow

As already indicated, Agbogbloshie has suffered lots of media sensationalism and techno-fanaticism. EIT Digital (2016, p. 1) states, "Agbogbloshie is probably the world largest E-waste dump in the world [not a landfill; E-waste is dumped, not managed]. People are scavenging the E-waste to retrieve copper and in the process [they burn the devices/equipment] they disperse dangerous substances: mercury, lead, cadmium and arsenic [. . .] Incidentally, Ghana is a major exporter of cocoa beans and we may find some of these pollutants in that nice chocolate bar we like so much" (EIT Digital, 2016, p. 1). Such sensational, unsubstantiated reporting seems to compel the government to do something, and this makes the settlement's destructive demolitions legitimate (Afenah, 2012). We do not discount the health hazards associated with poor E-waste management as prior studies had documented these severally (see Table 15.2). However, Chama and Oteng-Ababio (2016) assessment of the levels of polybrominated diphenyl ethers (PBDEs) in sampled soils,

Table 15.2 Health hazards associated with poor E-waste management.

Computer/ E-waste component	Process	Potential occupational hazard	Potential environmental hazard
1. Cathode ray tubes	Breaking, removal of copper yoke and dumping	• Silicosis • Cuts from CRT glass • Inhalation or contact with phosphor • Containing cadmium or other metals	• Lead, barium, and other heavy metals • Leaching into ground water and release of toxic phosphor
2. Printer circuit boards	Desoldering and removing computer chips	• Tin and lead inhalation • Possible brominated dioxin, beryllium, cadmium, and mercury inhalation	• Air emission of the same substances
3. Dismantled printed circuit board processing	Open burning of waste boards	• Toxicity of workers and nearby residents rom tin, lead, brominated dioxin, beryllium, Cadmium, and mercury inhalation	• Tin and lead contamination of immediate environment, including surface and ground waters, and brominated dioxins
4. Chips and other gold-plated compounds	Chemical stripping using nitric and hydrochloric acid along riverbanks	• Acid contact with eyes, skin may result in permanent injury • Inhalation if mists and fumes of acids, chlorine, and sulfur dioxide gases can cause respiratory irritation to severe effects, including pulmonary edema, circulatory failure, and death	• Hydrocarbons, heavy metals, and brominated substances discharged directly into river and banks • Acidifies the river destroying fish and flora
5. Plastics from the computer and peripherals	Shredding and low-temperature melting	• Probable hydrocarbon, brominated dioxin and PAH exposure to workers living in the burning works area	• Emission of brominated dioxins • Emission of heavy metals and hydrocarbons

(*Continued*)

Table 15.2 (Continued)

Computer/ E-waste component	Process	Potential occupational hazard	Potential environmental hazard
6. Secondary steel or precious metal setting	Furnace recovers steel or copper from waste	• Exposure to dioxins and heavy metals	• Emission of dioxins and heavy metals
7. Wires	Open burning to recover copper	• Brominated and chlorinated dioxin and PAH exposure to workers living in the burning works area	• Hydrocarbon and ashes, including PAHs discharged into air, water, and soil

sediment, vegetables, and the livers of goats and sheep reared on the site conclude current PBDE levels do not pose a health threat.

In media and government circles, most outrageous claims or lopsided negative discourse completely overlook Agbogbloshie's community spirit, its advanced self-help, political and social configurations, and diverse income-generating opportunities. We caution about recycling of salacious anecdotes such as "recyclers are children between 11 and 18 years, with some are as young as five" (Pure Earth, 2014, p. 1). Though occasionally young children directly engage in some E-waste-related activities, they are an exception. But for individual interest, there is absolutely no evidence supporting wild headline that compares Agbogbloshie's toxicity to the 1986 Chernobyl disaster (Blacksmith Institute, 2013). Currently, there is a line of reasoning that notes the precedent set by other slums, such as Ashaiman and Nima, that have been normalized over time. The former was carved out of the Tema municipality in 2008 by LI 1889 and Local Government Act of 1993 (Act 462) to become a municipality, occupying a land area of about 45 km^2 for 90,721 persons (Ghana Statistical Services, 2014).

Agbogbloshie's internal politics is highly splintered. Many subgroups mirror, to some extent, the politics of informality (with the political party, ethnic, class, clan, family, religious, patronage networks), but the presence of a large E-waste economy compounds the political climate. Microcommunity politics is more informed by a greater appreciation of informal socioeconomic dynamics, but the state's concentration on the formal economy effectively undermines the case for everyday economic contributions and disables informal claiming the right to commercial space. Broad areas of agreement are discerned between the authorities and the NGOs supposedly committed to seeking "community" welfare, though they remain divided on the course of action and its governance. Be that as it may, the authorities' discourse of illegality and toxicity only divert and legitimize their aggressive and combative stance in pursuit of their neoliberal urban policy trajectory while denying the urban poor the right to inhabit.

15.5.3 Managing increased private sector interests

AMA's proclaiming Millennium City status in 2010 coincided with a new orthodoxy in governance that heavily promotes private sector participation (Melara et al., 2013). This paradigm shift ranges from leveraging private finances to enacting "light-touch" regulations and improving the physical environment to attract foreign business (Grant, 2015). Accra's contemporary urban space displays a considerable footprint of foreign capital: an Airport City enclave, shopping malls, and upscale gated communities. Equally illuminating is the opening of the Octagon Building Complex in the central business district (CBD), with 3500 m^2 of retail spaces and 1300 m^2 of underground parking spaces (Jade E-Services, 2014) that replaced a former open space whose continuous presence "was seen as undermining urban planning efforts around them…[CBD]" (PI, October 2016).

A senior AMA planning officer instructively revealed a planned upgrading scheme for Agbogbloshie that will enable "private-sector developers [to] build high-rise mixed-use edifices to make the place safer and secure using adequate zoning laws" (PI, October 2016). This kind of upgrading is meant not in the traditional sense of improving in situ housing but more in the spirit of a state-led gentrification to replace squatters with those who can afford access to hotels, offices, and apartments (Gillespie, 2016). Such (re)visioning dismisses the residents' place-making histories that have added value to once-derelict "wasteland," that sheltered and enabled the poor to engage in informal livelihoods while the state remained incapable of providing for them (Aalbers and Gibb, 2014). In changing times, increasing private interests are economically pricing out small-scale, informal enterprises, and this new arena underpins the violent confrontations and contestations between state agencies, private investors, and local communities.

15.5.4 (Re)claiming a traditional heritage

Agbogbloshie contestations transcend the informal and economic realms, as there is a legitimate claim the traditional authorities. The Ga traditional council has been intensifying their application to the property, officially acquired through Ordinance No. 28 of 1956 (Grant, 2006, p. 9). Their objections date back to the colonial era when the traditional leaders disputed the intended land use, which they claimed contravened their customary value attached to the Korle Lagoon as a "Holy [Spiritual] Place," and customary rights to this land and its use were raised again after independence (Grant, 2006, p. 9). An escalation in the traditional authorities' efforts to (re) claim the land coincided with the rising economic fortunes of the economy and a rise in the market value of prime properties (Grant, 2006). This time around, the traditional authorities have been emboldened to hold press briefings and public demonstrations to force the government's hand, warning that their people would fiercely resist the status quo (GhanaWeb, 2012). In press statements, the leadership openly lent support to an AMA's vision:

> *Yes, ... We are one spirit with him [the mayor] in his demolition exercise... Accra needs a sanitized and clean image that would mirror an actual capital... If planners of the fifties and sixties found it convenient to zone the area [Agbogbloshie] for recreational purposes, why change it to a residential slum in the 21st century?*
>
> *Acting President, Ga Traditional Council; GhanaWeb (2012)*

Tactically, the traditional authorities walk a thin line of being sympathetic to the struggles of the Agbogbloshie residents and clearing them from their land. Neither wanting to isolate the slum-dwellers nor move them onto a plane of equals in rights to property, the traditional authority is compelling the AMA to act hurriedly and "develop the site" as soon as the strangers are forcibly evicted, since allowing it to stay fallow will ginger them to Acting President, 2012. This pressure on the AMA to treat the residents as persona nongrata to maintain their traditional rights to the land means that their rights take precedence over the inhabitant's rights, though many occupiers have been present for 12 years and thus are legally entitled to stay and receive adequate compensation.

15.6 Lived spaces: a beginning to halt (ab)using informality and to (in)formalize Lefebvre

Our study illustrates a clash of rationalities in dealing with informal settlements in the global South: the neoliberal visioning of a modern, globally competitive, and orderly city, and the right of city authorities and the private sector to "upgrade" the city and the rights of ordinary citizens for access to services, housing, space, and a decent life. Both positions offer promises of a better future but cannot guarantee that experience will be improved for all, particularly the poor. Neither approach provides much clarity about the social and spatial outcomes and the effects of (re) making place on broader political, economic, and social processes of the city.

Nevertheless, in focusing on Agbogbloshie, we contend that Lefebvre's right to place provides both the analytical tools and approaches necessary to confront the informal settlement challenge in Accra and beyond. Lefebvre's right to take place can be concretely operationalized, and the lived experience (and those living) in informal settlements can be utilized. Recognizing the contradictions that bring about informal means of living and the dirty little secrets that are peddled to offset everyday lives at the expense of veiled boosterism, call for a deepening of engagement with these inherent contradictions in the contemporary era, from the perspective of ordinary people (the vast majority) who constitute the urban global South. This involves recognizing and valuing urban life and the form that emerges outside, even given the threat of spatial prohibitions by the state (Huchzermeyer, 2014).

One crucial element that makes African cities ever more complicated is the traditional use of space and traditional claims and rights to land. Correctly recognizing the right to inhabit would allow for greater urban democracy, although we acknowledge along with others (e.g., Purcell, 2003; Huchzermeyer, 2014) that this will not be easy and must be mediated by long political struggles.

Our analysis disaggregates essential aspects of daily life and informal E-waste activities as well as the politics of disenfranchisement in Agbogbloshie to understand how the spatialization of power both transforms and reinforces marginality, but through political and economic networking, informal connect to a broader spatial economy. Agbogbloshie is a problematic case. The political will exists (private capital and traditional authorities have adopted similar stances) to engage in a proper in situ upgrading. Funds, however, are lacking to augment the Adjen Kotoku site and to develop accommodations and other necessary services and employment opportunities there so as not to destruct, disperse, and dissipate informal livelihoods creatively. Authorities lack the lens to appreciate the role that informal settlements and economic activities play in providing for the poorest of urbanites. The government and municipal authorities prefer to showcase glossy new satellite developments such as Airport City and the Ningo Prampram city extension rather than to focus on best practices to upgrade circumstances of the poor.

Our concluding call is for a deeper appreciation and awareness of the dynamic tensions entangled in notions of informality. A place can be both informal and creative, productive and connected, which suggests the need for a complete understanding and more nuanced debates about informal settlements and informal economies (Rogerson, 2016; Lombard, 2014). As geographers, we believe it is essential to give prominence to residents' stories and to return continually to update their lived experiences (Lombard, 2014). Their stories should not, however, be romanticized or taken out of context by the media and others; they should be used by urban scholars to put forward more critical understandings of the theory and real geographies of informal settlements rather than some imagined utopian or dystopian views. Given the prevalence of informal settlements globally and their anticipated growth, their study, and their fundamental rights to inhabit and make a living is of the utmost importance.

References

Aalbers, M.B., Gibb, K., 2014. Housing and the right to the city: introduction to the special issue. Int. J. Housing Policy 14 (3), 207−213.

Acquah, I., 1958. Accra Survey. London University Press, London.

Afenah, A., 2012. Engineering a Millennium City in Accra, Ghana: the Old Fadama intractable issue. Urban Forum 23, 527−540.

AMP, 2017. #MadeinAgbogbloshie. <https://qamp.net> (accessed 16.05.17.).

Aryeetey, E., Kanbur, R., 2017. The Economy of Ghana Sixty Years after Independence. Oxford University Press, Oxford.

Bekoe, D., 2017. Ghana's Peaceful Elections Built on Trust and Accountability. Africa Center for Strategic Studies. <https://africacenter.org/spotlight/ghanas-peaceful-transition-power-effect-building-trust-accountability/>

Blacksmith Institute, 2013. The World's Worst 2013: The Top Ten Toxic Threats. Blacksmith Institute, New York.

Business & Financial Times, 2016. Gov't to Construct a US$30m e-Waste Facility at Agbogbloshie. <http://thebftonline.com/business/ict/22079/govt-to-construct-us30m-E-waste-facility-at-agbogbloshie.html#sthash.HQbfjjhs.dpuf>.

Chama, M.A., Oteng-Ababio, M., 2016. Qualitative Analysis of the Presence of PBDE in Ashes, Soils, and Vegetables from Agbogbloshie e-Waste Recycling Site. University of Ghana, ORID, Working Paper 2.

Cobbinah, P., Darkwah, R., 2018. Urban planning and politics in Ghana. GeoJournal 82, 1229−1245.

De Boeck, F., 2011. Inhabiting ocular ground: Kinshasa's future in the light of Congo's spectral politics. Cultural Anthropol. 26 (2), 263−286.

Deas, I., Headlam, N., 2015. In: Paddison, R., Hutton, T. (Eds.), Boosterism, Brokerage, and Uneasy Bedfellows: Networked Urban Governance and the Emergence of Post-Political Orthodoxy. Cities and Economic Change, Sage, London, pp. 127−143.

Deutsche Welle., 2017. Germany Supports e-Waste Disposal in Ghana. <http://www.dw.com/en/germany-supports-E-waste-disposal-in-ghana/a-38015011> (accessed 13.05.15.).

EIT Digital, 2016. Agbogbloshie: Are You Aware of This? <https://www.eitdigital.eu/blog/article/agbogbloshie-are-you-aware-of-this/> (accessed 15.05.17.).

Ghana Statistical Services, 2014. Ghana Living Standards Survey Six (With a Labor Force Module), 2012−2013. Round 6. <http://www.statsghana.gov.gh/nada/index.php/catalog/72/study-description>.

GhanaWeb, 2012. Ga Chiefs Throw Support for Accra Metropolitan Chief Executive. Regional News of Thursday. <http://www.ghanaweb.com/GhanaHomePage/NewsArchive/artikel.php?ID = 228625>.

Gillespie, T., 2016. Accumulation by urban dispossession: struggles over urban space in Accra. Ghana. Trans. Inst. Br. Geogr. 41, 66−77.

Government of Ghana, 1992. Constitution of the Fourth Republic. Ghana Publishing Corporation, Accra.

Grant, R., 2006. Out of place? Global citizens in local space: a study of the informal settlements in the Korle lagoon environs in Accra, Ghana. Urban Forum 17 (1), 1−14.

Grant, R., 2015. Sustainable African urban futures: stocktaking and critical reflection on proposed urban projects. Am. Behav. Sci. 59 (3), 294−310.

Grant, R., Oteng-Ababio, M., 2012. Mapping the invisible and real African economy: urban E-waste circuitry. Urban Geogr. 33 (1), 1−21.

Grant, R., Oteng-Ababio, M., 2016. The global transformation of materials and the emergence of an informal "urban mine" in Accra, Ghana. Africa Today 62 (4), 3−20.

Grant, R., Oteng-Ababio, M., 2019. Greater Accra's new city extension at Ningo-Prampram: Urban promise or urban peril? International Planning Studies. Available from: https://doi.org/10.1080/13563475.2019.1664896 (in press).

Harvey, D., 2003. The right to the city. Int. J. Urban Reg. Res. 27 (4), 939−941.

Harvey, D., 2008. The right to the city. New Left Rev. 53, 23−40.

Huchzermeyer, M., 2014. Humanism, creativity, and rights: invoking Henri Lefebvre's right to the city in the tension presented by informal settlements in South Africa today. Transformation 85, 64−89.

Iddrisu, L., 2015. Accra Mayor Returns to Demolish Re-Building at Old Fadama. <http://www.myjoyonline.com/news/2015/September-22nd/accra-mayor-returns-to-demolish-re-building-at-old-fadama.php#sthash.HwH8z18Z.dpuf>.

Jade E-Services, 2014. The Octagon, Comprising of Office Suites/Retail Space Selling Now. Retrieved from: <http://house.jumia.com.gh/the-octagon-comprising-of-office-suitesretail-space-selling-now-22120-9.html> (accessed 05.09.17.).

Leahy, S., 2013. The Sickest Places in the World. <http://www.ipsnews.net/2013/11/the-sickest-places-in-the-world/> (accessed 20.05.16.).

Lefebvre, H., 1996. Writings on Cities. Blackwell, Oxford.

Lombard, M., 2014. Constructing ordinary places: place-making in urban informal settlements in Mexico. Prog. Plan. 94, 1−53.

Lovering, J., 2001. The coming regional crisis (and how to avoid it). Reg. St. 35 (4), 349−354.

MasterCard, 2014. Accra, an Inclusive City to Watch in Africa. <http://mastercardcenter.org/news/accra-inclusive-city-watch-africa/> (accessed 15.05.17.).

Melara, J.E., Grant, R., Oteng-Ababio, M., Ayele, B., 2013. Downgrading—an overlooked reality in African cities: reflections from an indigenous neighbourhood of Accra, Ghana. Appl. Geogr. 36, 23−30.

Minter, A., 2015. The Anatomy of a Myth: The World's Biggest e-Waste Dump Isn't. <http://shanghaiscrap.com/2015/06/anatomy-of-a-myth-the-worlds-biggest-E-waste-dump-isnt/>.

Mitchell, D., Villanueva, J., 2010. Right to the city. In: Hutchinson, R., Aalbers, M., Beauregard, R., Crang, M. (Eds.), Encyclopaedia of Urban Studies. Sage, Los Angeles, CA, pp. 667−671.

Morrison, N., 2017. Playing by the rules? New institutionalism, path dependency and informal settlements in Sub-Saharan Africa. Environment and Planning A 1−20. Available from: https://doi.org/10.1177/0308518X17730581.

Murray, M., Myers, G., 2006. Cities in Contemporary Africa. Palgrave/Macmillan, New York.

Myers, G., 2016. Urban Environments in Africa: A Critical Analysis of Environmental Politics. Policy Press, Bristol.

New York Times, 2010. A Global Graveyard for Dead Computers. <http://www.nytimes.com/slideshow/2010/08/04/magazine/20100815-dump.html?_r = 0>.

Obeng-Odoom, F., 2011. The informal sector in Ghana under siege. J. Dev. Soc. 27, 355−392.

Obeng-Odoom, F., 2016. Governance for Pro-Poor Urban Development: Lessons from Ghana. Routledge, London.

Oteng-Ababio, M., 2018. Crossing conceptual boundaries: re-envisioning coordination and collaboration among women for sustainable livelihoods in Ghana. Local Environment 23, 1−19. Available from: https://doi.org/10.1080/13549839.2017.1418847.

Ottaviani, J., 2015. E-Waste Republic. Aljeezera. <http://interactive.aljazeera.com/aje/2015/ewaste/index.html> (accessed 11.05.17.).

Oteng-Ababio, M., van der Velden, M., 2019. 'Welcome to Sodom' - Six myths about electronic waste in Agbogbloshie, Ghana. Available at: https://www.smart.uio.no/blog/welcome-to-sodom.html.

Oteng-Ababio, M., Agyeman, E., 2015. The Okada War in Urban Ghana: A polemic issue or policy mismatch? African Studies Quarterly 15 (4), 1−20.

Oteng-Ababio, M., Grant, R., 2019. Ideological traces in Ghana's urban plans: How do traces get worked out in the Agbogbloshie, Accra? Habitat International . Available from: https://doi.org/10.1016/j.habitatint.2018.10.007.

Owusu, M., Braimah, R.F., 2012. "If in doubt, count": the role of community-driven enumerations in blocking eviction in Old Fadama. Accra Envir. Urban. 24 (1), 47−57.

Paller, J., 2012. Political Accountability in Ghanaian Slums: Evidence from the Grassroots. Briefing Paper 11, no. 1. Ghana Centre for Democratic Development. University of Ghana, Legon.

Paller, J., 2015. Politics of Daily Life: Process, Networks, Spontaneity. Political Concepts. Committee on Concepts and Methods Working Paper Series no. 64. International Political Science Association. <http://www.concepts-methods.org/Files/WorkingPaper/PC%2065%20Paller.pdf>.

People's Dialogue, 2010. People's Dialogue on Human Settlements: Final Report on Community-Led Enumeration of Old Fadama community, Accra-Ghana. Unpublished report. Accra.

Pierce, J., Williams, O., Martin, D., 2016. Rights in places, an analytical extension of the right to the city. Geoforum 70, 79−88.

PI, October, 2015 refers to Personal interviews conducted in 2015

PI, October, 2016 refers to Personal interviews conducted in 2016

Purcell, M., 2003. Citizenship and the right to the global city: reimagining the capitalist world order. Int. J. Urban Reg. Res. 27 (3), 564−590.

Pure Earth, 2014. Transforming Agbogbloshie: From Toxic Dump into Model Recycling Center. <http://www.pureearth.org/blog/photos-transforming-agbogbloshie-from-toxic-E-waste-dump-into-model-recycling-center/>.

Rogerson, C., 2016. Policy responses to informality in urban Africa: the example of Maputo, Mozambique. GeoJournal . Available from: https://doi.org/10.1007/s10708-016-9735-x.

Scott, A., 2001. Globalization and the rise of city-regions. Eur. Plan. Stud. 9 (7), 813−826.

Smith-Asante, E., 2015. Adjen Kotoku Market: Investment Gone Waste? Daily Graphic. <http://www.graphic.com.gh/features/features/adjen-kotoku-market-investment-gonE-waste.html>.

Songsore, J., 2017. The Complex Interplay between Everyday Risks and Disaster Risks: The Case of the 2014 Cholera Pandemic and 2015 Flood Disaster in Accra, Ghana. International Journal of disaster Risk Reduction 26, 43−50. Available from: https://doi.org/10.1016/j.ijdrr.2017.09.043.

Stacey, P., 2018. Urban development and emerging relations of informal property and authority in Accra. Africa 88 (1), 66−80.

Stacey, P., Lund, C., 2016. In a state of slum: governance in an informal settlement in Ghana. J. Mod. Afr. Stud. 4, 591−615.

Tornyl, E., 2015. Mahama Promise Again: Sodom and Gomorrah to be Demolished. <http://pulse.com.gh/news/mahama-promise-again-sodom-and-gomorrah-to-be-demolished-id3861516.html> (accessed 10.05.17.).

Watson, V., 2014. Africa urban fantasies: dreams or nightmares? Environ. Urban. 26 (1), 215−231.

World Bank, 2019. The World Bank in Ghana. Overview. <https://www.worldbank.org/en/country/ghana/overview>.

Yeebo, Y., 2014. The Bridge of Sodom and Gomorrah. The Big Roundtable. <https://thebigroundtable.com/the-bridge-to-sodom-and-gomorrah-d80d1ceaf560>.

Further reading

Government of Ghana, 2015. UN Appoints President Mahama as Co-Chair of Eminent Persons to Champion SDGS. <http://www.ghana.gov.gh/index.php/news/2338-un-appoints-president-mahama-as-co-chair-of-eminent-persons-to-champion-sdgs>.

Homeless International, 2006. Alternatives to Forced Evictions in Ghana. Resource Document. <http://www.homelessinternational.org/standard_1.aspx?id01:28712&id00:19430&id00:76&id00:262>.

Myers, G., 2011. African Cities: Alternative Visions of Urban Theory and Practice. Zed, London.

Oteng-Ababio, M., 2010. E-waste: an emerging challenge to solid waste management in Ghana. Int. Dev. Plan. Rev. 32 (2), 191−206.

Oteng-Ababio, M., 2013. Unscripted (In) justice: exposure to ecological hazards in metropolitan Accra. Environ. Plan. A 45 (5), 1199−1218.

Oteng-Ababio, M., 2014. Rethinking waste as a resource: insights from a low-income community in Accra, Ghana. City Territory Architect 1 (10), 1−14.

Pieterse, E., Parnell, S., 2014. Africa's urban revolution in context. In: Parnell, S., Pieterse, E. (Eds.), Africa's Urban Revolution. Zed Books, London, pp. 1−17.

Purcell, M., 2002. Excavating Lefebvre: the right to the city and its urban politics of the inhabitant. GeoJournal 58, 99−108.

E-waste situation and current practices in Brazil

16

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16.1 Introduction

Brazil is a country with huge territory and a population of approximately 200 million people. It is considered the largest E-waste producer in Latin-America, with estimated 7 kg E-waste per capita (StEP, 2017), and also a receiver of illegal E-waste exports from other industrialized countries (Lundgren, 2012). Some aspects which influence E-waste generation in the country are the population consumption patterns, market prices and offers, and technological evolution of equipment with consequent obsolescence of others.

Considering the amount of E-waste in the country, the concerns with its potential hazardousness and the potential added-value with its recycling, Brazil has established in 2010 its National Solid Waste Policy (PNRS), which determines that E-waste take-back implementation in mandatory countrywide. Following the PNRS, there was an increasing tendency on the development of E-waste management specific Standard and licensing schemes, businesses in E-waste take-back and recycling, researches, and other initiatives regarding the implementation of E-waste management solutions. However, the growing discussion on this complex subject revealed several difficulties for adequate E-waste take-back implementation in the Brazilian context. This chapter aims at describing the Brazilian E-waste scenario, and discussing the existing difficulties and opportunities for a sound E-waste management in the country.

16.2 Brazilian legislation and regulation on E-waste

16.2.1 The national solid waste policy

The mark for E-waste management legislation in Brazil is the National Solid Waste Policy—PNRS (Law No. 12305), established in 2010. Before this law, there were environmental regulations for production and treatment of specific E-waste appliances, like batteries and lamps. For example, the Resolution No. 401/2008 from the National Environmental Council (CONAMA) established requirements and

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00009-7

procedures for producers and importers of batteries, in order to promote environmentally sound management of their end-of-life products.

Another relevant mark prior to the PNRS is the Brazilian Standard no. 10004/2004, which defined the parameters to classify solid waste according to their hazardousness. Some kinds of E-waste, like lead batteries, mercurial lamps, and ashes from printed circuit boards (PCB) incineration, are specifically listed as hazardous, but the majority of E-waste types and components still need to be classified according to the procedures established in this Standard.

After the establishment of PNRS in 2010, take-back systems became mandatory for some kinds of special waste, including batteries; lamps; electrical and electronic equipment (EEE), and their components. Structuring and implementation of these take-back systems are an obligation of EEE producers, importers, distributors, and retailers.

The Decree 7404/2010, referred to the PNRS Law, defines that the instruments for implementation and operation of E-waste take-back systems are Sectorial Agreements (SA), regulations from the Government, and Terms of Engagement. The SA are contracts to be signed between representatives of EEE producers, importers, distributors and retailers, and the Government at all levels, focusing the implementation of shared responsibility for EEE life cycles. Some of the representatives currently engaged with E-waste SA in Brazil are ABINEE (Brazilian Association of EEE Industries); ABREE (Brazilian Association for EEE Recycling); and FECOMERCIO (State Federations for the Commerce of Goods and Services). Those representatives can create one or more E-waste management entities, who will be institutionally responsible for managing and contracting services for the implementation of the official E-waste take-back systems.

In 2013, the Ministry of Environment (MMA) opened a call for E-Waste Sectorial Agreement proposals, which should include, among others:

- Means for E-waste delivery and collection, defining: responsibilities, territorial coverage and delivery, collection, and recycling activities.
- Actions, criteria, and responsibilities over E-waste delivery points and transport activities.
- Procedures and responsibilities for operations of E-waste reuse, recycling, treatment and sorting; environmentally sound disposal of E-waste refuse.
- Possibility of hiring other entities, such as waste pickers' cooperatives.
- Progressive implementation targets, in terms of % of Brazilian cities.

Until mid-2018, the received proposals were still under discussion, negotiation, and revision between the signatories. According to the MMA, some of the most critical points that have hindered the reach for such agreement between the parties, mainly reflecting demands from EEE producers, importers, distributors, and retailers to the Government, are:

- The pecuniary participation of consumers in covering the costs of take-back systems: it should be clearly informed in the final price of purchased EEE, and free of taxes.
- The definition of E-waste as nonhazardous, prior to the modification of their physical or chemical properties: this should avoid high costs of treating all E-waste as hazardous in all steps of the take-back systems, to facilitate environmental licensing of E-waste

collection companies, and to avoid restriction of hazardous waste transport across some States with specific prohibitive legislation.
- Creation of a nationwide valid documentation of E-waste transport, for the registry of source and nature of the load, exempting the need for other waste transportation documentation.
- The recognition that E-waste delivery at take-back points implies in the loss of property of such goods by their owners: it could be solved with some documentation to be signed by the deliverers at the points, or the emission of a report stating such transfer of property after the delivery at the points.
- Who should be the responsibility for “orphan” products (illegal or fake EEE products that normally enters Brazilian market informally).
- The biding engagement of all EEE life cycle actors in the Sectorial Agreement, and not just its signatories: this issue was recently resolved by the Decrete 9177/2017, referred to the PNRS, which determines all producers, importers, distributors, and retailers acting in the country are responsible for what was agreed by signatories of the Sectorial Agreement.

16.2.2 States legislation

As in the national level, some Brazilian States already had specific legislation for some kinds of E-waste, prior to the PNRS, or created particular State Laws after it. Most of this legislation has been tracked in the StEP E-waste World Map (StEP, 2017). For example, before the PNRS, States like Espírito Santo (ES) and São Paulo (SP) already had specific Laws for the correct management of E-waste (SP Law No. 13576/2009) or waste containing mercury and heavy metals (ES Law No. 9163/2009). There were also some municipal Laws on this regard, as in the city of Cascavel, State of Paraná (Law No. 4726/2007). Many of these were moved by the previous countrywide discussions that resulted in the PNRS in 2010.

Other States and municipalities developed specific E-waste legislation after the PNRS. For example, the Rio de Janeiro State (RJ) created, in its State Law no. 8030/2018, the E-waste take-back Program for all of its territory. This Law determines that all administrative buildings of the State Government, as well as their autarchies, foundations, and entities of the indirect public administration, must make available E-waste delivery points to the external public, with visual communication referring to the risks related to E-waste. In accordance to the PNRS, the collected appliances must be forwarded to EEE producers, importers, distributors, or retailers, and the municipalities can be hired to promote E-waste collection within the take-bake system under their direct responsibility.

Some States, like São Paulo (SP), are ahead in the regulation and implementation of E-waste take-back schemes in their territories. In 2015, the State Environmental Secretary (SMA-SP) issued a Resolution (No. 45/2015) determining that this Secretary and the State Environmental Company (CETESB) can celebrate Terms of Engagement for monitoring and implementation of take-back systems (in line with the aforementioned PNRS Decree No. 7404/2010). In 2017, such Term was signed between the following parties: SMA-SP; CETESB; and Green Eletron, a take-back management entity created and represented in this Term by ABINEE and FECOMERCIO-SP. In addition, in order to tackle some of the already discussed critical issues regarding the E-waste SA, CETESB issued in 2016 a Decision (No. 120/2016/C) in which it determined that E-waste can be classified as nonhazardous in operations that do not involve separation of components, and therefore do not promote exposition to potential hazardous constituents—except final disposal. Furthermore, in 2018 CETESB issued another Decision (No. 076/2018/C), establishing the required conditions for environmental licensing of take-back activities, what, among other definitions, limits the Operation Licensing of all producers, importers, distributors, and retailers in the State, to the approval of a take-back plan for their related end-of-life products.

16.2.3 Brazilian standardization on E-waste take-back systems

The Brazilian Association for Technical Standards (ABNT) has published, in 2013, a Standard on Requisites for E-waste Reverse Manufacturing (ABNT, 2013). This is the reference Standard for E-waste management implementation in Brazilian companies. It establishes requisites for the implementation, maintenance, and continuous improvement of an E-waste management system, which is based in other Standards such as ISO 9000 series and ISO 14001.

According to this Standard, the E-waste management system to be implemented in Brazilian companies includes:

- An environmental policy.
- Planning, comprehending: environmental and health and safety aspects; legal requisites; objectives, targets, and programs.
- Implementation and operation aspects, such as: resources, functions, responsibilities, authorities, competences, training, awareness, communication, documentation, and its controlling, operational controlling, preparation, and response to emergencies.
- Verification aspects like monitoring and measurement, compliance assessment and others, corrective and preventive measures, registry controlling, and internal auditing.
- Administration analysis, focusing diagnosis, and opportunities for improvement.

Although this Standard is still not certifiable, it has been guiding the implementation and enhancement of organizational maturity of many E-waste businesses in the country. Some of its main contributions to Brazilian E-waste management companies regard the creation of standardized documentation for mass balance control along operational steps like E-waste reception, storage, dismantling, and commercialization; the standardization of operational procedures; adequate management of hazardous components; E-waste traceability from reception to final destination; and reporting to clients and environmental authorities.

16.3 E-waste generation in Brazil

Brazil is still far from having a fully controlled scheme to manage E-waste. Therefore all figures related to E-waste generation in the country are based on estimation methods. A highly referenced estimate is 7 kg/capita in 2014 (StEP, 2017), or a total of 1.4 Mt in that year, what was calculated based on a correlation with Purchase Power of the Population (PPP). One study developed by request of the Federal Government, to assess the feasibility of possible E-waste take-back schemes in Brazil, estimated a range of 4.79 − 7.19 kg E-waste/capita (ABDI, 2012), based on a correlation with the GDP per capita of some European countries, as previously presented by Huisman et al. (2008). Other Brazilian studies estimated E-waste generation per capita as 3.77 kg in 2008 for seven types of appliances (Araújo et al., 2012) and 4.8 kg in the city of São Paulo (Rodrigues et al., 2015). These latter studies adopted estimation methods like the Market Supply and the Time-Step, that rely on variables like amount of EEE products put on market each year, the EEE in stock (in use), and average lifespans for each kind of appliance.

Those estimates are much necessary in order to support the planning of take-back schemes in the country. However, all of them have downsides due to uncertainties and adopted approaches. For example, the correlation with PPP and GDP per capita depends on previous data with real E-waste generation accounting in a considerable sample of places, which could be comparable to the country under study. In this case, a correlation based on European countries from 10 + years ago may not be reliable to estimate E-waste generation in Brazilian context nowadays. Another restriction is the dependence on data such as average lifespan of products, what may also vary according to social-economic contexts in each place, to the period under study, and the evolution of technologies. On this regard, all of the aforementioned Brazilian studies adopted average lifespans from the international literature in previous years, what may not reflect the patterns of Brazilian consumers. Finally, most of these studies adopted methods that depend on the amount of EEE products put on market in different years. Such data, when available, usually reflects the EEE consumption countrywide. Thus, the E-waste generation estimates represent an average of the country population, what does not reflect the specific social and economic contexts in the different regions (e.g., according to IBGE (2015), the estimated GDP per capita in the country was R$ 29k in 2015, but varied from as much as 43.5k in the State of Sao Paulo to 11.4k in Maranhão).

An attempt to reduce those uncertainties was done by Abbondanza and Souza (2018), by using surveys to collect data for the Market Supply E-waste estimation method. These surveys were applied to a sample population with 5% margin of error, which is representative of different city zones of the city of São José dos Campos, State of São Paulo, Brazil. The interviewed households informed data as the number of appliances acquired in past years, number of appliances currently in use, and the age of appliances lately discarded as E-waste. With this, the estimated E-waste generation in this city was 4 kg/capita in 2017. The observed lifespans varied considerably in comparison to those adopted by the aforementioned studies. For example, adopted lifespans of mobile phones ranged from 2 to 4 years in those studies, whilst in this case the observed average was 1.98 year (smartphones) to 2.5 years (nonsmartphones). The study found the average lifespan of 7 years for a washing machine, compared to 7−11 from the previous studies. Another advantage of this study was to produce lifespan distributions, rather than just averages, what does not restrict the E-waste generation projections to a discrete lifespan value. It also represented those lifespan profiles by regions of the city, thus seeking to represent the social-economic contexts. For example, the probability of a smartphone becoming E-waste in the city was around 45%, but this varied from 40% to 55% depending on the zone of the city. Such information can be useful to support planning of E-waste take-back systems in the country, especially because, as seen in Section 16.2, such implementation in the country must be progressive and cities are the basic units for the systems.

16.4 Currently known E-waste routes in Brazil

As mentioned before, in Brazil there is still very few control on E-waste generation and destinations, because a countrywide formal take-back system is still in its very early steps. Based on empirical evidences and previous literature, the known current routes for E-waste in the country are summarized in Fig. 16.1, and further discussed.

A particular issue in Brazil regarding E-waste management is that most adequate systems, or the more specialized operations within the take-back routes, tend to be located in the Southeast (SE) and South (S) regions on the country, the most developed ones, but as far as 3.500 km from poorer regions like North (N) and Northeast

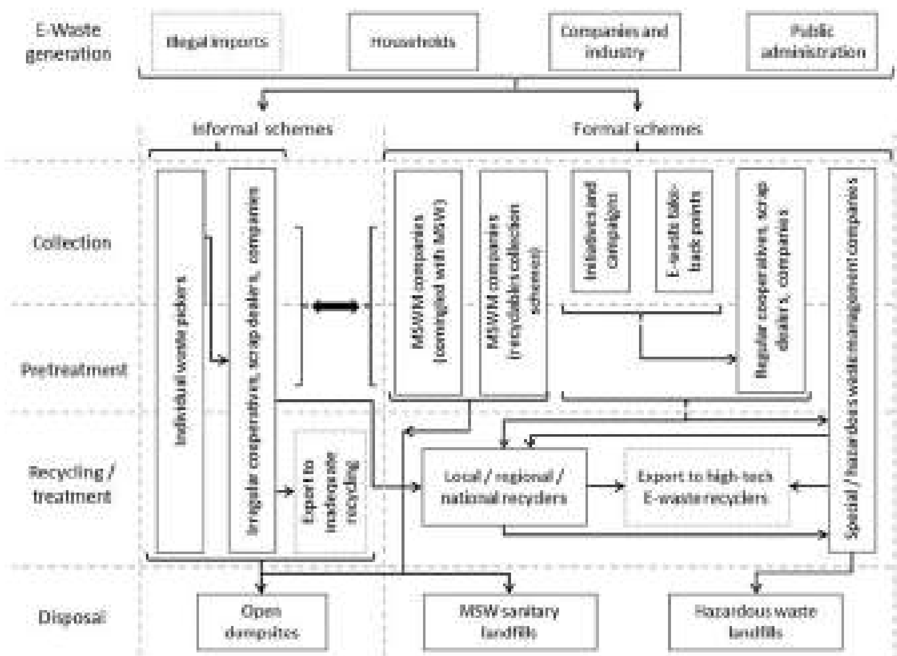

Figure 16.1 Currently known E-waste formal and informal chains in Brazil.

(NE). The study by ABDI (2012) identified, in 2012, 94 E-waste recyclers in the country, of which 50 were located in the SE region (37 just in SP State) and 34 in the South region, compared to 4 in the NE and 3 in the North regions. Considering that Brazil is a continental country in terms of its territory, and that its logistical infrastructure is highly dependant on road transport, this poses a huge logistical challenge that hinders the feasibility of E-waste take-back systems countrywide. The concentration of E-waste take-back activities in southern regions, particularly in the São Paulo State, can be illustrated with data collected from a Brazilian database of waste management companies (CEMPRE, 2017). Late in 2017, there were 150 cooperatives registered in this database that were doing business with E-waste, from which 63 were located in the SP state. Regarding scrap dealers, 87 registered companies were doing business with E-waste, 49 just in SP. And concerning recycling companies, 129 were registered for E-waste business, 60 of these in SP.

It is also worth mentioning that those identified E-waste recyclers can only process some types of E-waste and components at a limited capacity. This is going to be discussed further in this section.

16.4.1 Informal schemes

The informal sector in Brazilian waste management is widely known and observed in all regions, bus still very few data are available, and especially concerning E-waste. However, we can consider that informality plays a huge role in waste management recycling chains in the country, and this also applies for E-waste. The adequate E-waste recycling rate in Brazil is estimated at 2% (Araújo et al., 2012). E-waste corresponds to 2% of all waste collected by recyclables collection schemes (CEMPRE, 2016), what is far from being widespread in the country, as discussed further.

16.4.1.1 Individual waste pickers, irregular cooperatives, scrap dealers, and companies

It is estimated that in 2008 around 70.5k waste pickers were acting in urban areas, 18% of those in the State of São Paulo, and 5.5k being children under 14 year old. Out the 5760 Brazilian cities, 27% acknowledged the presence of waste pickers in their municipal solid waste (MSW) disposal sites (Silva et al., 2013).

There are evidences that waste pickers and scrap dealers handle E-waste in the country (Ongondo et al., 2011), what is also highly supported by empirical experience. Some of these were found to make rough acid leaching of PCBs, as well as open burning of components like cables (Lundgren, 2012; Souza, 2014).

A very common scene in Brazilian cities, especially in the poorest areas, in presented in Fig. 16.2. It clearly represents the activity of individual waste pickers, who collect E-waste from households or businesses, dismantle the appliances, separate the most valuable components for commercialization (usually to scrap dealers), and leave the less valuable parts at open dumps, like vacant lots, green areas, or public parks.

Figure 16.2 Informal dismantling and dumping of CRT TVs in a Brazilian city.

The activity of cooperatives or scrap dealers who are not formally licensed to process E-waste is also very common. Because E-waste has a considerable market value in the recycling business, those actors also apply irregular processing in order to separate valuable materials for commercialization. Fig. 16.3 shows the working area of a recyclables cooperative, where some dismantled or to-be-dismantled E-waste can be seen directly over the ground, and exposed to weather.

In some cases, the informal E-waste sector is already involved with organized crime schemes. For example, it was reported in the city of Belo Horizonte a significant shift in the stealing of electrical cables from public traffic lights. From January to June, 2018, the municipal administration reported the stealing of 64 km of cables from traffic lights, against 5 km in the same period in 2017. In the city of Sao Paulo, in the first semester of 2018, 32 km of cables were reportedly stolen, in a total of 1000 occurrences. Such crime is also widespread in the country, with other cases affecting systems as federal roads, water supply, and healthcare facilities. So far, identified receivers of such stolen cables are scrap dealers, who have paid for the material either in cash or with alcoholic drinks (dia Brasil, 2018).

Some of these informal actors go further into irregular E-waste processing, searching to extract valuable metals. Acid leaching seems to be a very common activity within the E-waste informal sector, despite no formal data are available. In the city of São José dos Campos (SP), we could identify at least one small company, not licensed for WEEE, who not only crashed CRT tubes to reduce volume but also applied acid leaching of PCBs. This company provided a simple recipe for this process, consisting of acid leaching of PCBs with *acqua regia*, followed by filtering, heating on hot plate, and precipitation of gold using a reagent. It is also very easy to find Brazilian videos on YouTube, where this process is homemade by informal actors. As it can be observed in these cases, the informal process does not make use of adequate laboratory conditions, and neither health and safety cares like the use of adequate personal protective equipment.

Figure 16.3 E-waste irregularly stored and processed by a recycling cooperative.

16.4.1.2 Open-dumping

Besides the prohibition of open dumping by PNRS, in Brazil most of the municipal solid waste management (MSWM) systems still rely on comingled waste collection and inadequate disposal, open dumpsites being a very common final destination. According to ABRELPE (2015), about 60% of Brazilian cities had open dumps or controlled (not sanitary) landfills as final MSW disposal. Besides the open dumpsites that accumulate all mixed MSW of many Brazilian cities, including E-waste, there are also uncountable smaller open dumping areas, like those mentioned in Section 16.4.1.1 and illustrated in Fig. 16.2. This situation is also enhanced by the lack of coverage of MSW collection schemes, especially in the North and Northeast regions (around 80% coverage, according to ABRELPE, 2015), provoking people either to dispose of their waste at open dumps, or open burn them.

16.4.2 Formal schemes

16.4.2.1 Municipal solid waste management systems and landfills

In addition to the widespread informal E-waste schemes, another very common destination of E-waste in Brazil are the MSWM systems. Because of lack of information or lack of adequate delivery points in most cities, citizens have regularly disposed of their E-waste mixed with MSW.

Besides MSWM systems can be considered formal schemes, this is still not an adequate situation, especially considering the Brazilian scenario. Only 18% of Brazilian cities have some implemented separate recyclables collection scheme (CEMPRE, 2016), meaning that in most cases MSW is collected without previous sorting. Moreover, 42% of Brazilian MSW is destined to inadequate landfills or open dumps. This corresponds to the largest share of Brazilian cities (60%), consisting mostly of small and medium cities, and more concentrated in the North, Northeast, and Midwest regions, the poorest in the country.

Even where there are sanitary landfills, E-waste is regularly being landfilled mixed with MSW. This is the case, for example, of Rio de Janeiro, the second biggest city in the country. The E-waste share within commingled MSW has shifted from 0.2% in 2010 to 0.48% in 2016, what varies significantly depending on the MSW collection areas (COMLURB, 2016). Considering the average MSW generation of 1.39 kg/capita in the city in 2016, and the estimated population of 6,476,631 inhabitants in the same year (IBGE, 2017), the E-waste amount landfilled in 2016 can be estimated in 9k tonnes.

16.4.2.2 Initiatives and campaigns

There are several and an increasing number of initiatives for the collection and adequate destination of E-waste in Brazil. In many cases, delivery points are made available by the municipalities, in partnership with take-back and recycling companies, in determined periods of a year. There are also several initiatives for the collection of E-waste by delivery points placed at universities and schools.

Some cities have established specific services for the door-to-door collection of E-waste under demand. This is the case, for example, of the "e-lixo" (E-waste) service in the city of São José dos Campos. This city also has several delivery points for recyclables and special MSW, including E-waste. From both systems, the E-waste collected is destined to a cooperative (Coopertech) specialized in E-waste dismantling.

One example in the city of Rio de Janeiro is a partnership of the companies Tech Trash and Zyklos, who installed dozens of E-waste delivery points at shopping centers and several partner shops along the city. Those companies also provide door-to-door collection under a fee.

A reference E-waste take-back initiative at universities is the Centre for Discard and Reuse of IT Waste (CEDIR), at São Paulo University (USP). This center has a partnership with recyclers, promoting the adequate E-waste destination. Most of the biggest Brazilian universities have already installed special E-waste collection points. Some of them, like the Federal University of Rio de Janeiro (UFRJ), also have a sorting area, operated by a partner cooperative, where E-waste can be sorted and dismantled, before promoting the correspondent adequate destination to each fraction.

A well-structured initiative is a pilot project implemented in the Lapa neighborhood in the city of São Paulo, called "Descarte ON" ("Discard ON"). This initiative aimed at testing a small-scale take-back system, to be a further model for the E-waste take-back implementation in Brazilian cities. E-waste delivery points were placed at large shops and supermarkets, and the collection, pretreatment, and recycling are operated by partner companies. Such initiative is the result of a partnership between the Japan International Cooperation Agency (JICA), the Brazilian Federal Government, the São Paulo Municipality, and representative associations and federations for Brazilian EEE industry and commerce, and E-waste recyclers.

16.4.2.3 Formal E-waste take-back systems

Many of the cases mentioned in the Section 16.4.2.2 can be considered formal E-waste delivery systems, especially those consisting of initiatives and programs by the municipalities. However, those systems still cannot be considered official under the framework of the PNRS legislation, municipalities can only operate E-waste take-back processes under a contract and payment by the E-waste management responsible entities, as defined in the Sectorial Agreement (which is still not formalized, as previously discussed).

A pioneer initiative in the country was the signature of a Term of Engagement in the State of São Paulo (see Section 16.2.2), with the creation of a Management Entity for the E-waste take-back system to be implemented in this State. This Entity, called Green Eletron (www.greeneletron.org.br), was created by ABINEE, and is a signatory of the São Paulo Term of Engagement. The system under management of Green Eletron in the State is still expanding since the signature of the Term of Engagement, and up to August 2018, had installed 35 standardized delivery points (Fig. 16.4) at partner shops and commerce representatives, having collected a total of 98t of E-waste. As seen in Fig. 16.2, those delivery points allow for E-waste collection in separate drawers for IT equipment (computers, printers, tablets); mobile phones; and screens (bottom drawer). This system is operated by two hired companies: GM&CLOG and Sinctronics (see Section 16.4.2.5), who are

Figure 16.4 E-waste delivery point installed by Green Eletron and Sinctronics.

responsible for all operational steps from collection to processing and final destination.

Besides those systems that focus the final consumers, there are also formal take-back schemes implemented by specific companies to recover their end-of-life products. Brands like Dell, HP, and Lexmark have their own take-back schemes, operated by partners like Sinctronics (see Section 16.4.2.5), after the demand by consumers willing to deliver their spent equipment, who request the service by phone of by filling a form in their websites.

16.4.2.4 Regular cooperatives and companies

A growing number of cooperatives and small companies are developing capacity and getting authorization to adequately handle E-waste. In general, the largest amount of E-waste collected by such businesses comes from large companies and the public administration, who regularly upgrade their computers and other IT appliances, and dispose of their old equipment in batches.

In São Paulo, the cooperative Coopermiti has a partnership with the municipality, and promotes E-waste dismantling and adequate destination. This cooperative collects E-waste from the municipal MSW delivery points, and by demand. Their management system is certificated with ISO 9001 and ISO 140001.

In Rio de Janeiro, the cooperatives COOPAMA and Céu Azul are good examples of such kind of institution. They have been trained in adequate E-waste dismantling and management, and authorized by the municipality to operate in this business. COOPAMA (Fig. 16.5A) has a team of 11 trained staff in E-waste dismantling, and has been processing tonnes E-waste/month, after a partnership with large retailing networks. Another example is in São José dos Campos, where Coopertech (Fig. 16.5B) is also working in partnership with the municipality, and collecting E-waste mainly from the municipal E-waste special collection service, and from large companies and public agencies—an average of 5 ton/month. In particular, this cooperative has been implementing the requisites for the Brazilian Standard on E-waste (Section 16.2.3), aiming at being the one of the first cooperatives which satisfies such Standard.

An example of a small company in the Brazilian E-waste business is Zyklos (mentioned in Section 16.4.2.2). This company operates in Rio de Janeiro, collecting and dismantling E-waste from large and medium partner companies. Their operational area has a capacity to process 20+ tonnes of E-waste per month (Fig. 16.5C), depending on the type of appliance. Currently they have processed an average of 8 ton/month. Their main operational processes are E-waste collection, dismantling, sorting for reuse, recycling, and destination of hazardous components, and repairing. The E-waste collection is subcontracted to authorized companies, and the destination of hazardous components is to a specialized company which makes coprocessing or adequate landfilling. A network of recyclers purchases the recyclable components.

Some challenges for the financial sustainability of such small business are the fluctuations in prices and in the E-waste supply, also influenced by the large competition in this business; and the large amount of less valuable E-waste that they have to collect under demand of their suppliers-clients. For example, a huge issue in the country in the 2010s decade was the large number of CRTs discarded as E-waste. This was shifted not only by the technological evolution of TVs and monitors, but also after a National policy to quit analogic TV signal and implement digital signal countrywide. CRTs have been a critical component to be recycled or disposed of, because of the large volumes of such E-waste generated in the 2010s. Because of its volume and weight, this waste can represent a major cost if destined to hazardous waste treatment by E-waste generators or dismantlers. However, the E-waste collection and dismantling companies are very often pressured to receive such material as a share of a full batch of E-waste, containing also the more valuable appliances (e.g., IT) that make the service worth.

Besides those cooperatives and companies whose business is focused in E-waste collection and dismantling, there are also specialized companies in providing logistical services for the E-waste recycling business. This is the case, for example, of

(A)
(B)
(C)

Figure 16.5 (A) E-waste dismantling station at COOPAMA, lightened by reused parts of a LED TV; and the production lines of (B) Cooperative Coopertech; and (C) Zyklos.

GM&CLOG, who is one of the logistical operators for the system implemented in São Paulo State, after the Term of Engagement explained above.

16.4.2.5 Brazilian recyclers

Although E-waste recycling is a growing business in Brazil, as previously mentioned, most of the recycling companies are concentrated in the SE and S regions, the most industrialized in the country. Most E-waste components can be recycled in the country, even those considered hazardous, but still no large-scale technology is installed to recover precious metals from PCBs.

For example, a few industries are able to recycle batteries collected by take-back schemes and companies such as those mentioned in Section 16.4.2.4. These recyclers apply either chemical or thermal processes after shredding the batteries, in order to recover metals.

Regarding CRTs recycling, only one company in the country, located in the State of São Paulo, is known to recycle CRT glasses, producing ceramic glazes. Because of the large demand on this company, many times they could not absorb the full amount of CRTs they have been offered by E-waste dismantlers. However, the peak generation of CRT E-waste was around 2015–16, and such kind of waste is now decreasing in volume.

A good benchmark for Brazilian E-waste recycling is Sinctronics, a company owned by the Flextronics International group. Sinctronics is another operator of the São Paulo State E-waste take-back system. Besides an efficient E-waste dismantling line (Fig. 16.6A), the company also has technology to separate cooper from cables, and to recycle E-waste plastics (Fig. 16.6B), including thermoset polymers like ABS. A particular market niche for this company is the recycling of plastics from printer cartridges and tonners, what are often discarded as hazardous waste. The recycled plastic products range from handles for new printers' boxes, ecological plastic wood (Fig. 16.6C), and other resins that are turned into new EEE parts (e.g., printers, air conditioners). Their whole production line implements lean manufacturing principles.

16.4.2.6 Large waste management companies

Besides a large number of relatively small companies working in the E-waste business, as mentioned in Section 16.4.2.3, there are also some few large companies who are very active in Brazilian waste management systems, especially those offering hazardous waste treatment and MSWM services. Because of their operational capacity, territorial coverage, and financial conditions, these companies are also large players in the E-waste business. Mostly, those companies purchase valuable E-waste components, or offer treatment and disposal of hazardous E-waste parts. Regarding the PCBs market, these companies usually separate and shred the cards to export to large PCB recyclers in the international market. At least one of these large MSWM companies had a unit for metals recovery from waste, based on hydrometallurgy, but it is know that this unit has been inactive for large periods because there was no sufficient E-waste amount reaching the system to make its operation feasible.

(A)
(B)
(C)


Figure 16.6 Sinctronics production: (A) E-waste dismantling line; (B) plastics recycling plant; and (C) E-waste plastic recycled products.

16.5 Brazilian research and projects on capacity building

It is known that some of the large waste treatment companies cited in the Section 16.4.2.6 are investing and making partnerships to develop technologies to extract precious metals from E-waste. This is the case, for example, of the Rematronic project, in which a biohydrometallurgic technology is being developed by the Renato Archer IT Institute (CTI) for the extraction of gold and other precious metals.

Besides the CTI Institute, several Brazilian universities and research centers have developed a growing number of studies focusing the E-waste analysis and development of recycling technologies. Analyzing the publications indexed in Scopus, until mid-2018, the leading research institution in this area is São Paulo University (USP), followed by the Federal University of Rio Grande do Sul (UFRGS), Federal University of São Carlos (UFSCar), and Federal University of Rio de Janeiro (UFRJ).

Some of these studies have focused the chemical analysis of E-waste, considering either the organic and inorganic components for further recycling or treatment (Santos et al., 2011; Yamane et al., 2011; Aquino and Pereira-filho, 2015). An interesting study analyzes efficient techniques for E-waste disassembly (Duflou et al., 2008). Other studies have analyzed techniques to extract metals from E-waste, like copper (Rubin et al., 2014; Calgaro et al., 2015; Silvas et al., 2015) and silver (Dias et al., 2016).

Besides the growing number of Brazilian researches, there are also many funded projects aiming at capacity building for sound E-waste management in Brazil. Some funding schemes by large private companies and public agencies (like the Banco do Brasil Foundation) have supported specific initiatives from companies and cooperatives in the E-waste sector. Other projects are focused in a wider range of targeted public, and in developing knowledge and capacity for an adequate and efficient E-waste management. An example of such projects is Ambientronics by the aforementioned CTI, which as a public scientific institute linked to the Ministry of Science, Technology and Innovation. Started in 2006, this Project aims at the capacity building for sustainability in the Brazilian EEE complex. It also has the goal of developing and implementing Brazilian Standards on E-waste and Restriction of Hazardous Substances (RoHS). It was under this initiative that CTI played a leading role in the development of the Brazilian E-waste Standard (Section 16.2.3). This Project has also offered several training courses on E-waste management the respective Standard requisites, to small companies and cooperatives in the State of São Paulo. They have also supported the creation of E-waste commercialization networks to empower those companies and cooperatives, aiming at a better feasibility for these businesses.

Another example of capacity building project focusing Brazilian E-waste management is LaWEEEda—Latin-American-European Network on Waste Electrical and Electronic Equipment Research, Development and Analyses. This Project started in 2016 with the support from Erasmus + funding scheme by the European

Commission, and includes 11 partners—universities and E-waste business partners—from 5 countries—Austria, England, Germany, Brazil, and Nicaragua. This Project offers a series of training courses in relevant E-waste management topics, from practical dismantling techniques, to chemical analysis, business planning, recycling and treatment techniques, and others. The targeted public are not only companies and cooperatives acting in the Latin-American E-waste business but also technicians from environmental agencies, municipalities, and a strong focus in university students. The courses are offered in four adequately equipped Training Centers established in Brazil and Nicaragua.

16.6 Challenges and further steps for sound E-waste management in Brazil

Observing the scenario described in this chapter, there are still many challenges, but also opportunities, for the implementation of a sound E-waste management in Brazil:

- *Implementation of the Sectorial Agreements*: as previously discussed, there are still several tangles until the responsible entities reach an agreement on how the Brazilian take-back scheme must be structured, and what are the respective responsibilities and implementation solutions. Once the Sectorial Agreement is established, the country will be able to shift the velocity and adequacy of E-waste take-back implementation.
- *Environmental licensing and formalization of the businesses*: the creation of new E-waste businesses, and the licensing of new and existing ones, still face many difficulties concerning the involved bureaucracy. Environmental agencies of some States have established standards and procedures to enable such businesses, but in most cases it is still rather unclear, even for the governmental bodies, what should be the adequate procedure to formalize these businesses. This is also true concerning the tributary and fiscal aspects, what pose many burdens for the E-waste businesses. Some of these difficulties could be relieved by the creation and revision of Federal environmental laws, as well as of the tributary and fiscal rules.
- *Capacity building for adequate and efficient E-waste management*: many E-waste businesses have been created as a response to a new market opportunity in the country. However, in many cases, and especially when it comes to waste pickers' cooperatives, it is necessary to develop a basic level of knowledge regarding legislation, E-waste take-back operation, business management, and others. With this, the emerging companies can manage their businesses more effectively and efficiently.
- *Expansion of recycling capacity in the country:* the Brazilian recycling capacity is still pretty much concentrated in the South and Southeast regions, and especially in the Sao Paulo State. This causes a complex logistical challenge for the E-waste take-back from farthest regions, what is increased by the existing transport infrastructure issues. It is also necessary to develop feasible technology for the recycling of a wider range of E-waste components, especially PCBs. Furthermore, the country needs to establish financial and tributary incentives for the expansion of the E-waste recycling businesses countrywide.
- *Inclusion of capacitated cooperatives:* the existence of a large number of waste pickers' cooperatives is a particular scenario in Brazil, which could be explored and is stimulated

by the PNRS, concerning their inclusion in the E-waste take-back systems. Such potential can only be explored once these cooperatives have adequate training, working conditions, licensing, and financial incentives, what is still the reality of very few cases. Working on the aforementioned challenges would also foster the expansion of E-waste management cooperatives countrywide, favoring the wider coverage of implemented take-back systems. This is also true for small E-waste management companies.

References

Abbondanza, M.N., Souza, R.G., 2018. Estimating household e-waste generation in municipalities using primary data from surveys: case of Sao Jose dos Campos, Brazil. Waste Manag. (submitted).

ABDI, 2012. Logística Reversa de Equipamentos Eletroeletrônicos Análise de Viabilidade Técnica e Econômica. Agência Bras Desenvolv Ind - ABDI, p. 177.

ABNT, 2013. ABNT NBR 16156: Waste electrical and electronic equipment: requirements for the activity of reverse manufacturing.

ABRELPE, 2015. Panorama of solid waste in Brazil 2015. doi:ISSN 2179-8303 9.

Aquino, F.W.B., Pereira-filho, E.R., 2015. Analysis of the polymeric fractions of scrap from mobile phones using laser-induced breakdown spectroscopy: chemometric applications for better data interpretation. Talanta 134, 65–73. Available from: https://doi.org/10.1016/j.talanta.2014.10.051.

Araújo, M.G., Magrini, A., Mahler, C.F., Bilitewski, B., 2012. A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. Waste Manag. 32, 335–342. Available from: https://doi.org/10.1016/j.wasman.2011.09.020.

Calgaro, C.O., Schlemmer, D.F., Silva, M.D.C.R., Maziero, E.V., Tanabe, E.H., Bertuol, D. A., 2015. Fast copper extraction from printed circuit boards using supercritical carbon dioxide. Waste Manag. 45, 289–297. Available from: https://doi.org/10.1016/j.wasman.2015.05.017.

CEMPRE, 2016. Pesquisa Ciclosoft 2016. <http://cempre.org.br/ciclosoft/id/8>.

CEMPRE, 2017. Serviços: Recicladores. <http://cempre.org.br/servico/recicladores>.

COMLURB, 2016. Caracterização dos Resíduos Sólidos Domiciliares da Cidade do Rio de Janeiro. Rio de Janeiro.

dia Brasil, B., 2018. Roubo de cabos de energia se espalhou pelo país.

Dias, P., Javimczik, S., Benevit, M., Veit, H., Bernardes, A.M., 2016. Recycling WEEE: extraction and concentration of silver from waste crystalline silicon photovoltaic modules. Waste Manag. 57, 220–225. Available from: https://doi.org/10.1016/j.wasman.2016.03.016.

Duflou, J.R., Seliger, G., Kara, S., Umeda, Y., Ometto, A., Willems, B., 2008. Manufacturing technology efficiency and feasibility of product disassembly: a case-based study. CIRP Ann. 57, 583–600. Available from: https://doi.org/10.1016/j.cirp.2008.09.009.

Huisman, J., Delgado, C., Magalini, F., Kuehr, R., 2008. Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). United Nations University, Bonn, Germany.

IBGE, 2015. Contas Regionais do Brasil: 2015. <www.ibge.gov.br> (accessed 21.07.18.).

IBGE, 2017. IBGE Cidades.

Lundgren, K., 2012. The Global Impact of E-Waste Addressing the Challenge. International Labour Office, Programme on Safety and Health at Work and the Environment (SafeWork), Sectoral Activities Department (Sector)., Geneva.

Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manag. 31. Available from: https://doi.org/10.1016/j.wasman.2010.10.023.

Rodrigues, A.C., Gunther, W.M.R., Boscov, M.E.G., 2015. Evaluation of Waste of Electric and Electronic Equipments Generation From Households: Proposal of Method and Application to the City of São Paulo. Estimativa da geração de resíduos de equipamentos elétricos e eletrônicos de origem domiciliar: Pro. Eng Sanit E Ambient, Brazil, p. 20. Available from: https://doi.org/10.1590/S1413-41522015020000133701.

Rubin, R.S., Castro, M.A.S.D., Brandão, D., Schalch, V., Ometto, A.R., 2014. Utilization of life cycle assessment methodology to compare two strategies for recovery of copper from printed circuit board scrap. J. Clean. Prod. 64. Available from: https://doi.org/10.1016/j.jclepro.2013.07.051.

Santos, M.C., Nóbrega, J.A., Cadore, S., 2011. Determination of Cd, Cr, Hg and Pb in plastics from waste electrical and electronic equipment by inductively coupled plasma mass spectrometry with collision: reaction interface technology. J. Hazard. Mater. 190, 833−839. Available from: https://doi.org/10.1016/j.jhazmat.2011.04.004.

Silva, S.P., Goes, F.L., Alvarez, A.R., 2013. Situação Social das Catadoras e dos Catadores de Material Reciclável e Reutilizável Brasil. IPEA, Brasilia.

Silvas, F.P.C., Jiménez, M.M., Caldas, M.P.K., Moraes, VT De, Espinosa, D.C.R., Tenório, J.A.S., 2015. Printed circuit board recycling: physical processing and copper extraction by selective leaching. 46, 503−510. <https://doi.org/10.1016/j.wasman.2015.08.030>.

Souza, R.G., 2014. Modelling and Sustainability Assessment of Waste Management Systems Based on Multiple Stakeholders' Perspectives. Universidade Federal do Rio de Janeiro.

StEP, 2017. StEP E-Waste World Map. <http://www.step-initiative.org/step-e-waste-world-map.html> (accessed 15.08.17.).

Yamane, L.H., Moraes, V.T. De, Crocce, D., Espinosa, R., Alberto, J., Tenório, S., 2011. Recycling of WEEE: characterization of spent printed circuit boards from mobile phones and computers. Waste Manag. 31, 2553−2558. Available from: https://doi.org/10.1016/j.wasman.2011.07.006.

The impact of waste of electrical and electronic equipment public police in Latin America: analysis of the physical, economical, and information flow

17

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17.1 Introduction

The waste electrical and electronic equipment (WEEE)-stream comes mostly from households rather than from business sector. In the Netherlands only 19% comes from this sector (Huisman et al., 2012) meanwhile in Sao Paulo—Brazil, 30% comes from commercial enterprises (ABDI, 2013); however, in general there is underreporting worldwide, so its exact origin remains uncertain (Baldé et al., 2017). Nowadays, purchasing household appliances increases not only due to basic needs satisfaction but also for comfort seeking in developing countries (Rao & Ummel, 2017). This is reinforced by technological changes, programmed or perceived obsolescence, which make the appliances life shorter and therefore generate more WEEE (Kumar et al., 2017; Wang et al., 2013). Electrical and electronic equipment (EEE) have negative environmental impact at all life cycle phases. While refrigerators have a greater impact in the use stage (Xiao et al., 2015), cell phones have an impact on the production and disposal stages (Yang et al., 2004; Yu et al., 2010; Park et al., 2006) without disregarding its contribution on material extraction, use, and disposal (Yu et al., 2010; Park et al., 2006). Although, disposal is one of the most studied problems in order to reduce its impact and improve the efficiency of resources, including energy (Bian et al., 2016).

Seeking to transform from a linear to a circular economy (CE) one implies to have a wider perspective in mind not only the end of life stage but also whole stages of the life cycle, facing challenges such as waste generation, lack of resources, and sustainable economic benefits for stakeholders (Lieder and Rashid, 2016; Parajuly and Wenzel, 2017; Ghisellini et al., 2016). Different business

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00010-3

models of CE are implemented such as cradle to cradle, take back management like reverse logistic, refurbishment, including resale, repair, deposit system, remanufacturing, and rematerialization including recycling and cascading use (Ellen Macarthur Foundation, 2012; Bakker et al., 2014; EU, 2016; Islam and Huda, 2018).

The extended responsibility of the producer (EPR) (Lindhqvist, 2000) that aims to enhance the circularity of products and materials. EPR arises as one of the cornerstones of the transition toward a CE (Zero Waste Europe, 2017). It is the most applied environmental policy principle in Latin America (OECD, 2014). This principle seeks to assign physical, financial responsibility to the producer because it is able to make changes at the source, bringing strong incentive to reuse, recycle, or dispose products at the end of life (Lindhqvist, 2000; Manomaivibool and Hong, 2014). This principle is made effective through administrative, economic, and informative policy instruments (Tojo et al., 2008), which allow the integral management of the physical, economic, and information flows of WEEE.

In developing countries, household electronic appliances increase with income (Rao and Ummel, 2017). In addition, the amount of WEEE is more directly correlated to country's GDP than to population (Kumar et al., 2017), which implies that socio-economic condition strongly affects the EEE Life Cycle.

In the context of a geographically region, Latin American covers 20 different countries sharing similar socio-cultural features with a population close to 610 million people, representing approximately 9% of the world (World Bank, 2017a,b). The regional average GDP per capita is close to US $12000, considered medium-high, yet it combines three differentiated country groups. A great socio-economic contrast can be observed because some groups have high, others have medium high, and others have low income; this contrast can be a reflex of each country's internal socio-economic structure, evidenced in the average inequality index, which is high, 48 (World Bank, 2015). The final expenditure of households represents 69% of the GDP, an average in global sense. Television is the appliance showing higher penetration followed by the refrigerator, washing machine, stereo system, and the Internet access equipment; the later exhibits a regional penetration of 49.1%, higher than the world average by 5% (ITU, 2017). The regional amount of WEEE generated is 5.3 kg/inh/year, lower than the world average and represents 9% of the worldwide (Baldé et al., 2015).

Around 30% of Latin American countries have WEEE legislation (Baldé et al., 2015; Misiones online, 2017; RELAC, 2017). Notably there is a remarkable subregistry of the generated and recycled amounts because the informal chains prevail in the collection, dismantling, and recycling (Ardi and Leisten, 2016; Cao et al., 2016; Islam et al., 2016; Liu et al., 2016). Latin American legal frameworks are rigid and show lack of integrated, collective, and coordinated management system schemes (GSMA, 2014). In most of Latin America countries, there are no management policies for WEEE or road maps indicating the actions to be taken by the State, involving all stakeholders, to obtain better long-term results (SRI, 2017). Those countries who lead these policies are Colombia, being a pioneer in the establishment of comprehensive WEEE management policy (SRI, 2017; MADS, 2017), Brazil that has established action plans for WEEE and its selective collection and Peru with its WEEE management plans (ITU, 2016).

Other common feature in Latin America is the lack of infrastructure for collection, dismantling, recycling, and recovery of current WEEE, that is, not be sufficient for the increasing amounts of these, which stimulates informality. It is estimated that Brazil loses USD 13 billion annually because of the infrastructure lack to treat solid waste that includes WEEE (GSMA, 2014). The existing collection infrastructure is concentrated in the main cities, covers only up to the preprocessing that involves the dismantling and often does not include mechanical separation. That is why the end-processing technologies that include the pyro/hydro/bio metallurgical treatment and allows the recovery of valuable materials are in foreign hands, associated to the export of circuit cards and other components (MADS, 2017; Kumar et al., 2017).

Given the aforementioned specific characteristics, we want to estimate "what are the impacts of administrative, economic and information policy instruments, on the physical, economic and information flow of WEEE" that produce an increase of valuable, toxic material, and those that go to landfill, as well as energy consumed, to demonstrate the effects at different stages of the life cycle. Including in the panorama that the management policies and plans have been formulated, only in three representative Latin American countries, and considering there is a lack of instruments for its implementation the model contributes to estimate the scenario that gives greater results within the socio-economic context of the region.

Under this perspective, the chapter is structured as follows: Section 17.2 presents the state of the art and shows the analysis of the administrative, economic, and informative policy instruments that have been proposed or used to increase reuse, collection, recycling, and recovery materials, related to the EPR principle and CE. In addition, it explains the use of system dynamics (SD) as an appropriate technique to establish the relationships between the different actors and the policy instruments impact on the variables selected in the different flows. The context describes the situation of three countries in the region that reflect the socio-economic differences and different levels of implementation of legislation, which allow modeling the relevant characteristics.

In Section 17.3, we present the selection criteria that were applied in order to define the appliances to be studied, obtaining five devices: television, refrigerator, computer, cell phones, and light bulbs. In Section 17.4, the simulated management model of WEEE is described together with the physical, economic, and information flows. In Section 17.5, policy instruments are applied to different scenarios and the impact of these is determined in the stages of the life cycle of WEEE.

In the results section the importance of intervening several phases of the life cycle at the same time is highlighted; specifically, in the usage phase three energy efficiency technological changes are modeled in refrigerators and the model determines the impacts on energy consumption and purchase decision of a new ones. Finally, in the last section the conclusions.

17.2 State of the art

17.2.1 Extended responsibility of the producer and EPR policy instruments

CE suggests an economic model regulated according to the laws of the nature, networks of interacting components, exchange of material and energy flows, recycling patterns, and environmental mimicry (Ghisellini et al., 2016). The CE seeks to apply principles to close the loop of products life cycles through greater reuse, recycling, and recover, with the purpose of protecting the environment, resources, and the economy (Lieder and Rashid, 2016). It also aims to extend the lifespan of materials through longer use and the increase of secondary raw materials incorporation (OECD, 2014). This concept is relevant to the WEEE management model because implies a complex mixture of material, some with hazardous content, which can cause major environmental and health problems. Moreover, the production of modern electronics requires the use of scarce resources: around 10% of total gold worldwide is used for EEE production (EC, 2017). EPR is one of the key principles for the transition of the economy circular (Zero Waste Europe, 2017).

EPR has two environmental objectives: one to encourage the eco-design and second to ensure adequate end of life through better collection, treatment, reuse, and recycling. The implementation of EPR in Europe have strengths basically on the improvement of the collection and recycling rates and costs, reduction of the burden on public budgets for municipal. The market and quantity for high quality recovered material has increased, contributing to resource security and potential opportunities to promote the eco-design (Watkins and Pantzar, 2017). EPR is identified as an effective policy instrument to engage producers in the broader efforts on sustainable material management. There are various types of EPR schemes, mandatory and voluntary; assigning the physical, financial, and information responsibility that is made effective through different policy instruments.

In a study made by Tojo et al. (2008), in the European Union the physical responsibility of the WEEE has been differently assumed. By the producer in four countries, by the government in one country, by the producers and traders in five countries, by the traders and the government in ten countries, by the producers, traders, and the government in two countries, and there is not enough information in three of them. In contrast, the producer assumes financial responsibility in eight countries, the producer and traders in five countries, and the traders and the government in six countries.

The policy instruments seeking to increase the waste management efficiency in specific socio-economic contexts have been applied in a regional fashion (see Table 17.1). In the European Union, administrative, economic, and information instruments have been applied (Tojo et al., 2008). In Asia, several policies have been proposed to improve the management of WEEE focused on determining financial and physical responsibility, as well as the incorporation of the informal sector (Yu et al., 2014; Cao et al., 2016; Shinkuma and Huong, 2009; Mashhadi and Behdad, 2017). One of the most relevant policies implemented since 2016 is the Chinese fund policy that states that producers and importers must pay disposal fees,

Table 17.1 Applied, proposed, and needed policy instruments in WEEE.

	Policy instruments/authors	1	2	3	4	5	6	7	8	9	10
Administrative instruments	Substance restriction	x						x			x
	Source separation	x									
	Producers take-back (and emerge internet sales)	x	x				x			x	
	Collection/reuse/collection, recycling/recover targets (and resource scarcity)	x					x		x		x
	Minimum recycled material content standards	x									
	Landfill restriction/diversion targets	x					x				x
	Environmentally sound treatment/disposal standards (included hazardous waste)	x	x	x			x	x	x		
	Track WEEE export at proper recycling facilities				x		x			x	
	More restriction of WEEE trade into bilateral agreements			x			x	x			
	WEEE recycling programs in rural areas			x							
	Role and responsibility of actors (included informal recyclers)						x	x			x
	Reusability index					x					
Economic instruments	Landfill tax	x									x
	Waste Disposal Tax	x			x					x	x
	Recycling Credit Scheme	x	x								
	Subsidies for secondary Materials/ quarry tax	x									
	Pay as you throw	x						x			
	Deposit-refund systems	x	x					x			
	Subsidies to eco-design or incorporate recover material				x		x			x	
	Tax/subside to improve technical progress and recycling rate to recyclers							x	x		
	Governmental responsibility by orphan products		x								
	Funding to infrastructure and human training						x	x	x		
	Waste Tax into the energy consumption bill										x
Informative	Eco-labeling scheme	x									x
	Green shopping guidance	x									
	Marking of products and components	x									
	Information campaign to residents	x		x				x			
	Information to treatment facilities	x						x			
	Transparent data and cost management						x		x		x

Constructed by the authors based on these sources: (1) Tojo et al. (2008); (2) Yu et al. (2014); (3) Cao et al. (2016); (4) Shinkuma and Huong (2009); (5) Mashhadi and Behdad (2017); (6) OECD (2014); (7) Kumar and Dixit (2018); (8) Wang et al. (2018); (9) Gu et al. (2017); (10) This research.

while qualified dismantlers and disposers obtain subsidies under the allocation and supervision of the government but remanufacturing is not included in the agreement. Since 2016, approximately 109 formal WEEE recycling enterprises have obtained official license for the treatment and disposal of WEEE (Liu et al., 2017). The effects of this policy have been studied by Zhou et al. (2017), Gu et al. (2016), Gu et al. (2017), Liu et al. (2016), Li et al. (2017), and Wang et al. (2018). It has enhanced the competitive advantage of formal recyclers, although informal recyclers, besides promoting the healthy development of WEEE recovery industry, dominate the market (Liu et al., 2016; Zhou et al., 2017). In Chile, the fund for recycling was created, with educational purposes for the citizens, the scavenger, and the infrastructure (MMA Chile, 2017).

These policy instruments must resolve what other authors have identified as barriers: policies and regulation, infrastructure, knowledge, socio-economic, socio-cultural, technological, and financial barriers (Kumar and Dixit, 2018). Also, challenges and constraints of EPR and general implementation are an unclear role and responsibilities of the actors, lack of data, free-riders, lack of enforcement mechanism, lack of collective schemes, lack of incentive of environmental design, unknown disposal cost, informal sector, recycling and material recovery targets, and the auditing and compliance of material flows within the system (OECD, 2014; Morris and Metternicht, 2016; Islam and Huda, 2018). In the same Table 17.1, the instruments that will be simulated in the different scenarios are shown, which will be discussed in Section 17.5.

17.2.2 System dynamics

SD as a simulation technique allows to model complex, closed-cycle systems and analyze the variables and implications for the system (Sterman, 2000), which is why it has been applied in several environmental, economic, and social studies (Ardi and Leisten, 2016; Georgiadis and Vlachos, 2004). SD has a qualitative and quantitative approach. The scope of the system, the variables and their relationship make up the causal loops diagram (Sterman, 2000), which represents the real model. Through arrows, the causality between the variables is shown and positive circularity is formed when the variables go in the same direction, in contrast, the negative sign in loop variables generate the balance of the system. In addition, stock and flow diagram is established (Sterman, 2000), where stocks are accumulators that are influenced by flows, as well as connectors and auxiliary variables. The quantitative approach is carried out through computer simulation models with specialized software, in this case Vensim, which generate results that are studied in the analysis phase through different "*what if*" scenarios that allow to reduce the uncertainty in the decision-making throughout the simulation period.

Several studies have applied SD with various purposes associated with changing the behavior toward recycling, including the informal population, determining policy impacts, and closing material cycles. Specifically, Georgiadis and Vlachos (2004) studied the impact of the environmental policy and the corporate image of environmental practices on market behavior. Spengler and Schröter (2003) and Georgiadis and Besiou (2008, 2010) studied EEE using SD to investigate closed-loop material flows, focused on supply chain management and the influence of consumer behavior. Besiou et al. (2012) studied the impact of the waste picker's activities in the WEEE recovery system using the environmental, economic, and social dimensions of sustainability. Nguyen et al. (2015) understand smartphone usage in Singapore by exploring the leverage points and resistance to change. Ardi and Leisten (2016) assessed the role of informal sector in WEEE management system. Sinha et al. (2016) modeling approach investigated the dominant paths and drivers for closing the metal flow loop through the concept of eco-cycle in the global mobile phone product. Rodríguez et al. (2013, 2015) and Rodríguez and Estupiñán (2018) applied different policies in the life cycle of EEE in order to reuse, recycling, and recover more materials. Fan et al. (2018) predicted the recycling behaviors of various user groups using the E-waste recycling in Taiwan. Yao et al. (2018) explored the influences of different recycling scenarios for mobile phone in China.

17.3 Contextualization and electrical and electronic equipment scope

In Latin America, socio-economic differences are wide, so, putting into context three different studies reflecting the reality of the region is proposed, namely, Sao Paulo, Bogotá, and La Paz. Brazilian city is the most populated of the country; Colombia and Bolivia cities were selected due to their importance in the country's economy, and the most representative characteristics are shown in Table 17.2. These cities were determined because of their different levels of informality in the management of WEEE; besides the actors and the physical, economic, and informative responsibilities are differentiated and diverse; therefore in these context the modeling results distinguishes the best policies.

Several Latin American countries have implemented primal EPR schemes, especially those that are part of the OECD: Chile, Mexico, and Brazil. In addition, Argentina and Colombia have also worked on EPR schemes (OECD, 2014). Countries like Bolivia, Costa Rica, Ecuador, Guatemala, Panama, Peru, and Uruguay follow those implementation efforts. Countries studying or promoting its application are El Salvador, Honduras, Nicaragua, Paraguay, and the Dominican Republic. Most of these initiatives are motivated on achieving development plans, climate change, and sustainable development goals (RELAC, 2017). Likewise, only regulatory policy instruments are applied and express the need for economic and informative instruments (OECD, 2014), since physical and financial responsibility is still more alongside the government.

In Latin America due to socio-economic conditions, the decision to dispose of EEE is postponed, so they are stored in households or sent to reuse, due to the perceived material value by users. Once the disposal decision is made, preference is given to the informal channel, since the consumer has little information about the formal recycling options and formal infrastructure lacks nearby disposal places (MADS, 2017). In addition, the informal sector often offers economical retribution

Table 17.2 Characteristics of countries studied.

Representative country	Brazil	Colombia	Bolivia
City studied(Population 2017)	Sao Pablo(12,106,920)	Bogotá(8,181,047)	La Paz(1,890,000)
GDP miles of millions US$ (World Bank, 2017a).	High(more US$17,836)	GDP medium high(US $17.836–US$10,000)	GDP medium(less US $10,000)
Similar GDP countries (World Bank, 2017b).	Argentina, Brazil, Chile, Costa Rica, Panamá, and Uruguay	Colombia, Ecuador, México, Perú, República Dominicana, and Uruguay	Bolivia, El Salvador, Guatemala, Haití, Honduras, Nicaragua, and Paraguay
Informal economy (Americas Society, 2015)	36.5%	54.5%	70%
WEEE Generation 2014 (Balde et al., 2017)	7.0 kg/inh/year1412 kt/year	5.3 kg/inh/year252 kt/year	4.0 kg/inh/year45 kt/year
WEEE Legislation	National Policy on Solid Waste (Law 12.305/2010). Decree 9.177/2017 Compulsory Reverse logistics (Brasil, 2010).	WEEE National Policy. Law 1672/2013 and decree 284 of February 2018 (SIR, 2017)	Integral Waste Management Law 755/2015. Supreme Decree 2954/2016
WEEE infrastructure	38 Licensed Recycler, 4 Hazardous waste treatment, 16 Informal Recycler, 10 Technical assistances, 13 Scrap metal, 6 Sale of used, 2 Recycling store (MDIC, 2017)	36 WEEE Managers with license and 13 managers export (MADS, 2017)	ONG Fundare y Fundación Viva, 5 operators (Fundación viva, 2017)
Physical and Economic Responsibility	Government(ABDI, 2013; MDIC, 2017)	Government and private Company through the postconsumer programs.	Government initiatives, NGOs and private companies
Energy Efficiency policy instruments (BID, 2015)	Ecolabels from 1984Dec 132/2006 to illumination	Voluntary Ecolabel from 2000. Obligatory from 2015 (Ley 1715/2015)	The government delivered efficient bulbs in 2008) (Greenpeace, 2010)

Table 17.3 Criteria for selecting the study EEE.

EEE	Penetration in homes	Technological change	Hazardous materials	EEE weight (kg)	Valuable materials with high demand
TV	High	High	High	Medium	High
Fridges	High	High	High	High	Low
Computers	Medium	High	Low	Medium	High
Mobile	High	High	Low	Low	High
Light Bulbs	High	High	High	Low	Low

Constructed by the authors based on these sources: DANE (2017); Delfín et al. (2009); MDIC (2017); ABDI (2013); Grant Thorton (2011); EU (2011); Wang (2014); Cucchiella et al. (2015); Zhang et al. (2017); Chancerel et al. (2015); Van Eygen et al. (2016).

in exchange for WEEE and picks them up door-to-door. Nevertheless, more than recycling there is dismantling, yet the lack of recovery standards affects the health and environment (de Oliveira et al., 2012; Ghisolfi et al., 2017). The informal sector has an advantage because it avoids formalization costs and extracting the materials requires less technification. Colombia and Bolivia informal data are inaccurate. Brazil exhibits the following figures: collection from households is 50% informal, 15% public, 2% formal, and 33% falls into reuse. In contrast, those who come from companies have a higher proportion of 62% reuse and informality falls to 19%, formal increases to 5% and public is 14% (MDIC, 2017).

Household EEE somehow reflects the socio-economic differences of the region, so they are selected according to the following criteria: (1) the EEE household penetration is high when it is greater than 70%; (2) technological change is high when there is functionality or energy consumption innovation in a period shorter than the device's useful life; (3) hazardous materials are high if they are part of the substance of ROHS Directive (Pb, Hg, Cd, Cr^{6+}, PBB, BDE, DEHP, BBP, DBP, DIBP) (EU, 2011); (4) product's weight is high if greater than 40 kg and is low if less than 3 kg (Wang et al., 2013); and (5) quantity and demand of valuable materials is high when any of the 78 fundamental raw materials are found among their components (EC, 2017). Specially Co, Ga, In, Ta, Au, Pd, Ag, and REE and whose demand is greater than 30% relative to world mining production (Zhang et al., 2017), or metal has a concentration greater than 0.25 g per unit of product (Cucchiella et al., 2015). The application of these criteria is shown in Table 17.3.

17.4 Model

Three base models are simulated independently to model each country characteristics. Model includes the retailing, use, and end of the life cycle stages of the EEE, as shown in Fig. 17.1. The causal diagram allows visualizing how the variables of

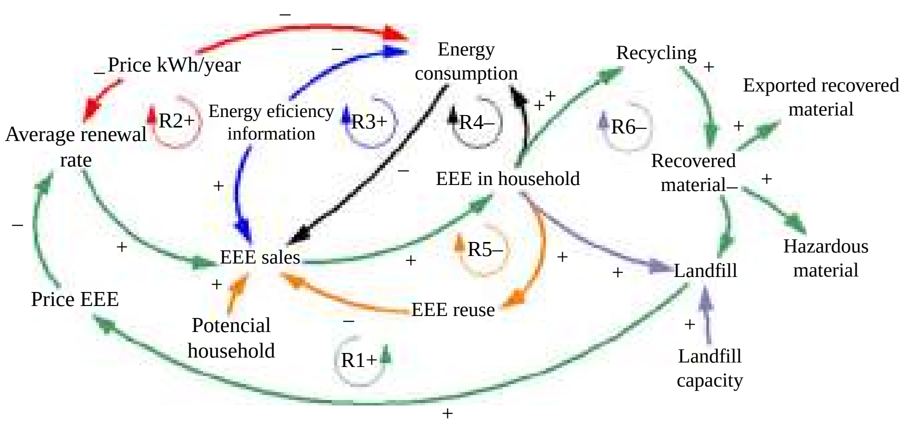

Figure 17.1 Causal loops diagram of EEE in stage marketing, use, and end of life.

the WEEE management system are related and it represents the real situation through the most significant variables. This has four basic elements: the variables, the relationship between these, represented through an arrow, the arrow direction from the cause to the effect and the sign of the loop that shows the positive or negative relationship between the variables. Fig. 17.1 shows six loops or closed cycles of interrelation between the variables. The R1 green cycle shows that an increase in EEE sale, there would be more EEEs in households. Therefore there will be more quantities for recycling and thus greater opportunity to recover material, so less material will go to the landfill and therefore its capacity will be exhausted. Thus, the WEEE tax is increased and the price of the new EEA increases, so that the rate of renewal of new equipment is lower and whenever this rate increases, the sales will be higher. Moreover, since there is a positive relationship between the variables, then the loop is positive. The R2 red loop is associated with energy prices, R3 blue for energy efficiency information, R4 black for energy consumption, R5 yellow for reuse, and R6 purple for recycling. These relationships are explained in the physical, economic, and information flow, which are described below.

The simulation scope covers a 40-year horizon, starting in 2001. These flows are affected with different policy instruments to see their influence on the outcome variables.

17.4.1 Physical flow

The physical flow shows the EEE forward movement through the stages: production, use, and up to the end as WEEE. In the production stage, data production, imports and exports data are obtained mostly from the Trade Map platform and from national statistical institutions in each country: IBGE (Brazil), DANE (Colombia), and INE (Bolivia). Households EEE in use are determined by the penetration rate, households that acquire EEE for the first time, households that renew the EEE by perceived obsolescence or by programmed obsolescence and also by those repaired, donated, thus extending their useful life. 30% of household appliances and some light bulbs contemplate reuse. The WEEE stock contemplates the formal and informal channel, and their ability to retrieve material is differentiated. The recovered materials can be incorporated into the productive cycle, guaranteeing a CE.

17.4.2 Economic flow

When the EEE average renewal rate is estimated, socio-economic aspects of each country are taken into account, as this depends on the price, the cost of repair in case of minor damage, the purchasing power determined by household income and finally access to financing or discounts that can be provided either by retailers or financial institutions. Another involved economic variable is an ex ante tax on the consumer for EEE disposition, which value is adjusted according to the excess capacity of the sanitary landfill.

Brazil is the unique country with available collection costs and WEEE dismantling information, as shown in Table 17.4. A clear difference is made for medium-sized EEE that are collected in a consolidation center (CC) by traders and then taken to dismantling plants, while large EEE also have the option to go to dismantling directly from the consumer.

The energy cost is a factor that could affect the purchase decision and consumer usage habits, which is directly reflected in the electricity consumption bill. When the energy cost increases, the user is willing to make changes in his consumption habits or even looks for more energy-efficient EEEs.

17.4.3 Information flow

Aiming to achieve full-informed consumer's decision-making when purchasing or renewing appliances, energy efficiency labels were defined as an informative tool.

Table 17.4 Unit costs of WEEE disposal (US$/ton).

Costs	Medium, with CC	Large, without CC	Large, with CC
Primary transportation	479.3	1010.4	414.5
Separation and storage	362.7	0.0	272.0
Secondary transportation	90.7	0.0	129.5
Dismantling	621.8	440.4	440.4
Public relations	25.9	25.9	25.9
Data monitoring	25.9	25.9	25.9
Total	1606.2	1502.6	1308.3

Convention: 1US$: 3.86 $Real, CC.
Source: Adapted from Agência Brasileira de Desenvolvimento Industrial (ABDI), 2013. Logística Reversa de Equipamentos Eletroeletrônicos Análise de Viabilidade Técnica e Econômica. Retrieved from: <https://corporativo.abdi.com.br/conhecimento/Publicaes1/Log%C3%ADstica%20reversa%20de%20Equipamentos%20Eletroeletr%C3%B4nicos%20-%20res%C3%ADduos.pdf>.

In the European Union, the scale goes from A +++ to C, in accordance with Directive 2010/30/EU; in North America it is determined by Energy Star, and in Brazil and Colombia the scale goes from A to G, and Bolivia still does not have this instrument yet (IDB, 2015). Three categories were defined for the simulation model: T1 with a consumption of (+59%) with respect to type T2, which has average values and T3 with consumption of (−42%).

17.4.4 Validation

The model is validated through comparison with secondary information used for the first 15 years. Raw data come from different studies and sources related in Table 17.2; additional sources are used in the description of the model. Informal sector information sources are very descriptive since it represents the majority of the sector but not accurate. Once governmental global and the formal sector data is acquired, an estimate of the informal sector is obtained as the complementary of the formal. Likewise, dimensional consistency is performed; parameters verification was cross-checked with real data to observe their consistency and additional simulations with extreme data were made finding a logical behavior of the system.

17.5 Scenarios

Six scenarios were simulated with different policy instruments in order to discern the impacts of these in the amount of TV, fridges, computers, mobile, and light bulbs in use; energy consumption, landfill material, recovered material, and hazardous material. Those scenarios are selected because they implement the more applied, proposed, and needed policy instruments in WEEE related in Table 17.1.

17.5.1 Scenario 1: prohibition of hazardous substances

Different authors considered that more than 3% of the WEEE components are hazardous (Zhang et al., 2017; Cucchiella et al., 2015). Fluorescent luminaires contain mercury and according to the Minamata Convention that came into force in August 2017, "there should be no processes that use mercury", and although many Latin American countries have not signed yet, there are specific laws that eliminate their use by 2026 (MCIT, 2017). Likewise, refrigerators contain gases that deplete the ozone layer and generate high environmental impact. According to the Montreal Convention, by 2020, the use of HCFCs must be reduced by 99.5% and eliminated by 2030 (UNEP, 2006), which will be reinforced by the Kigali amendment.

17.5.2 Scenario 2: improvement in the collection and recovery

Seeking to overcome the infrastructure barriers, the nonincorporation of the informal sector, the lack of collection and recovery goals, policy instruments such as funds for infrastructure and education are established in this scenario. As well as the determination of the each role responsibilities of the actors facing the physical, economical, and information flow, the latter two being poorly developed, so the current baseline is not known with certainty. The implementation of these administrative and economic instruments will achieve improvements in the collection of 50% and in the recovery of 40% for Brazil, which are different for the other countries, since their baselines are different. Thus, Colombia will increase the collection up to 45% and recovery up to 30%, and Bolivia would achieve 15% in collection and 30% in recovery.

17.5.3 Scenario 3: energy efficiency

Brazil has energy efficiency labels since 1984. In 2006, interministerial ordinances determined minimum efficiency values for compact fluorescent lamps, in 2007 for refrigerators, and in 2010 for incandescent lamps (Cepal, 2015). In 2000, Colombia introduced voluntary labeling and in 2015 mandatory national labeling regulation (IDB, 2015). On the other hand, Bolivia has not implemented this initiative to empower the user at the purchasing time. This information policy instrument covers the refrigerator, since it is responsible for more than 30% of consumption in a household (UPME, 2006). The aim is that users move from a less efficient to a more efficient technology.

17.5.4 Scenario 4: increase in the price of energy

Historically, in times where energy consumption is greater than supply, energy rationing is generated: in Brazil, it occurred in 2001 (Cepal, 2015); in Colombia, it happened in the period 1993 (UPME, 2006). In Bolivia in 2008, the government bought and delivered efficient lighting to reduce consumption (Greenpeace, 2010). In these periods, the value of kW/h increases to discourage consumption, so in this scenario this economic policy instrument is applied, and the KWh is increased by 20%.

17.5.5 Scenario 5: end of life tax

In order for the user disposes the WEEE through the formal channel, he must pay an ex ante tax when he buys the new EEE. At the time the WEEE is delivered, the user receives a discount voucher for the next purchase. The value of the tax can be increased according to the available capacity of the sanitary landfill, which although it is currently prohibited to receive WEEE in most countries, this is still happening (IDB, 2013). The model estimates the depletion of the capacity of the landfills of Sapopemba, Doña Juana, and Alpacoma in 2043, 2037, and 2025, respectively.

17.5.6 Scenario 6: synergy of all the previous instruments

Given that policy instruments are applied in different stages of the life cycle, synergy is expected when these are applied together. The substance restriction acts in the design of the product and the improvement in the collection and recovery of materials. Although it implies the intervention in different stages of the life cycle, it centers its results in the end-of-life. Likewise, energy efficiency and increase in the price of energy applies in the use phase.

17.6 Results and discussion

Table 17.5 shows the application results of the different scenarios. The variation with respect to the base scenario is shown.

The model indicates that the policy instruments generating the best results in the recovery of materials are those aiming to obtain end-of-life results, which are applied in the E2 scenario. It allows increases between 6.4% and 10.9%. This scenario is the one that allows the greatest collection of hazardous material and the one that reduces the material that reaches the landfill. In Bolivia, higher results are achieved in relation to the baseline, given that it is the country with a more incipient base.

One of the instruments that generates most change in energy consumption is the energy efficiency labels E3, which although in this case only applies to refrigerators, allows intratechnological mobilization, that is, the user makes an informed decision at the time purchase and acquires a new refrigerator more efficient than the one he owned. Likewise, the increase in the price of kWh, E4, generates a reduction in consumption, but it is minimal in relation to that obtained by energy efficiency labels. Indirectly restricting hazardous substances (HCFC and Hg) that are present in the refrigerators and light bulbs, makes the consumer look for the change of EEE and contributes to a rational decision of buying those available with greater efficiency. The result of the scenario allows the greatest reduction in energy consumption, since it not only includes refrigerators but also light bulbs. Bolivia is the one to achieve greater reductions over the 40 years, since it is considered that in the baseline it had less efficient technologies than Colombia and Brazil. Nevertheless, all countries have the same tendency to reduce consumption when applying the policies.

The substances prohibition, E1, increases the EEE in use, since the user perceives the need for change and applies the perceived obsolescence, despite the fact that the programmed goods obsolescence may be greater. In this way, it generates a reduction in the lifetime of the EEE, increases the amount of WEEE, therefore increases the material recovered, and increases the material in the landfill, as the recovery processes are not completely efficient. The low technification implies that the hazardous material that is recovered is relatively low. This phenomenon, where perceived obsolescence takes precedence over the programmed one, is accentuated in the scenario of an increase in energy prices, where the EEE in use increase up to 2.9%. This fact is more visible in Brazil because its population has a greater purchasing power, which means that the speed of replacement is greater.

The scenario E5, where the tax for the adequate disposal of WEEE is introduced, generates a decrease in the acquisition of EEE by up to 3.5% and causing a slight

Table 17.5 Results of scenarios in countries of study.

Country	Scenario	Light bulbs in use (%)	EEE in use (%)	Total energy (%)	Material in landfill (%)	Recovered material (%)	Hazardous material (%)
Brazil	E1	0.1	0.4	− 7.6	6.5	7.2	0.5
	E2	0.0	0.0	0.0	− 2.1	8.9	6.9
	E3	0.0	0.8	− 6.4	5.9	6.5	0.5
	E4	2.9	2.9	0.1	17.1	16.1	13.9
	E5	0.0	− 2.2	− 0.8	− 0.5	− 0.4	− 0.5
	E6	3.2	0.5	− 7.6	20.0	33.3	21.4
Colombia	E1	0.1	0.7	− 8.8	3.3	3.5	0.5
	E2	0.0	0.0	0.0	− 1.5	6.4	3.5
	E3	0.0	0.9	− 7.4	2.7	2.9	0.4
	E4	2.3	2.4	− 0.3	16.6	16.0	9.3
	E5	0.0	− 3.1	− 0.9	− 0.3	− 0.4	0.0
	E6	0.6	− 0.6	− 9.8	16.3	25.3	13.2
Bolivia	E1	0.3	0.5	− 11.5	8.6	5.8	1.4
	E2	0.0	0.0	0.0	− 1.1	10.9	10.9
	E3	0.0	1.7	− 7.9	7.5	5.0	1.2
	E4	1.7	0.9	− 0.2	12.5	5.3	3.4
	E5	0.0	− 3.5	− 1.2	− 0.6	− 0.4	− 0.2
	E6	2.1	− 2.8	− 12.5	17.9	23.6	15.7

reduction for landfill, recovered, and hazardous material. Bolivia is the country most susceptible to the result of increasing the price of acquisition of the good by the tax, associated with having a lower socio-economic condition and greater restriction in the sanitary landfill.

Best results of the model are obtained in the scenario where all the simulated policy instruments intervene, E6, since each of these generates impacts in different stages of the life cycle of the EEE. It is possible to recover material between 216% and 395% higher than the best individual scenario E2, likewise higher hazardous material is recovered, between 44% and 377% of the baseline. Unfortunately, the material that reaches the landfill grows a lot, which is why it is necessary to increase the efficiency of the recycling and recovery processes. In the synergy scenario, energy consumption is similar to the E1 scenario, which implies that if energy efficiency labels are introduced for other EEE not only for fridge, energy consumption would decrease even more. Therefore it would be better to include other EEE that have an important energy consumption, associated to the penetration at homes and the hours of use, like the TV sets.

It must be guaranteed that higher efficient EE are found in the market so that the change generates improvement. Therefore the policies should be aimed at the design, not only focused on energy consumption, but on the ease of disassembly, hazardous, scarce and valuable materials recovery, parts replacement, replacement and reduction of polluting substances, and reduction of the amount of material used. That is, encourage eco-design, with policies that have worked or would work in the long term (Gottberg et al., 2006; Dalhammar, 2016), reaffirming the opportunity for an EPR stronger and broader implementation (Watkins and Pantzar, 2017).

The flow of information is necessary for the control of the physical and economic flow, and must cover all the actors involved in the management system, with the purpose of monitoring, measuring, analyzing, and evaluating the system. Then, continuous improvement associated to the obtained results, anticipating decisions of reinforcement or change will be enabled. This will eliminate underreporting and the continued effort to obtain real data from the physical flow and in contrast, the information system will guarantee quantitative, continuous, timely, and reliable information, achieving benefits such as those proposed in the two cases of study in China (Sun et al., 2018).

The instruments, proved by the model, to adopted the EPR in Latin America are the prohibition of hazardous substances, securing funds for infrastructure, imposition of collection and recovery targets, definition of the roles and responsibilities of the actors in the physical, economic and information flow, as well as, energy efficiency labels and the end of life tax. These instruments ratify the advantages achieved in Europe by applying EPA schemes as they state by Watkins and Pantzar (2017). In addition, the dynamic model is robust because in its scope it contemplates the TV, fridge, computer, mobile, and light bulbs, take into account different stage of the life cycle, the behavior of the user, and the informality of the system. For that reason, this SD model shows more complexity and it is better describes the reality than previous studies.

Moreover, once its successful implementation is achieved, there will still be many orphan products, generated by old brands that have been kept at households, discontinuance of EEE assembling brands or because it is not within the scope determined by the producers, so it will be the government who must determine if it will assume such responsibility. Leaving this issue pending to study.

The informal sector should be incorporated in the collection and not necessarily in the WEEE pretreatment and treatment, given the technology levels and cost involved in recovery industries. Therefore policies should prefer specialized promoters with high technological capacity of recovery and installed capacity. Therefore the informal sector should be incorporated in the collection processes, favoring their expertise and taking advantage of the high collection rate by offering money to the user in exchange for WEEE and the opportunity of door-to-door collection (Besiou et al., 2012; Ardi and Leisten, 2016; Ghisolfi et al., 2017). In addition, given the level of informality of the regional economy, this alternative would guarantee recoverers formalization, emulating the formalization of the recovered solid waste that was made in Bogota, thus guaranteeing social results (Rodríguez et al., 2016). Actions that must be deepened through more specific studies.

Keeping the aim on the CE it is necessary to carry out studies in reuse, given the socio-economic context of the population, which generates great social, economic, and environmental benefits. For the model, a reuse of 30% was simulated, but this figure is higher when considering WEEE coming from business and not only from households. In addition, jobs generated by repair or revision and adaptation schemes for reuse must be considered.

17.7 Conclusions

An information flow of the EEE management system is required to control the physical and economic flow. In addition, the application of a set of policy instruments, recognizing that priority must be those that favor the development of a technological infrastructure to achieve higher rates of recovery of materials, the recoverers' formalization and their specialization in the collection processes, taking advantage of their expertise. Besides, the incorporation of energy efficiency labels in the use in EEE of higher energy consumption, penetration, and use in homes. In addition, formalizing the reuse due to the social progress could provide and above all stimulate the eco-design actions of products to strengthen the other stages of life cycle. The information system will allow quantified real information of the economic, social, and environmental benefits but not only projected data.

In order to obtain the benefits of the EPR and CE, the need for collaborative work among all actors is recognized, especially from the producers. In addition, the differences between the behavior of the different countries analyzed is given by the socio-economic characteristics that impact the replacement speed of the devices, the higher the income, the greater the change and the generation of WEEE, and the technological infrastructure. However, for the remaining aspects, the trends are the same, considering that there are different levels of maturity in the region, but the same solutions are required. Noting that countries that have had successful initiatives they influence of others in the region. Thus it can be inferred that the same policy instruments work but their results are differentiated by initial conditions and socio-economic differences.

It is recommended to model other policy instruments that enhance reuse, design, and all preventive actions that may affect the first stages of the EEE life cycle, as well as analyzing the impact of these policies in rural areas, whose socio-cultural and economic conditions are different. Using the SD model guarantees the circularity of the variables that represent the real world and allows a multipurpose analysis taking into account the different actors.

References

Agência Brasileira de Desenvolvimento Industrial (ABDI), 2013. Logística Reversa de Equipamentos Eletroeletrônicos Análise de Viabilidade Técnica e Econômica. Retrieved from: <https://corporativo.abdi.com.br/conhecimento/Publicaes1/Log%C3%ADstica%20reversa%20de%20Equipamentos%20Eletroeletr%C3%B4nicos%20-%20res%C3%ADduos.pdf>.

Americas Society - Council of the Americas - AS COA, 2015. Weekly chart: Latin America's informal economy. Retrieved from: <http://www.as-coa.org/articles/weekly-chart-latin-americas-informal-economy>.

Ardi, R., Leisten, R., 2016. Assessing the role of informal sector in WEEE management systems: a system dynamics approach. Waste Manag. 57, 3–16.

Bakker, C., Wang, F., Huisman, J., Hollander, M. Den, 2014. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The global e-waste monitor – 2014. United Nations University, IAS – SCYCLE, Bonn, Germany.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global E-Waste Monitor – 2014. United Nations University, IAS – SCYCLE, Bonn, Germany.

Baldé, C.P., Forti V., Gray, V., Kuehr, R., Stegmann,P. 2017. The Global E-waste Monitor – 2017, United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna.

Besiou, M., Georgiadis, P., Wassenhove, L.N.V., 2012. Official recycling and scavengers: symbiotic or conflicting? Eur. J. Oper. Res. 218 (2), 563–576.

Bian, J., Bai, H., Li, W., Yin, J., Xu, H., 2016. Comparative environmental life cycle assessment of waste mobile phone recycling in China. J. Clean. Prod. 131, 209–218.

BID, 2015. Guía E. Programas de Normalización y Etiquetado de Eficiencia Energética. Retrieved from: <https://publications.iadb.org/bitstream/handle/11319/7326/Guia-E-programas-%20normalizacion-etiquetado-eficiencia-energetica.pdf?sequence = 1>.

Brasil, 2010. Decreto n° 7.404, De 23 De Dezembro De 2010. Regulamenta a Lei n°12.305, De 2 De Agosto De 2010. Política Nacional de Resíduos Sólidos. Official Retrieved from: <http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/Decreto/D7404.htm>.

Cao, J., Lu, B., Chen, Y., Zhang, X., Zhai, G., Zhou, G., et al., 2016. Extended producer responsibility system in China improves E-waste recycling: government policies, enterprise, and public awareness. Renew. Sustain. Energy Rev. 62, 882–894.

Cepal, 2015. Informe nacional de monitoreo de la eficiencia energética del Brasil. Retrieved from: <https://repositorio.cepal.org/bitstream/handle/11362/38863/1/S1500636_es.pdf>.

Chancerel, P., Marwede, M., Nissen, N.F., Lang, K.D., 2015. Estimating the quantities of critical metals embedded in ICT and consumer equipment. Resour. Conserv. Recycl. 98, 9–18.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future E-waste streams. Renew. Sustain. Energy Rev. 51, 263–272.

Dalhammar, C., 2016. Industry attitudes towards ecodesign standards for improved resource ef fi ciency. J. Clean. Prod. 123, 155–166.

DANE, 2017. Encuesta Nacional de Calidad de Vida. Retrieved from: <https://www.dane.gov.co/files/investigaciones/condiciones_vida/calidad_vida/Boletin_Tecnico_ECV_2017.pdf>.

Delfín, M., Guzman, D., Garay, E., Yañez, P., Delfín, M., 2009. Diagnóstico de Residuos Electrónicos en Bolivia. Retrieved from: <http://www.residuoselectronicos.net/archivos/panama/fichasasistentes/FICHAS%20PDF/0904_DiagnosticoRAEE_%20Bolivia.pdf>.

EC, 2017. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU. Retrieved from: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri = CELEX:52017DC0490>.

Ellen Macarthur Foundation, 2012. The Circular Economy System Diagram. Retrieved from: <https://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram>.

EU, 2011. Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment Text with EEA relevance. Retrieved from: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri = celex%3A32011L0065>.

EU, 2016. Closing the loop: new circular economy package. Retrieved from: <http://www.europarl.europa.eu/RegData/etudes/BRIE/2016/573899/EPRS_BRI(2016)573899_EN.pdf>.

Fan, C., Fan, S.K.S., Wang, C.S., Tsai, W.P., 2018. Modeling computer recycling in Taiwan using system dynamics. Resour. Conserv. Recycl. 128, 167–175.

Fundación Viva, 2017. Reciclaje de Residuos Eléctricos y Electrónicos. Retrieved from: <https://fundacionviva.org/memorias/2017/Memoria_FVIVA17-WEB.pdf>.

Georgiadis, P., Vlachos, D., 2004. The effect of environmental parameters on product recovery. Eur. J. Oper. Res. 157 (2), 449–464.

Georgiadis, P., Besiou, M., 2008. Sustainability in electrical and electronic equipment closed-loop supply chains: a system dynamics approach. J. Clean. Prod. 16 (15), 1665–1678.

Georgiadis, P., Besiou, M., 2010. Environmental and economical sustainability of WEEE closed-loop supply chains with recycling: a system dynamics analysis. Int. J. Adv. Manuf. Technol. 47 (5–8), 475–493.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32.

Ghisolfi, V., De Lorena, G., Chaves, D., Ribeiro, R., Helena, L., 2017. System dynamics applied to closed loop supply chains of desktops and laptops in Brazil: a perspective for social inclusion of waste pickers, 60, 14–31.

Gottberg, A., Morris, J., Pollard, S., Mark-Herbert, C., Cook, M., 2006. Producer responsibility, waste minimisation and the WEEE Directive: case studies in eco-design from the European lighting sector. Sci. Total Environ. 359 (1–3), 38–56.

Grant Thorton, 2011. Estudo de viabilidade. Viabilidade técnica económica em logística reversa na organizacao da colecta e reciclagem de residuos de lampadas no Brasil.

Greenpeace, 2010. Análisis de Derecho Comparado sobre la Prohibición de Focos Incandescentes. Retrieved from: <http://www.greenpeace.org/mexico/global/mexico/report/2010/3/derecho_comparado.pdf>.

Gu, Y., Wu, Y., Xu, M., Wang, H., Zuo, T., 2016. The stability and profitability of the informal WEEE collector in developing countries: a case study of China. Resour. Conserv. Recycl. 107, 18–26.

Gu, Y., Wu, Y., Xu, M., Wang, H., Zuo, T., 2017. To realize better extended producer responsibility: redesign of WEEE fund mode in China. J. Clean. Prod. 164, 347–356.

GSMA, 2014. eWaste en América Latina. El aporte de los operadores móviles en la reducción de la basura electrónica—Estudio de casos.

Huisman, J., van der Maesen, M., Eijsbouts, R.J.J., Wang, F., Baldé, C.P., Wielenga, C.A., 2012. The Dutch WEEE Flows. United Nations University, ISP – SCYCLE, Bonn, Germany.

Islam, M.T., Abdullah, A.B., Shahir, S.A., Kalam, M.A., Masjuki, H.H., Shumon, R., et al., 2016. A public survey on knowledge, awareness, attitude and willingness to pay for WEEE management: case study in Bangladesh. J. Clean. Prod. 137, 728–740.

International Telecommunication Union – ITU, 2016. Sustainable management of waste electrical and electronic equipment in Latin America. Retrieved by <https://www.itu.int/en/ITU-T/climatechange/Pages/publications.aspx>.

International Telecommunication Union – ITU, 2017. Country ICT Data (until 2016). Percentage of individuals using the Internet. Retrieved from: <https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx>.

Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment (WEEE)/E-waste: a comprehensive literature review. Resour. Conserv. Recycl. 137 (May), 48–75.

Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32–42.

Kumar, A., Dixit, G., 2018. Evaluating critical barriers to implementation of WEEE management using DEMATEL approach. Resour. Conserv. Recycl. 131, 101–121.

Li, Y., Xu, F., Xiong, Z., 2017. Governance mechanisms of dual-channel reverse supply chains with informal collection channel. J. Clean. Prod. 155, 125–140.

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51.

Lindhqvist, T., 2000. Extended producer responsibility in cleaner production. IIIEE Dissertation 2000:2. Lund: IIIEE, Lund University.

Liu, H., Lei, M., Deng, H., Keong Leong, G., Huang, T., 2016. A dual channel, quality-based price competition model for the WEEE recycling market with government subsidy. Omega 59, 290–302.

Liu, Z., Tang, J., Li, B. yi, Wang, Z., 2017. Trade-off between remanufacturing and recycling of WEEE and the environmental implication under the Chinese fund policy. J. Clean. Prod. 167, 97–109.

Manomaivibool, P., Hong, J.H., 2014. Two decades, three WEEE systems: how far did EPR evolve in Korea's resource circulation policy? Resour. Conserv. Recycl. 83, 202–212.
Mashhadi, R.A., Behdad, S., 2017. Optimal sorting policies in remanufacturing systems: application of product life-cycle data in quality grading and end-of-use recovery. J. Manuf. Syst. 43, 15–24. Available from: http://doi.org/10.1016/j.jmsy.2017.02.006.
Ministério da Indústria, Comércio Exterior e Serviços – MDIC, 2017. Projeto para a Melhoria da Logística Reversa de Resíduos Elétricos e Eletrônicos (REEE) no Brasil.
Ministerio de Ambiente y Desarrollo Sostenible – MADS, 2017. Política nacional para la gestión integral de los residuos de aparatos eléctricos y electrónicos (RAEE), Bogotá, Colombia.
Ministerio de Comercio, Industria y Turismo - MCIT, 2017. Decreto 2133 de 2016. Control a la importación y comercialización de mercurio y los productos que lo contienen. Retrieved from: <http://es.presidencia.gov.co/normativa/normativa/DECRETO%202133%20DEL%2022%20DE%20DICIEMBRE%20DE%202016.pdf>.
Ministerio Medio Ambiente- MMA Chile, 2017. Reglamento del Fondo para el Reciclaje. Retrieved from: <http://portal.mma.gob.cl/transparencia/mma/doc/DS_No7-de-2017-Reglamento-del-Fondo-para-el-Reciclaje.pdf>.
Misiones online, 2017. Argentina tiene pendiente el debate por una ley específica de gestión de residuos electrónico. Retrieved from: <http://misionesonline.net/2017/06/16/argentina-pendiente-debate-una-ley-especifica-gestion-residuos-electronico/>.
Morris, A., Metternicht, G., 2016. Assessing effectiveness of WEEE management policy in Australia. J. Environ. Manage 181, 218–230.
Nguyen, N.C., Bosch, O.J., Ong, F.Y., Seah, J.S., Succu, A., Nguyen, T.V., et al., 2015. A systemic approach to understand smartphone usage in Singapore. Syst. Res. Behav. Sci. .
OECD, 2014. Global forum on environment: promoting sustainable materials management through extended producer responsibility (EPR). Tokyo, Japan. Retrieved: <http://www.oecd.org/environment/waste/Global%20Forum%20Tokyo%20Issues%20Paper%2030-5-2014.pdf>.
de Oliveira, C.R., Bernardes, A.M., Gerbase, A.E., 2012. Collection and recycling of electronic scrap: a worldwide overview and comparison with the Brazilian situation. Waste Manag. 32, 1592–1610.
Parajuly, K., Wenzel, H., 2017. Potential for circular economy in household WEEE management. J. Clean. Prod. 151, 272–285.
Park, P.J., Lee, K.M., Wimmer, W., 2006. Development of an environmental assessment method for consumer electronics by combining top-down and bottom-up approaches. Int. J. Life Cycle Assess. 11 (4), 254–264.
Rao, N.D., Ummel, K., 2017. White goods for white people? Drivers of electric appliance growth in emerging economies. Energy Res. Soc. Sci. 27, 106–116.
RELAC, 2017. Plataforma Regional de Residuos Electrónicos en Latinoamérica y el Caribe. Retrieved: <http://www.residuoselectronicos.net/>.
Rodríguez, L.A., González, N., Reyes, L., Torres, A., 2013. Management system of waste electrical and electronic equipment. System dynamics approach. Revista S&T, Sistemas y Telemática, 11 (24), 55–71. ISBN 1692-5238. <http://www.icesi.edu.co/revistas/index.php/sistemas_telematica/issue/view/179>.
Rodríguez, L.A., Estupiñán, E., Jaimes, S., 2015. Product policy impact in the lifecycle of light bulbs though system dynamics. International System Dynamics Conference. Boston, USA. July 2015. <https://www.systemdynamics.org/assets/conferences/2015/proceed/index.html>.

Rodríguez, L.A., Escalante, E., Reyes, L., 2016. From Recoverers to Recycling Organization, Socio-Economic and Environmental Considerations on Residential Waste Management. In: 34th International Conference of the System Dynamics Society. Conferencia presentada en Ámsterdam, Países Bajos. <https://www.systemdynamics.org/assets/conferences/2016/proceed/index.html>.

Rodríguez, L.A., Estupiñán, E., 2018. "Public Policy Impact in the Life Cycle of the Electrical and Electronic Equipment Waste. Colombia exemplifies Latin America Status" International System Dynamics Conference 2018, Reykjavik, Islandia.

Sinha, R., Laurenti, R., Singh, J., Malmström, M.E., Frostell, B., 2016. Identifying ways of closing the metal flow loop in the global mobile phone product system: a system dynamics modeling approach. Resour. Conserv. Recycl. 113, 65−76.

Shinkuma, T., Huong, N.T.M., 2009. The flow of E-waste material in the Asian region and a reconsideration of international trade policies on E-waste. Environ Impact Assess Rev. 29 (1), 25−31.

SRI - Sustainable Recycling Industries. (2017). Practical guide for designing WEEE management policies in developing countries now available. Retrieved of https://www.sustainable-recycling.org/weee-policy-guidebook-launched/

Spengler, T., Schröter, M., 2003. Strategic management of spare parts in closed-loop supply chains − a system dynamics approach. Interfaces 33 (6), 7−17.

Sterman, J.D., 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World.. McGraw-Hill, New York, NY.

Sun, Q., Wang, C., Zuo, L., Lu, F., 2018. Digital empowerment in a WEEE collection business ecosystem: a comparative study of two typical cases in China. J. Clean. Prod. 184, 414−422.

Sustainable Recycling Industries − SRI, 2017. Practical guide for designing WEEE management policies in developing countries now available. Retrieved from: <https://www.sustainable-recycling.org/weee-policy-guidebook-launched/>.

Tojo, N., Neubauer, A., Bräuer, I., 2008. Waste management policies and policy instruments in Europe: an overview. International Institute for Industrial Environmental Economics.

UPME, 2006. Determinación del consumo final de energía en el sector residencial urbano y comercial y determinación de consumos para equipos domésticos de energía eléctrica y gas. file:///E:/PHD/Articulos%20PHD%20LARB/UPME_415_Determinacion%20del%20consumo%20final%20de%20energia%20%20en%20sectores%20residencial%20%20urbano%20y%20comercial.pdf.

Van Eygen, E., De Meester, S., Tran, H.P., Dewulf, J., 2016. Resource savings by urban mining: the case of desktop and laptop computers in Belgium. Resour. Conserv. Recycl. 107, 53−64. Available from: https://doi.org/10.1016/j.resconrec.2015.10.032.

Wang, F., Huisman, J., Stevels, A., Baldé, C.P., 2013. Enhancing E-waste estimates: improving data quality by multivariate input-output analysis. Waste Manag. 33 (11), 2397−2407. Available from: http://doi.org/10.1016/j.wasman.2013.07.005.

Wang, F., 2014. *E-Waste: Collect More, Treat Better. Tracking Take-Back System Performance for Eco-Efficient Electronics Recycling*. Dissertation, Delft University.

Wang, J., Wang, Y., liu, J., Zhang, S., Zhang, M., 2018. Effects of fund policy incorporating extended producer responsibility for WEEE dismantling industry in China. Resour. Conserv. Recycl. 130 (June 2017), 44−50.

Watkins, E., Pantzar, M., 2017. EPR in the EU plastics strategy and the circular economy: a focus on plastic packaging.

World Bank, 2015. GINI index. Retrieved from: <https://data.worldbank.org/indicator/SI.POV.GINI?>.

World Bank, 2017a. A. GDP per capita, PPP (current international $). Retrieved from: <https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD>.

World Bank, 2017b. Population total. Retrieved from: <https://data.worldbank.org/indicator/SP.POP.TOTL>.

Xiao, R., Zhang, Y., Liu, X., Yuan, Z., 2015. A life-cycle assessment of household refrigerators in China. J. Clean. Prod. .

Yang, J.X., Wang, R.S., Fu, H., et al., 2004. Life cycle assessment of mobile phone housing. J. Environ. Sci. 16 (1), 100−103.

Yao, L., Liu, T., Chen, X., Mahdi, M., Ni, J., 2018. An integrated method of life-cycle assessment and system dynamics for waste mobile phone management and recycling in China. J. Clean. Prod. 187, 852−862.

Yu, J.L., Eric, W., Ju, M.T., 2010. Analysis of material and energy consumption of mobile phones in China. Energy Policy 38 (8), 4135−4141.

Yu, L., He, W., Li, G., Huang, J., Zhu, H., 2014. The development of WEEE management and effects of the fund policy for subsidizing WEEE treating in China. Waste Manag. 34 (9), 1705−1714.

Zero Waste Europe, 2017. *Extended Producer Responsibility—Creating the Frame for Circular Products*. Zero Waste Europe, Brussels.

Zhang, S., Ding, Y., Liu, B., Chang, C.C., 2017. Supply and demand of some critical metals and present status of their recycling in WEEE. Waste Manag. 65, 113−127.

Zhou, W., Zheng, Y., Huang, W., 2017. Competitive advantage of qualified WEEE recyclers through EPR legislation. Eur. J. Oper. Res. 57, 641−655.

Further reading

BID, 2013. Situación de la gestión de residuos sólidos en América Latina y el Caribe <https://publications.iadb.org/handle/11319/7177?locale-attribute = es&>.

Ministerio de Ambiente y Desarrollo Sostenible − MADS, 2018. Listado de puntos de recolección de residuos posconsumo. Retrieved from: <https://www.datos.gov.co/Ambiente-y-Desarrollo-Sostenible/Listado-de-puntos-de-recolecci-n-de-residuos-posco/m79k-beyn/data>.

PNUMA, 2006. Tratados internacionales para la protección a la capa de ozono. <http://www.pnuma.org/ozono/Documentos/DiaOzono/tratados%20internacionales%20ozono.pdf>.

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Environmental pollution of E-waste: generation, collection, legislation, and recycling practices in Mexico

18

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18.1 Introduction

The accelerated technological progress has led to massive manufacturing of electrical and electronic equipment (EEE) with shorter lifetime span due to technological change. At present, the lack of prevention, control, and information measures has led to the development of improper practices in the management and disposal of waste electrical and electronic equipment (E-waste).

Given the growing technological development, it is time to analyze and make decisions in the search for alternatives for the sustainable management of this type of waste. With the arrival of the information society and the high consumption of EEE, the authorities face the challenge of managing E-waste flow in a sustainable and responsible manner. Electronic equipment turns obsolescent at a rapid pace, generating a growing stream of E-wastes that require a proper channel for disposal and recycling. However, most E-wastes are disposed on the streets and vacant lots, or mixed with municipal solid wastes and buried in local dumps. At present, the lack of prevention, control, and information measures has led to the development of improper practices in the management and disposal of waste electrical and electronic equipment (E-waste). Local authorities need to develop new strategies for the sustainable management of these wastes.

Consumers are replacing their products more frequently, and the lifespan of the EEE is shrinking. It is important to highlight that the periods of obsolescence are increasingly shorter, complemented by a cost of acquisition with a downward trend; in this sense, Vega (2012) indicates that technological obsolescence is a growing phenomenon in the information society and knowledge, which causes an

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00021-8

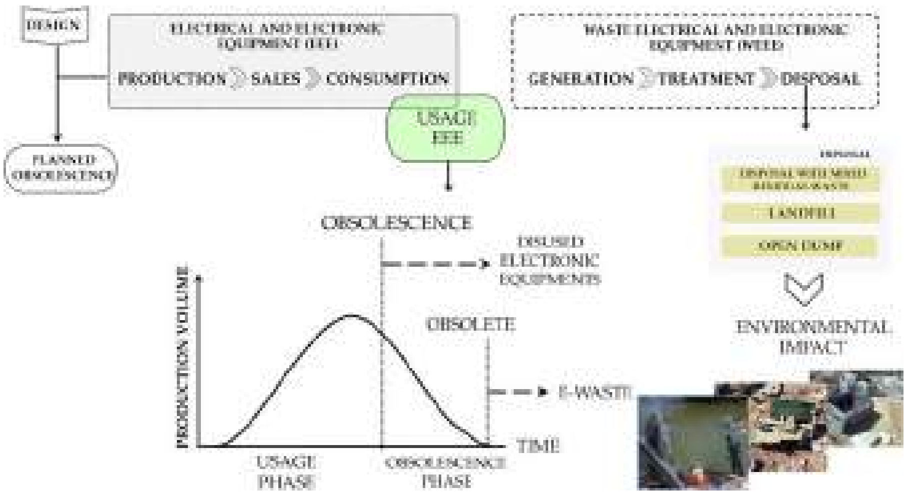

Figure 18.1 Obsolescence and life cycle of electric and electronic equipment.

environmental problem by generating electronic waste. This has influenced the exaggerated increase of products that become electronic garbage because the useful life of many devices is reduced to the minimum before the production of new EEE. Fig. 18.1 shows a diagram that shows the flow of electronic devices from production to final disposal, it is observed that in the culture of consumption the obsolescence of the EEE influences the generation of E-waste, so that it is important to establish mechanisms to size the problem and carry out generation and quantification studies to know the recovery potential of the electronic components and materials that can be recycled, as well as the equipment that can be reused before they become obsolete. This will prevent the improper disposal of E-wastes from ending up in the final disposal sites that tend to throw residential generators among them sidewalks, vacant lots and open dumps, causing environmental impacts and damage to health.

The E-wastes make up a complex and rapidly growing waste stream, increasing at a rapid pace. According to Cucchiella et al. (2015), it grows three times faster than urban waste. It is estimated that by 2021, the generation of E-waste will increase to 52.2 million metric tons (Mt) or 6.8 kg/inhabitant, with an annual growth rate of 3% to 4% (Baldé et al., 2017). The problem of electronic waste is global, this waste stream is part of the urban waste stream. Fig. 18.2 shows a diagram of the flow of electronic waste in the current of the MSW. The term E-waste is used to include all electrical and electronic devices, as well as their components that have been discarded by their owner as waste without the intention of reuse. For this research, E-waste refers to damaged or obsolete EEEs that are discarded by the consumer. It includes a wide range of devices such as computers, consumer electronic equipment, cell phones, and household appliances that are no longer used or desired by their users, including all the components, subassemblies, and consumables that a user considers obsolete or undesirable (Kahhat, et al., 2008).

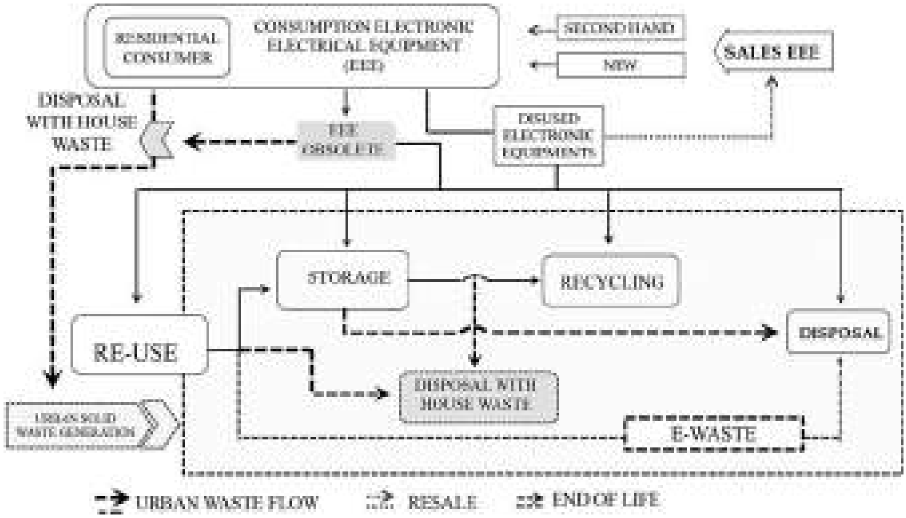

Figure 18.2 E-waste and the flow of urban solid wastes.

The E-waste according to the Organization for Economic Cooperation and Development (OECD) is any device powered by a power supply that has reached the end of its useful life. Many of the EEE that are approaching the end of their useful life; they can be reused, restored, or recycled, depending on the country that manages them and, above all, on the legal regulations regarding their management, as mentioned by Widmer et al. (2005). Other authors such as Sinha et al. (2009) define E-waste as any electrical device that has failed to fulfill the purpose for which it was manufactured. The E-waste designation includes all electrical and electronic devices that are nearing the end of their useful life and become waste, considering all those components and subsets that are part of the product at the time it is discarded. Many of these products can be reused, restored, or recycled. In the case of Mexico, electronic waste is defined by the legislation as technological waste coming from the informatics industries, from the manufacturers of electronic products that, at the end of their useful life due to their characteristics, require special handling (DOF, 2015).

E-waste is an emerging waste stream globally due to the high consumption of electronic products. However, integral E-waste management presents great challenges for developing countries such like Mexico without the proper recovery technology. The complexity of diverse components of electronic equipment and products make them difficult to recycle, however a number of shops using human labor work on disassembling the main component and materials to sell them on local recycling markets (Huang et al., 2009, and Mihai et al., 2019).

The lack of E-waste collection infrastructure, as well as the absence of consumer awareness are the main obstacles for an environmentally sound E-waste management program.

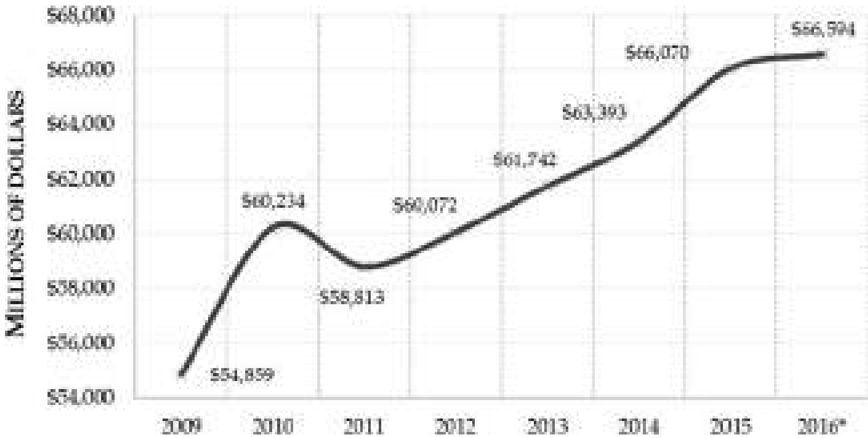

Figure 18.3 Production of electronic goods in Mexico.

18.2 Electronic industry in Mexico

Nowadays E-waste has emerged as one of principal types of waste in the world because of market expansion and shorter life cycles of electronic products. Electronic industry is responsible for 10%−20% of global environmental impact related to depletion of nonrenewable resources (Araújo et al., 2012 and Georgiadis and Besiou, 2009). Electronic industry has an important role in country's economy and Mexico is well-positioned worldwide as an exporting country and electronic products assembly. Fig. 18.3 shows the value of electronic production in Mexico and by 2016 the electronic production will be worth 66,500 thousand millions of dollars and it also shows how has this sector behaved since 2009 (Promexico, 2016).

In the electronics sector, the Secretariat of Economy points that Mexico is one of principal countries in terms of electronic export and assembly. The country has been the main exporter of flat-screen TVs, the fourth place in computers export, and the eighth-place in production of cellular phones worldwide. United States was the primary exportation destination and this country represents 85.4%, followed by Canada, Colombia, and the Netherlands. Fig. 18.4 shows the destination of electronic equipment and products manufactures or assembled in Mexico.

18.3 Consequences for health and the environment

E-waste contains a wide range of substances, some of which are economically valuable and others are harmful to health and the environment. Fig. 18.5 shows the characteristics that differentiate them from other waste streams: among them are their potential for use, having high value recoverable materials; the presence of toxic elements and dangerous substances that, although they are necessary to

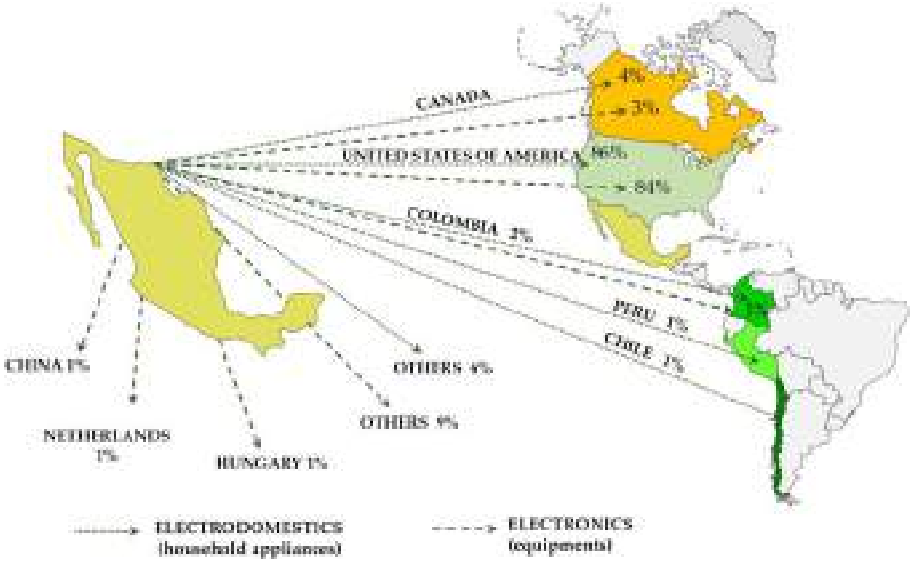

Figure 18.4 Home appliances exportation flow of Mexico and other countries.

Figure 18.5 Characteristics that differentiate E-waste from other waste streams.

guarantee their functionality, when released to the environment can be harmful to health and cause pollution problems, therefore they require an environmental management that protects ecosystems and public health; and its volumes and accelerated rate of growth, determined by the phenomena of technological change, associated with the culture of consumption and obsolescence.

The management of E-waste is complex since its material composition is very heterogeneous and may contain a variety of hazardous components, which represent a problem during the management and final disposal phase. Among the most problematic substances contained in these wastes are heavy metals, including mercury, lead, cadmium, and chromium. Halogenated substances such as chlorofluorocarbons (CFCs), chlorinated biphenyls (PCBs) and polyvinyl chloride (PVC), as well as some flame retardants.

Some of the hazardous substances are compounds that include metals and organic compounds emitted during the combustion process and those that form immediately after combustion. Some of the organic compounds are persistent organic pollutants (POPs) such as brominated flame retardants (BfR), polybrominated diphenyl ethers (PBDE), polycyclic aromatic hydrocarbons (PAHs), polychlorinated Dibenzo-p-dioxins and furans (PCDD/FS), these have significant implications for human health and environmental safety (Ohajinwa, et al., 2019).

The E-wastes are some of the agents that pollute the subsoil, water, and air, and consequently, threaten human health. In emerging countries such as Mexico, this is aggravated due to the lack of control in their management and final disposal, since a large number of electrical and electronic devices at the end of their useful life reach final disposal sites mixed with MSW, increasing the heterogeneity, dangerousness, and impact of the resulting mixture.

Electronic equipment and appliances contain different toxic substances such as lead, mercury, zinc, tin, silver, arsenic, cadmium, selenium, hexavalent chromium, and flame retardants. When E-waste is improperly disposed, there is a high risk of pollution of local water sources. Another problem is the common practice of burning wire and other electronic components that generate toxic fumes.

It is important to highlight that the health of the human being and the care of the environment are the determining factors to take measures against this problem. The health effects from exposure to any hazardous substance are diverse, in different organs and different magnitudes, depending on the duration and form of exposure (inhalation, ingestion or direct contact), dose (amount), and range from nausea, pain (head and chest), respiratory failure, decreased concentration to congenital disorders, and cancer, among others.

Another factor that we must consider is that these components are not regularly found purely or naturally, but are combined with thousands of kilos of other electronic devices and various wastes that are mixed to generate new toxic products that have different and harmful behaviors.

In electronic devices and, therefore in the E-waste stream generated there are two groups of substances considered toxic to the environment and human health polybrominated organic compounds and heavy metals.

Printed circuit boards (PCB) may contain components that contain toxic metals such as beryllium, lead, and cadmium. Metal parts, such as housings and screws, can be protected against corrosion with a layer of hexavalent chromium carcinogen. Some components, such as specific switches and the backlights of liquid crystal displays (LCD) contain mercury. Hazardous organic substances such as chlorinated biphenyls (PCBs) can be found in condensers. Plastics in the EEE use brominated flame retardants to meet fire safety requirements. Some substances of this group have a high potential for dioxins and furans if they are burned, among which are the polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE).

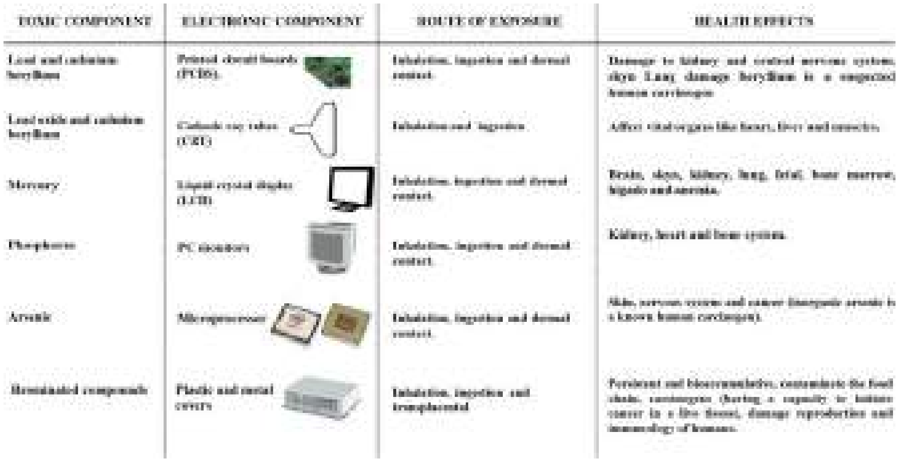

Figure 18.6 E-waste, toxic substances, and health.

Brominated flame retardants or polybrominated organic compounds are persistent chemicals in the environment and some of them are highly bioaccumulative and capable of interfering with the normal development of the brain in animals. Polybrominated diphenyl ethers (PBDE) are flame retardants for use in electronic products and potentially harmful for fetal development, even at very low levels. Metals are the main core of the E-waste, but at least their recycling is feasible since reusing metals saves their extraction. Some of the problems associated with the handling of electronic waste are the cross-border flows from developed countries to third world countries becoming receptors of pollution. By not having management systems for their management and final disposal, mechanisms must be implemented to prevent and mitigate the costs and impacts on the environment and the effects on human health. Fig. 18.6 shows some of the health effects associated with the toxic components of E-waste.

The proper treatment of electronic waste can limit the impacts of hazardous substances on electronic waste. The know-how and technologies are available and applied at least in some developed countries. Heavy toxic metals, such as lead can be recycled to a certain extent, otherwise they can be controlled and prevented from being released into the environment. However, the high amounts of electronic waste generated in emerging countries, which are not collected properly and, therefore are very likely to end up on the streets, vacant lots, and outskirts of urban settlements.

Orlins and Guan (2016) point out that informal recycling of E-waste generates work for the informal sector, but inadequate dismantling and burning of E-waste for resource recovery exposes workers to toxins and heavy metals and causes a serious air, water, and soil pollution. E-waste recycling practices can result in direct or indirect exposure to a variety of hazardous substances that are contained in the EEE and are released by unsafe recycling practices.

Direct exposure involves the contact of the skin with harmful substances, the inhalation of fine and coarse particles, as well as the ingestion of contaminated dust, in addition those who participate directly in the recycling of E-waste with little protection incur in high levels of direct exposure. Unsafe recycling techniques used to recover valuable materials often increase the risk of hazardous exposures, for example, plastics burn out, often at low temperatures, to get rid of computer cases or to recover metals. The valorization of printed circuit boards and other components. Even though incineration releases heavy metals such as lead, cadmium, and mercury, the toxic fumes released by these practices often contain polyhalogenated dioxins and furans, generated by incomplete combustion at low temperatures.

Therefore, in countries such as Mexico, in which the informal sector plays a central role in the recovery of waste, it is important to establish proper regulations in order to avoid exposure to toxic substances when disassembling E-wastes. The country also needs an innovative public policies and legal framework to regulate de production, disposal and recycling of electronic equipment in order to prevent the disposal of E-waste in municipal dumps.

18.4 Estimating quantities for E-waste

Bernache and Chávez (2014) studied the production of electronic waste, in the context of the national program of replacement of cathode ray tube televisions by flat televisions. E-waste is a broad category of waste that is associated with both electrical appliances, electrical appliances and a whole range of electronic devices commonly used in academic, institutional, and domestic contexts. The presence of E-waste is increasing in the urban waste stream because of the high consumption of electrical and electronic equipment, by the short life cycle (two to five years), and renovation of this type of goods (Román, 2007). In 2013 it was estimated that post-consumer electronic waste production in Mexico was 338,194 tons per year (Table 18.1).

According to Baldé et al., the region of Latin America generated 4.2 Million tons (Mt) of E-waste during 2016, with an average of 7.1 kg/person. Latin American countries with the highest E-waste generation are Brazil 1.5 Mt, Mexico 1 Mt, and Argentina 0.4 Mt. The top three countries in Latin America with the

Table 18.1 Postconsumer E-waste generation (2013).

	E-waste in tons
México	338,194
Jalisco State	21,983
Metropolitan Area of Guadalajara	13,190

Source: Estimates from data reported by Román Moguel, Guillermo, 2007. Diagnóstico sobre la generación de residuos electrónicos en México. Informe Final. Instituto Nacional de Ecología, desarrollado por el CIIEMAD del Instituto Politécnico Nacional, México, D.F.

highest E-waste generation in relative quantities in 2016 were Uruguay (10.8 kg/person), Chile (8.7 kg/person), and Argentina (8.4 kg/person).

The Ministry of the Environment in Mexico has taken up the figures published by Baldé et al. (2017) and refers that the country generated 1.1 Mt of E-waste in 2015, with an annual growth rate of 2.18%, so that the amount of annual production of electronic waste could reach 1.35 Mt for the year 2026 (SEMARNAT, 2018a,b: 17). The same source reports a generation range of 8.2 to 9.2 kilos per year per person. The commercial exchange of Mexico with the United States and the movements of goods used at the border generated in 2011 a transfer of electronic waste from the US to Mexico of 80,000 Mt, especially TVs and monitors. Mexico in turn exports printed cards and circuits obtained from electronic waste to the United States (SEMARNAT, 2018a,b: 20). Under certain conditions the amount of electronic waste may suffer significant variations, this happened in 2014 and 2015 in Mexico with the program of transition to digital television. The federal government distributed 13.8 million flat TV sets of digital LED technology free of charge. This program will have the side effect of converting cathode ray tube analog TVs into obsolete ones. So that would be discarding 276,000 tons of this type of TVs in the 30 months of effectiveness of the program of delivery of flat TVs, June 2014−December 2015. As of January 1, 2016, television signal would be transmitting only in digital format.

18.5 E-waste legislation

The regulation of waste in Mexico is based on an international framework that includes agreements and treaties that it has signed, such as the Basel, Stockholm, and Rotterdam agreements, among others. In addition to a regional approach, which is applied by the situation of North America and Latin America in terms of electronic waste, in which Mexico has participation in different programs and agreements related to the subject in both areas, such as the Commission for the North American Environmental Cooperation (CCA) and the Regional Platform on Electronic Residues in Latin America and the Caribbean (RELAC). Fig. 18.7 shows a scheme that shows the legislation that applies to E-waste in Mexico and shows the planning instruments that have been developed to address this waste stream. It mentions the international framework that our country must respect, as well as the policies of the regional framework.

The inclusion of the international and regional framework for the management of electronic waste is important because it establishes a point of reference in the development of public policies on waste at the national level. The management of electronic waste in Mexico has become important mainly due to the presence of some contaminants that are found in these wastes and that, when disposed of improperly, can be released to the environment.

In the international context, Mexico adhered to the *Basilea Convention*, in the 1990s, taking important steps in the protection of the environment, through the legal

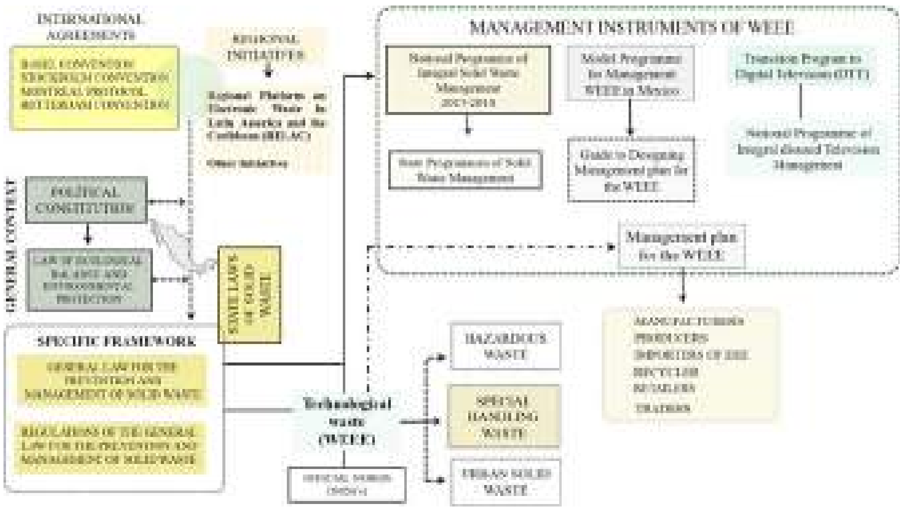

Figure 18.7 Regulatory framework international and regional for E-waste.

regulation of transboundary movements of hazardous wastes, by establishing a framework of general obligations for the countries that participate. The agreement seeks to minimize the generation of hazardous waste and the transboundary movement of these, ensure their environmentally sound management, as well as promote international cooperation to achieve it; create mechanisms for coordination, monitoring, and regulating the application of procedures for the peaceful settlement of disputes. In addition, it encourages its elimination, through environmentally sound management, as close as possible to the site where they are generated. It also seeks to minimize the production of hazardous waste, this involves strong controls during storage, transportation, treatment, reuse, recycling, recovery, and disposal. It promotes the substitution of hazardous substances in production and extended producer responsibility (REP) from the design and production of the product to the treatment of waste. Currently, this agreement has included within its regulations the transport of electrical and electronic waste, cell phones and computers. Likewise, it contains fractions that specifically limit the export of electronic waste including metal waste, electronic assemblies such as printed circuits, accumulators, other batteries and cathode ray tubes.

The Stockholm Convention seeks to limit pollution caused by persistent organic pollutants (POPs), such as brominated flame retardants, as well as heavy metals since at the end of their life cycle, these pollutants can be released and cause adverse effects to the environment and health. The Rotterdam Convention promotes shared responsibility and the joint efforts of countries adhering to it in the field of international trade in certain hazardous chemicals. Its objective is to protect human health and the environment against possible damage and contribute to its environmentally sound use, facilitating the exchange of information about its characteristics, establishing a national decision-making process on its import and export and disseminating those decisions between the members.

The Montreal Protocol was signed with the purpose of regulating the issue of substances that deplete the ozone layer, in which deadlines were established for the elimination and consumption of these substances. To this end, it establishes restrictions on trade with countries that are not part of the protocol, prohibiting the importation and/or exportation of exhausting substances or products that contain them. It also gives importing countries the means and information they need to recognize potential hazards and exclude chemicals that they cannot handle safely. If a country consents to the import of chemical products, the protocol promotes the safe use of these through labeling rules, technical assistance and other forms of support.

At the regional level, in 1994 Mexico signed the Agreement on Environmental Cooperation of North America (ACAAN). This agreement reflects the commitment of Mexico, Canada, and the United States to environmental improvement in the region. As a result of the ACAAN, the Commission for Environmental Cooperation of North America emerged, formed by the three federal environmental entities of the signatory countries of the North American Free Trade Agreement (NAFTA).

Since 2004 the three countries have worked within the framework of the CEC to develop projects for the adequate management of E-waste. The Commission considers that the electrical and electronic waste represents an environmental and commercial issue both for the waste generated and for the flows with use and unknown destination to other regions such as Africa or Asia. Therefore the problem of electrical and electronic waste in North America must be addressed jointly, given the geographical proximity and the permeability of the borders. The differences in national legislations and the complex institutional coordination represent significant challenges that can be faced in the context of the CEC to contribute to the control of illegal flows of electrical and electronic waste, and the efficient application of local regulations to improve their management, in other aspects.

In relation to RELAC, it is not a normative instrument, but rather an associative, nonprofit project. Its objective is to promote, articulate, and disseminate initiatives that promote solutions for the prevention, proper management, and correct final treatment of electronic waste in Latin America. Its fields of action are prevention, reuse, and recycling. Its foundation is focused on identifying the social, economic, and cultural particularities of Latin America and the Caribbean and responding to them in the electronic waste treatment initiatives that are implemented in the countries of Latin America. It seeks to recognize, highlight, and respond to the social, economic, and cultural peculiarities of Latin America and the Caribbean in the electronic waste treatment initiatives that are implemented. For this, it is committed to reconditioning initiatives to reduce the digital divide and promotes the social business, to promote the possibilities of equal access to market initiatives for the treatment of electronic waste. The national framework established for the management of electronic waste starts from the Political Constitution of the United Mexican States, the General Law of Ecological Equilibrium and Environmental Protection (GLEEEP), the General Law for the Prevention and Integral Management of Solid

Residues (GLPIMSR), from which follows the Regulations of the General Law for the Prevention and Integral Management of Waste (RGLIMSR), and the official regulations. In Mexico, electronic wastes, according to the LGPGIR, are classified as especial management wastes (EMW), so the law establishes the obligation to develop management plans and specific programs for their disposal The General Law for the Prevention and Integral Management of Residues as an instrument of environmental policy establishes a general classification for waste: hazardous waste, special handling, and urban solid waste; the first and last classification are residues whose identity is unquestionable; however, as regards the residues of special handling, their definition and understanding has not been very clear, which makes the handling of E-waste more complex in Mexico. This could be handled as dangerous, of special management or as an urban waste, when it is generated in a house, so the areas of competition involved are the three levels of government. The GLPIMSR establishes environmental policy instruments to regulate waste management plans that require it, for this purpose, Mexican Official Standards are generated that establish criteria for the development of management plans. It establishes a framework of shared responsibility among several industry players, as well as general principles for waste management, valorization, shared responsibility, and integral management, under criteria of environmental, technological, economic, and social efficiency. In Mexico, the federal entities have the power to formulate, conduct, and evaluate the state policy, as well as to prepare the programs on electronic waste. They are also responsible for authorizing the integral management of these, and identify those that may be subject to management plans. For this reason, Fig. 18.8 presents a scheme to give its identity and indicates the level of

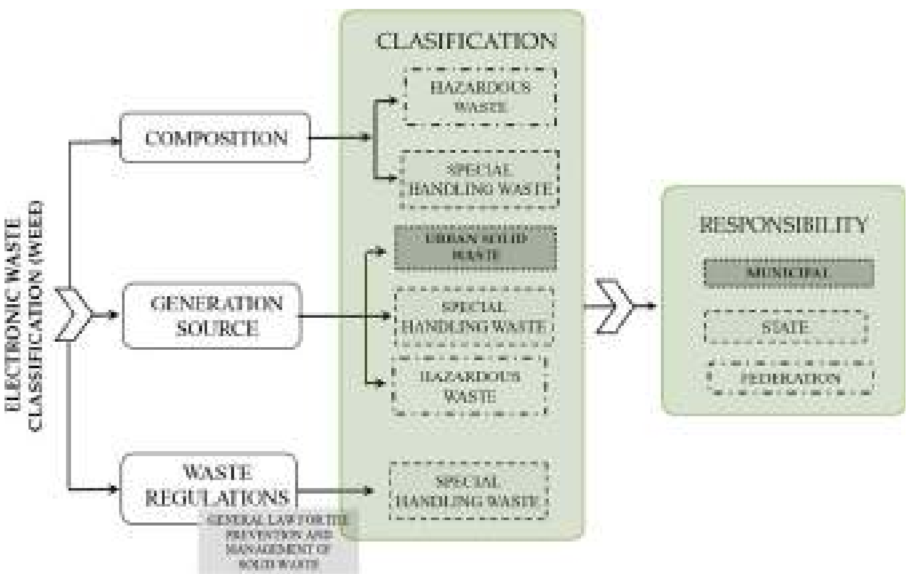

Figure 18.8 E-waste according to composition, source, and regulations.

competence in terms of authority to be involved in the regulations and waste management strategies, based on their classification, which is associated with the source of generation, composition, and regulations. Depending on the source and type of products, E-waste in Mexico is classified in three different forms: hazardous wastes (industrial), special wastes when generated in great quantities and municipal solid waste when generated by households. However, most E-waste is improperly disposed with municipal solid wastes.

In relation to the large generators of waste of special handling, among which electronic waste is found, Standard 161 in Mexico establishes classification criteria and determines that they are obliged to submit management plans (SEMARNAT, 2018a,b). This Standard 161 identifies the "Technological waste of computer industries and manufacturers of electronic products", such as computers, cell phones, televisions and cathode ray tube monitors, liquid crystal and plasma screens, printers, photocopiers and multifunctional, as well as audio and video players, and cables for electronic equipment.

However, for microgenerators such as individuals, households, small commercial establishments, offices, and schools, among others, there is no regulation, nor a program for the management of postconsumer electronic waste.

18.6 Current practices

Mexico is among the Latin American countries that has a higher percentage of separation and use of electronic waste. Among public programs, private companies, university programs, and the informal sector, 358,000 Mt of electronic wastes are collected nationwide, representing 36% of the total (Baldé et al., 2017). For the Secretary of the Environment, the integral management of electronic waste in Mexico faces important challenges, among which are the following:

- Combat the informal market.
- Control imports (mainly with the United States).
- Generate sufficient WEEE processing capacity.
- Create quality systems in your treatment.
- Avoid the presence of WEEE in final disposal sites.
- Open burning.
- The lack of norms or instruments for its management.

(SEMARNAT, 2018a,b: 17)

A federal government program for the switch to digital television in 2014–15 had unplanned consequences for E-waste management practices. The federal government delivered 13.8 million flat-panel televisions and caused millions of obsolete television sets to be discarded. Cathode ray tube television sets should be delivered to special collection centers, but the centers did not operate efficiently and managed to collect only a minimum percentage (5%) of the total of obsolete television sets. Bernache and Chávez (2015) report that in June 2015, after 1 year of the start of the television delivery program, there was no waste management strategy for analog televisions, people had nowhere to turn to deliver their old televisions. The answers they observed were: keep them at home; sell them to chachareros; incorporate them into domestic garbage; and throw them in the street or in vacant lots (solar). The federal government did not have a management plan for analog televisions, which led to the informal market for metals, mainly copper, which these analog devices contain. The three types of hazardous waste that can be contained in an analog television set are lead oxide (Pb), cadmium (Cd), and polybrominated flame retardants. The total amount of electronic waste resulting from the transition to digital television in Mexico was 278,000 tons. In addition to encouraging the informal activities of scrap dealers and pepenadores, due to the lack of a collection program, the waste stream from old televisions destabilized several recycling programs that were carried out in some states of the republic, “reciclatrones”. Because in 2015 large amounts of televisions and monitors were received, which had a high cost to send them to their final destination and processing.

18.6.1 Universities

Several universities across the country have developed their campus programs focusing on E-waste collection and the subsequent transportation to authorized recycling centers.

In response to the problem of inadequate waste management some universities in México have organized collection activities of electronic waste, including the University of Guadalajara, the University of Veracruz, the Autonomous University of Baja California and the Autonomous Metropolitan University (UAM), and Universidad Michoacana de San Nicolás de Hidalgo in Morelia.

In the case of UAM, during three electronic waste collection programs conducted in 2013, 2014, and 2015, a total of 442 kilograms was collected. Such a program increases collection of E-waste is an indicator of social participation and awareness (SEDEMA, 2016).

An example is the program of selective collection of E-waste called “*Reciclatron*” which has been implemented in the Autonomous University of Nayarit (UAN)—Mexico with the aim of promoting in the university community and society, mechanisms to promote organized cooperation to improve the environment. The objective of this program is to promote a sustainability culture in higher education, and at the same time develop in students the abilities of leadership, cooperation, and responsibility in actions that favor the environment. A relevant result of the program during the four periods in which it was carried out, a total of 28.8 tons of electronic waste was collected and taken to a certified recycler. The results show that the program was also a success in terms of the environmental awareness of participants of students, employees, and professors.

18.6.2 E-waste collection campaigns in the state of Jalisco, Mexico

A recent study estimated a production of electronic waste of 21,983 tons for the state of Jalisco and 13,190 for the metropolitan area of Guadalajara. These amounts of thousands of tons per year are a serious problem since a large part of this E-waste is improperly disposed in landfills or disposed of with municipal solid waste. In a joint effort of civil society organizations, municipalities, state government, universities, and recycling companies, five *Electroacopio* campaigns were carried out in Jalisco as of 2010. These campaigns have involved up to 49 municipalities that have organized education programs and environmental workshops, have trained groups of volunteers and have installed temporary collection centers for electronic waste. In this type of campaigns, the relationship between society and government is emphasized. In this effort, social and public stakeholders have been integrated since the first campaign in 2010. It is important to note that up to 2014, a total of 456.2 tons of electronic waste have been collected (Bernache and Chávez, 2014). The 2014 campaign adopted the official name of "*ElectroAcopio* Jalisco". This campaign was organized following the logic established previously. The organization work begins 6 months in advance, the Organizing Committee was formed, in which The Ecovía Project, Vías Verdes A.C. and the Secretary of the Environment and Territorial Development (SEMADET) play a central role. The SEMADET held the Call for the participation of the town councils. From that Call, in November 2013, sessions were held to agree on dates, programs, advertising campaigns, transport routes, and logistics of the campaign. A new company was also selected to work in 2014, Belmont Bt Recycling Solutions (hereinafter referred to as Belmont). The company received all the REEs collected in the campaign and contributed with transportation and personnel for the loading and transfer of the E-wastes from the 11 regional collection centers that were established in the state of Jalisco (Bernache and Chávez, 2014). It is important to emphasize that in this campaign there was no purchase-sale of waste and there was no economic transaction between the parties.

The Organizing Committee also has a Technical Committee, made up of a group of university researchers, as well as the *Ecovía Project* experts. This Committee carries out technical advisory activities, evaluates the recycling companies, and also collaborates in the design and operation of the records and analysis of data resulting from the campaign. In this campaign, in addition to the weighing, registration of collection amounts in each location, and type of REE collected, a survey was also developed on consumption, management, and disposal of electronic waste that was administered to a sample of 581 participating citizens.

Three companies participated in the *electroacopio* campaigns in different times: in the first three campaigns (2010–12) the company that receives the electronic waste collected was *Recicla Electrónicos* located in the city of Querétaro.

In the last two campaigns, two companies located in the city of Guadalajara that have experience in disassembling and commercializing electronic waste materials participated. The company *MAC Grupo Ecológico* worked on the 2013 Collection Campaign. On the one hand, MAC has the advantage that at its plant, in addition to the REE treatment, it also carries out the recycling of mercury vapor bulbs and large domestic appliances such as refrigerators, stoves, and washing machines among other white goods. The company has important certifications, including the e-Stewards certification, which recognizes it as an environmentally responsible company in the recycling of E-wastes. However, the MAC company reported that

Table 18.2 *ElectroAcopio* intermunicipal campaigns in the state of Jalisco.

Intermunicipal campaign	Number of municipalities involved	Tons of E-wastes collected
2011	23	100.2
2012	30	104.4
2013	46	110.6
2014	49	90.3

they could participate in 2014 but that they would establish a fee for transporting and processing electronic waste.

Given that the results of the 2013 collection reflected a small volume of bulbs and white goods collection and given the complexity of their management, it was decided to choose a different management of these wastes, which opened the door to the possible participation of other companies to be depositaries of the collected in the program. In this sense, it was agreed to approach the company Belmont to know if it was interested in participating. The company Belmont is the only other company in Jalisco that holds the e-Stewards certification. There was a first approach with Belmont and the company agreed to participate under the terms that were established in a letter of commitment. The total amounts ORFE-waste collected in each campaign is presented in (Table 18.2).

The decrease in the amount of E-waste collection in the 2014 campaign may be explained by the following reasons. First, some important municipalities for their contribution did not have a good organization of the campaign and their collection was significantly less than previous campaigns. Second, the sector of the population that has participated in these campaigns previously has less waste to deliver. Third, in some municipalities there were situations in which "scrap merchants" who buy old equipment passed precisely a few days before the campaign and left little to deliver. One last reason is that a problem arose with the weighing in a regional route, since it was not possible to verify the exact tonnage delivered by three municipalities, so we could be underestimating the total tonnage received in this campaign.

When the trucks loaded with E-waste entered the plant of the recycling company, the employees classified the different types of E-waste and recorded the weight in kilograms of each type of electrical and electronic waste. The results of this record were: TVs added 28%, monitors 16%, and printers 15%. The set of "other electronics" added 38% of the total weight. Fig. 18.9 shows the proportion of each type of E-waste received in the *ElectroAcopio* 2014, according to its weigh.

On the other hand, records were taken of the number (frequencies) of each type of E-waste reported by citizens in the delivery format, which was filled when it arrived at the Collection Center. The participants reported that they were delivering an REE number by type. According to this report, we have the main types of E-waste were cell phones (23%), followed by monitors (19%), Desktop (16%), and

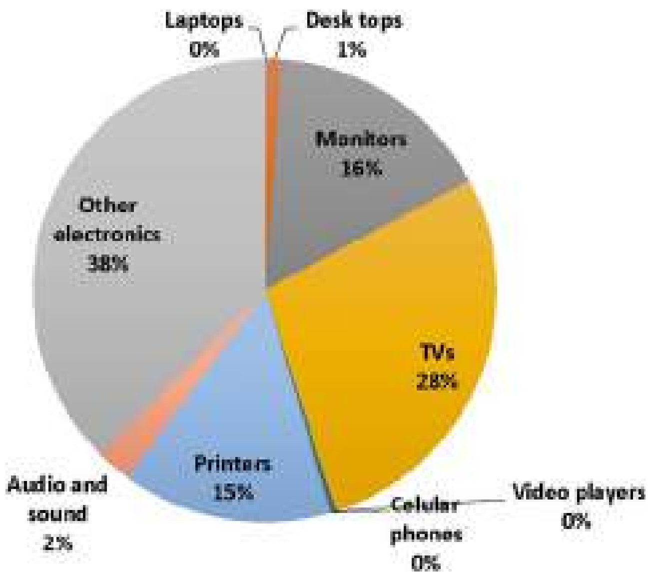

Figure 18.9 Percent of E-waste according to weight (2014).

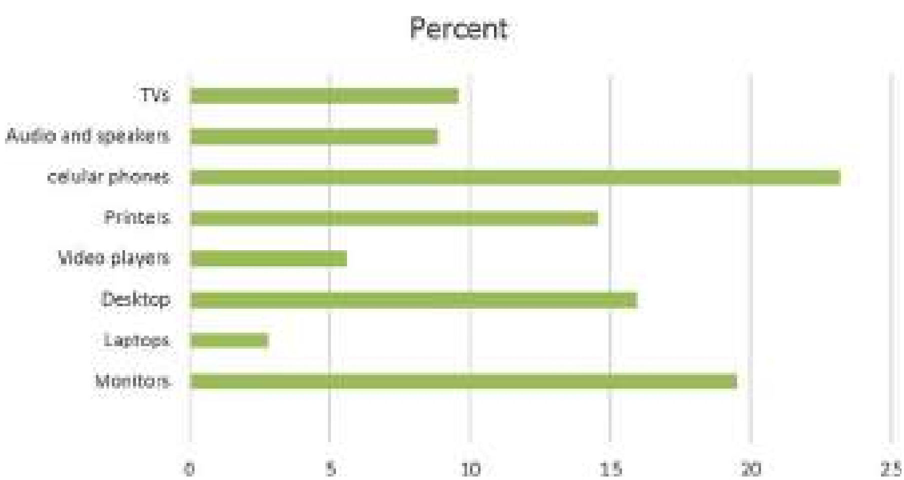

Figure 18.10 Types of E-waste, percent of frequencies (2014).

printers (15%). Fig. 18.10 shows the percentage distribution profile of E-waste delivered by citizens.

The graph shows that the monitors and televisions are two types of waste that have similar characteristics: together they reach 28% of the electronic waste units delivered, so they are a type of waste to avoid its inadequate disposal. In both cases (computer monitors and TVs) the main concern is the disposal of the cathode ray

Table 18.3 Nonparticipant resident E-waste disposal practices.

Question: Those persons that do not participate in the electronic waste collection campaign? How they dispose of their electronic wastes?	**Percentages**
Throw it to the garbage	58
Store them at home	13
Sell it to chatarreros	28
Other actions	1

tube which contain lead oxide residues that spread when the tube is broken during disposal. At the same time that the electronic waste collection campaign was carried out, a Knowledge and Management Survey of the E-waste was administered (Bernache and Chávez, 2014). Participation in the survey was 581 people from the 49 participating municipalities. Regarding the participation of citizens in the Campaign, the students were the ones who participated the most (30%) of the total, in second place were the employees with 19% and in third place were the housewives (18%). A fact that draws attention is that teachers only participated in a 5%, when it would have been expected a participation with greater presence of this type of professionals for their strategic activities in the training of students from basic education. The results indicate that the most common electrical and electronic devices in Jalisco homes are cell phones (35%), followed by television sets (27%), and desktops (17%), sound devices (13%) and video game consoles (8%) Regarding the management of devices that work but no longer used, 52% report that they keep them, or give them to relatives (16%), or donate them (13%). Regarding the management and disposal of E-wastes, an open question was asked and the answers are surprising since many report that they keep them for storage, but also throw other devices during the annual cycle or sell them to scrap metal. When asked more specifically about the management of E-wastes by their neighbors who do not participate in the *ElectroAcopio* campaign, the responses indicate that they are mainly thrown away in the MSW collection, as shown in Table 18.3.

When asked about the reason why other people from their colony do not participate in the *ElectroAcopio* Campaign, 43% indicated that it is due to a lack of timely information about the dates and places of the collection centers. While 45% of respondents answered that they do not give importance and care about the environment, this is a lack of education and environmental culture. Finally, regarding the motivation of those participating in the *ElectroAcopio* Campaign, the three main reasons are the following: 33% of respondents are motivated by an improvement in the environment, 28% say that their actions avoid pollution, and in third place 13% to promote good practices in the handling of electronic waste. In the period from 2010 to 2014, the campaigns for collection and recycling of electronic waste were consolidated in the state of Jalisco (Bernache and Chávez, 2015). The participation of 49 municipalities (out of a total of 125 municipalities) in this effort is important since it goes beyond the collection of physical waste. The environmental education programs, the workshops with practical activities, and environmental education for children and young people are also a transcendent component of these campaigns. Regarding advances in social participation, it can be said that the participants' environmental culture shows progress toward the integral management of E-waste. However, there are also traditional behaviors that lead to inadequate provision of E-wastes during the annual cycle, when there are no collection campaigns and access to an adequate route for the disposal of electrical and electronic waste generated in the context of the household life.

E-waste collection campaigns are very important and are a necessary step on the road to integral waste management. These are small steps and with discreet advances, but in a very positive orientation and leaving a mark on the citizens to inculcate the handling and recycling of this special type of waste that are generated, abundantly, by the contemporary consumer society.

It is necessary to point out that some town halls had problems with the organization of their campaigns. There were two main problems. On the one hand, several municipalities did not have an adequate organization at their headquarters and the dissemination was not timely or sufficient so the collection was much less than in previous campaigns. On the other hand, in some cases the weighing did not follow the protocol, the weighing receipts were not delivered and on a regional route that included at least three municipalities that did not report their weights well and this causes us to underestimate the total amount of the collection of REE in 2014, this underestimation is in the range of tons.

Finally, *electroacopio* campaigns in Jalisco stopped in 2015 before the irruption of thousands of tons of electronic waste product of the obsolete analog television that resulted from the program of transition to digital television in Mexico. By 2018, initiatives have returned, albeit on a smaller scale, to collect and give proper treatment to electronic waste.

18.7 Scavangers

In this group of informal workers there are several types: from the groups that pepenadores work in transfer plants and in final disposal sites, as well as those who buy waste in the streets and other actors. In the city of Mexico, *Colonia Renovación* is well known for carrying out storage, dismantling, and commercialization of electronic waste. In general, the informal sector in Mexico City could be handling 5000 to 10,000 tons per year (PNUD, 2018).

18.8 Industrial activities

There are four types of companies that are involved in the management and recovery of electronic waste (Table 18.4).

Table 18.4 Types of companies.

Processing level	Activities
0	Collection, transportation and storage
1	Gross selection of nonelectronic components
2	Selective separation of electronic components
3	Refinement

Source: PNUD, 2018.

In Mexico there are 153 registered companies dedicated to the handling and processing of electronic waste: 60% is classified as processing level 0 and 36% includes level 2 activities (PNUD, 2018).

The states with the highest number of companies dedicated to handling electronic waste are three: Jalisco with 25%, Baja California with 18%, and Guanajuato with 11%, while the State of Mexico and Mexico City participate with 8.5% and 7.8%, respectively. The rest is distributed in 10 other states of the republic.

Mexico, according to PNUD (2018), has an estimated generation of 383,424 tons E-waste in 2016; the industry has an installed capacity to handle up to 325,859 tons per year. Companies with processing level 2 (selective separation of electronic components) are located mainly in the states of Jalisco, Baja California, and Mexico City, which contributes to a handling of 50,431 tons per year.

18.9 Conclusion

E-waste production in Mexico is high, the country is ranked number three in the continent, only surpassed by United States and Brazil. The amounts given for a range that goes from 383,424 up to 1.1 million tons of E-waste. We consider that the first amount corresponds to postconsumer E-waste, and the second amount to all types of E-waste, considering wastes from production in electronic factories and large scale generators.

The organization of massive campaigns, locally organized provides events of collect E-waste, in Mexico, and it also provides the opportunity to collect and recover components that can be recycled. It prevents that these E-wastes being disposed mixed with municipal solid waste, therefore avoiding a negative impact on the environment. Events like *Reciclatron* o *ElectroAcopio* show that a collaborative effort to improve practices of E-waste management can be develop, involving, citizens, civil organizations, municipal and state environmental officials, and universities.

University campuses are another location for new initiatives, such a E-waste collection from computer rooms and laboratories. A number of associations of professors, employees, students, and other actors have emerged during the last decade, consolidating E-waste collection programs and taking those wastes to proper treatment and disposal. Such is the case with Universidad Autonoma Metropolitana in Mexico City, the Nayarit Autonomus University in Tepic, the Universidad Michoacana de San Nicolás de Hidalgo in Morelia, and some more.

In states with important presence of electronic industries, such as Jalisco, Baja California and Guanajuato, a growing number of E-waste processing plants have emerged.

The scope of the informal work conducted by scavengers is not well known at the time. We know that the informal sector has been involved in collection, separation, and commercialization of E-waste and material components. Colonia Renovation in Mexico City is an extended informal network of shops, street venues, organized commercialization, and control of their territory.

Searching alternatives for the management of E-waste, it is necessary for the intervention of all sectors and actors involved in the life cycle of E-waste from its generation. So this study sought to identify the level of knowledge of the generator regarding environmental problems due to the generation, consumption, and disposal of domestic products, and their perception of the problem and current management systems. In addition to obtaining a vision of the impact due to consumption and disposition practices in the search to establish background and possible strategies that support the need to implement measures for the use and recovery of this waste.

References

Araújo, M.G., Magrini, A., Mahler, C.F., Bilitewski, B., 2012. A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. Waste Manag. 32 (2), 335−342. Available from: https://doi.org/10.1016/j.wasman.2011.09.020.

Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The global E-waste monitor 2017: quantities, flows, and resources. In: United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/ Vienna.

Bernache and Chávez, 2014. Informe para la Secretaría de Medio Ambiente y Desarrollo Territorial. La Campaña de ElectroAcopio 2014 en el Estado de Jalisco. Manuscrito no publicado. Guadalajara, México. 15 pp.

Bernache and Chávez, 2015. Los residuos de la transición a la Televisión Digital Terrestre en México. VI Simposio Iberoamericano en Ingeniería de Residuos Sólidos. Tecnológico de Costa Rica. Cartago.

Cucchiella, F., D'Adamo, I., Koh, S.L., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future E-waste streams. Renew. Sustain. Energy Rev. 51, 263−272. Available from: https://doi.org/10.1016/j.rser.2015.06.010.

DOF (Diario Oficial de la Federación), 2015. Ley General para la Prevención y Gestión Integral de los Residuos. Cámara de Diputados del Congreso de la Unión. Última reforma 22/01/2019. Consultado en línea. https://www.gob.mx/cms/uploads/attachment/file/27266/Ley_General_de_Residuos.pdf.

Georgiadis, P., Besiou, M., 2009. Environmental strategies for electrical and electronic equipment supply chains: which to choose? Sustainability 1 (3), 722−733. Available from: https://doi.org/10.3390/su1030722.

Huang, K., Jie, G., Zhenming, X., 2009. Recycling of waste printed circuit boards: a review of current technologies and treatment status in China. J. Hazard. Mater. 164, 399−408.

Kahhat, R., Kim, J., Xu, M., Allenby, B., Williams, E., Zhang, P., 2008. Exploring E-waste management systems in the United States. Resour. Conserv. Recycl. 52 (7), 955−964. Available from: https://doi.org/10.1016/j.resconrec.2008.03.002.

Mihai F.C., Gnoni M.G., Meidiana C., Ezeah, C., Elia V., 2019. Waste electrical and electronic equipment (WEEE): Flows, quantities and management, a global scenario. Chapter 1 in Prasad M.N.V. and Vithanage, Meththika (Eds). Electronic Waste Management and Treatment Technology, Elsevier Science & Technology Books 1−34. Available from: https://doi.org/10.1016/B978-0-12-816190-6.00001-7.

Ohajinwa, C.M., van Bodegom, P.M., Osibanjo, O., Xie, Q., Chen, J., Vijver, M.G., et al., 2019. Health risks of polybrominated diphenyl ethers (PBDEs) and metals at informal electronic waste recycling sites. Int. J. Environ. Res. Public Health 16 (6), 906. Available from: https://doi.org/10.3390/ijerph16060906.

Orlins, S., Guan, D., 2016. China's toxic informal E-waste recycling: local approaches to a global environmental problem. J. Clean. Product. 114, 71−80.

PNUD, 2018. Industria formal e informal del reciclaje de residuos electrónicos en México. Infografía industrial del reciclaje. Available from: Obtenido en: http://www.residuoscop.org/wp-content/uploads/2018/06/Infograf%C3%ADa-Industria-Reciclaje.pdf.

Promexico, 2016. Industria Electronica. Diagnostico sectorial. Unidad de Inteligencia de Negocios de ProMéxico Secretaria de Economía. Mexico D.F.

Román Moguel, Guillermo, 2007. Diagnóstico sobre la generación de residuos electrónicos en México. Informe Final. Instituto Nacional de Ecología, desarrollado por el CIIEMAD del Instituto Politécnico Nacional, México, D.F.

SEDEMA (Secretaría de Medio Ambiente de la Ciudad de México). 2016 Reciclatrón: Jornada de acopio de residuos electrónicos y eléctricos. <http://www.sedema.df.gob.mx>.

SEMARNAT, 2018a. NORMA Oficial Mexicana NOM-161-SEMARNAT-2011, Que establece los criterios para clasificar a los Residuos de Manejo Especial y determinar cuáles están sujetos a Plan de Manejo; el listado de los mismos, el procedimiento para la inclusión o exclusión a dicho listado; así como los elementos y procedimientos para la formulación de los planes de manejo. Diario Oficial de la Federación, 1 de febrero 2013.

SEMARNAT, 2018b. Buenas prácticas para el manejo integral y ambientalmente adecuado de residuos de aparatos eléctricos y electrónicos: Marco General. Programa de las Naciones Unidas para el Desarrollo, Proyecto #92723 "Manejo Ambientalmente Adecuado de Residuos con Contaminantes Orgánicos Persistentes" (ResiduosCOP). México.

Sinha, K.D., Kraeuchi, P., Widmer, R., 2009. Producer responsibility for E-waste management: key issues for consideration: learning from the Swiss experience. J. Environ. Manag. 90 (1), 153−165.

Vega, O.A., 2012. Efectos colaterales de la obsolescencia tecnológica. Revista Facultad de Ingeniería, UPTC 21 (32), 55−62.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on E-waste. Environ. Impact Assess. Rev. 25, 436−458.

Improving sustainability of E-waste management through the systemic design of solutions: the cases of Colombia and Ecuador

19

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19.1 Introduction

19.1.1 The concept of sustainability in solid waste management

In the 1980s, the definition of the sustainable development emerged as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). The concept was formalized in the U.N.'s Agenda 21 (U.N., 1993), and likewise, it has been endorsed in the latest round of global summits and conventions, including Rio + 20 in Brazil (2012), the UN Conference of Parties (COP) on climate change in Peru (COP20) in 2014, and in France in 2015 (COP21). At present, several concepts of sustainability coexist, such as *environmental sustainability* (Ugochukwu et al., 2008), *corporate sustainability* (Marcelino-Sádaba et al., 2015; McManners, 2016), *economic sustainability* (Martens and Carvalho, 2015), and *supplier sustainability* (Craig R. Carter and Dale S. Rogers, 2008), among others.

A global concern regarding sustainability is climate change, which challenges stakeholders to develop coordinated solutions for countries to move toward cleaner, adaptive, and resilient economies (United Nations, 2018a). The Intergovernmental Panel on Climate Change (IPCC) recognizes a dual relationship between sustainable development and climate change; while climate change impacts natural and human living conditions, some activities performed toward sustainable development tend to magnify and strengthen the effects of climate change (IPCC, 2007). Thus, climate change has gained relevance within the global panorama, and it has been

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00012-7

addressed in several conferences, protocols, and agreements, for example, the Kyoto Protocol (2005), the Cancun Agreements (2010), the Durban Climate Change Conference (2011), the Warsaw Climate Change Conference (2013), the Paris Agreement, and the 2030 agenda (2015) (United Nations, 2018b). With this background, climate change policies are expected to be considered an integral part of national sustainable development plans in both developing and developed countries (IPCC, 2007). The primary cause of climate change is the increment of the "greenhouse effect" leading to global warming, which is fueled by human activity, such as fossil fuel burning, agriculture, and deforestation.

Improper solid waste management is another cause of global warming, especially originating from organic waste (Christensen et al., 2009; Hilty and Aebischer, 2014) which is expected to reach 3.40 billion tons by 2050 (Kaza et al., 2018). An attempt to design sustainable solutions for waste management has emerged as the theory of integrated solid waste management, which focuses on integrating processes as generation, segregation, transfer, collection, treatment, recovery, and final disposal (Tchobanoglous, 1994; Tchobanoglous et al., 1993). It has been widely applied in municipal waste management planning and public policy, and based on this concept, several decision-support systems have coupled simulation-based models to study waste generation dynamics (Antanasijevic et al., 2013; Benitez et al., 2008; Maddox et al., 2011), determine landfill allocation (Alves et al., 2009; Antanasijevic et al., 2013; Kollikkathara et al., 2010), and ascertain optimal SWM planning (Yeomans, 2004).

During the Fifth World Urban Forum in Rio de Janeiro in 2010, the management of waste wlectrical and electronic equipment (WEEE) assumed its role as a prominent issue within municipal solid waste in cities around the world (Basel Convention Parties, 2006; Wilson et al., 2012). This recognition demonstrates the relevance of WEEE as part of the discussion on urban sustainability, especially in developing countries (Karak et al., 2012; Oyoo et al., 2011). Similarly, during the COP20, the paradigm of Zero Waste was endorsed as a key sustainability strategy (Zero Waste Europe, 2014). Indeed, Heads of State and Government and High Representatives gathered in New York last September (2015) and declared the new Global Sustainable Development Goals (GSDG). The GSDG are constitutive elements of the 2030 Agenda for Sustainable Development entitled "Transforming Our World" (U.N., 2015). The 2030 Agenda includes 17 goals, two of which are specifically aimed at waste management targets (#2: "Make cities and human settlements inclusive, safe, resilient and sustainable"; #12: "Ensure sustainable consumption and production patterns"). Some cases aim to align the SDGs with public−private partnerships, achieving at least the enhancement of one of the dimensions of sustainability (ecological, economic, and social) depending on which SDG is prioritized. However, most of the studies of public−private partnerships focus on infrastructure and innovation (SDG 9) as well as transportation and education (SDG 4), whereas none of them adopts a holistic approach to sustainability assessment instead they adopt a reductionist view (Pinz et al., 2018).

Despite these advances, WEEE management systems have not yet been consummated in many developing countries, resulting in increased public health risks and generating environmental and socioeconomic problems (Duan et al., 2008;

Widmer et al., 2005). Impacts generated by processes along the life cycle, especially during production, which implicates the mining of metals, collection, and final disposal, do also contribute to climate change. Moreover, recycling of WEEE has become a relevant contribution to reduce the greenhouse gas emissions (Menikpura et al., 2014).

19.1.2 The systems approach and sustainability

As stated in Kveselis et al. (2017) and Méndez-Fajardo (2016), the traditional approach of policy and decision makers in developing waste management schemes involves mainly economic and political factors, which are insufficient to assure the sustainability of the system. Furthermore, to tackle WEEE management issues, and simultaneously achieve the objectives set out in the SDGs, studies argue that policymakers and waste management program designers should apply a systems approach, which provides interdisciplinary support involving technical, social, economic, legal, ecological, political, and cultural elements (Achillas et al., 2010; Chang et al., 2011; Eriksson and Bisaillon, 2011; Méndez-Fajardo and Gonzalez, 2014; Omran et al., 2009).

Usually, systems are defined as "A set of interrelated parts that we experience as a whole," "a set of related things with a purpose" (Espejo and Reyes, 2011), or "conceptual constructs used for engaging with and improving situations of real-world complexity" (Reynolds, 2010). S*ystems science* can be defined as the scientific exploration and theory of systems in various sciences such as biology, sociology, and economics (Klir, 2001) cited by Hieronymi (2013). S*ystems thinking* is a holistic way of thinking that avoids observing only isolated parts but includes understanding the relationships between them, processes, and context; and the *systems approach* refers to the way in which systems can be conceived and studied, and consists of methods and methodologies that incorporate aspects of systems theory to facilitate practice.

A systems approach includes three main foci: the *soft-systems* approach which addresses social systems consisting of human activities and relations which problems are hard to understand; the *hard-systems* approach that identifies purely technical, predictable, and optimizable systems; and the *critical-systems* approach which coordinates the two mentioned above under the definition of sociotechnical systems. Table 19.1 shows some of the primary authors of these approaches as follows.

Table 19.1 The main formal systems approach.

Foci	Formal system approach
Soft-system	Soft systems methodology (Checkland, 1984) Interactive management (Ackoff, 1981)
Hard-systems	Operations research (Churchman et al., 1957) Systems dynamics (Forrester 1971; Meadows, 1989)
Critical-systems	Critical systems heuristics (Ulrich, 1983) Liberating systems theory (Flood, 1990) Interpretive systemology (Fuenmayor, 1991)

The concept of sustainability implies thinking in a holistic way. From the approach of sustainable development, the Triple Bottom Line framework encompasses three perspectives: social, environmental, and economic (Elkington, 1994). International organizations such as the WBCSD and the UN have identified two common characteristics of sustainability: (1) a multidimensional approach that integrates social, environmental, and economic issues; and, (2) a temporal dimension expressed as "present and future" or "long-term" which implies a cause—effect way of thinking. The methodology described in this chapter named as *systemic-design* aims at orchestrating the previous elements of sustainability and some additional ingredients of systems theory and approaches. Thus, in this chapter the authors propose to include more dimensions, as well as to couple them with stakeholder's understandings, interests, and motivations; with life cycle processes, and address them from a cause-and-effect way of thinking (Méndez-Fajardo et al., 2017b). This methodology applied to policy design is fully described in Section 19.3.

19.1.3 The extended producer responsibility: a systemic approach toward improving sustainability

The extended producer responsibility (EPR) principle promotes the improvement, in environmental terms of production and manufacturing systems (Agamuthu and Victor, 2011; Herdiana et al., 2014) by placing the responsibility of end-of-life management on producers and distributors. According to Lindhqvist (2000), EPR aims at influencing production processes in one of two directions (upstream or downstream): shifting responsibility to downstream procedures that involve different actors in collection, recycling, and treatment processes; providing upstream incentives to producers to incorporate environmental considerations in the design of their products (Herdiana et al., 2014), for example, cleaner production or design for recycling (Mayers, 2007).

To implement this principle, it is necessary to count on significant levels of cooperation and coordination between actors, the inclusion of the value chain considering the product life cycle processes, and the creation of legal instruments that ensure the EPR's goals achievement. These requirements can be satisfied by conceiving the management system from a holistic approach.

The European Waste Electrical and Electronic Directive (WEEE Directive) categorizes WEEE since August 2018 in 6 groups: (1) temperature exchange equipment (TEE), (2) screens, monitors, and equipment containing screens having a surface greater than 100 cm^2, (3) lamps, (4) large equipment (any external dimension more than 50 cm), (5) small equipment (no external dimension more than 50 cm), and (6) small IT and telecommunication equipment (no external dimension more than 50 cm) (The European Parliament and The Council on WEEE, 2012). The main reasons for categorizing WEEE into these groups are the different logistics of collecting and transporting according to size and weight of equipment, and the components which require a differentiated treatment.

The reverse logistics chain has emerged as a key element of a WEEE management system. Usually, it entails collection points often located where EEE is sold and at municipal waste collection facilities. The organizational structure for a WEEE management system is often based on producer responsibility organizations (PRO), which implements EPR in a collective scheme of producers, importers, and distributors.

19.2 Waste electronic and electrical equipment management in developing countries

Since EEE consumption has overgrown over the last 5−10 years in all developing countries, WEEE or E-waste has become a pertinent global waste stream due to its resulting high growth rate (Ahluwalia and Nema, 2007). Hazardous components in WEEE can have public health effects and environmental consequences. These problems are exacerbated in developing countries due to low-tech recycling and disposal processes, poor operational practices, and characteristics inherent to some products and substances upon disposal. Studies performed in Peru, Colombia, China, India, Nigeria, and Ghana make it clear that the prevailing—inadequate—recycling operations can engender severe health and environmental effects (Amoyaw-Osei et al., 2011; Chi et al., 2011; Empa and CNPML, 2008; Espinoza et al., 2008; Ezeah and Roberts, 2012; Sinha-Khetriwal et al., 2005; Thanh and Matsui, 2011; Widmer et al., 2005).

In spite of the hazard presented in some WEEE components, it concurrently presents an opportunity, since WEEE contains base and precious metals (e.g., gold and silver solders), rare earth elements (e.g., neodymium in computer hard disks), and other critical raw materials (e.g., indium in screens and gallium in mobile phones). These elements can be recovered, yet, in some cases, they are lost in the recycling chain (Herat and Agamuthu, 2012; Reuter and Van Schaik, 2012; Widmer et al., 2005). Developed countries, such as Switzerland, began implementing WEEE collection and recycling programs in the 1980s. Therefore the technologies needed to recover valuable materials from WEEE are well-known, but mainly implemented in the industrialized world, while in developing countries strategies to create citizen awareness about the importance of sorting and recycling waste are a much more recent phenomenon.

19.2.1 Waste electronic and electrical equipment generation rates and management processes in developing countries

Recent statistics show that the global quantity of EEE entering the market in 2012 was around 65 Mt and the corresponding WEEE was between 42 and 49 Mt (Böni et al., 2015; GSMA TM and UNU-IAS, 2015), and it is expected to grow to 52.2 Mt in 2021, with an annual growth rate of 3%−4% (Baldé et al., 2017). In Latin America, the largest producer of E-waste is Brazil, with roughly 1.42 Mt in 2014, and 1.5 Mt in 2016. Mexico has jumped on the second place, from roughly 910 kt in 2014 to 1 Mt in 2016 (Baldé et al., 2017). In China, the per capita generation of WEEE is around 3.5 kg/inh/year (Araújo et al., 2012; Swiss E-waste programme and FEAM, 2009), while in Chile 8.7 kg; and in Argentina, 8.4 kg. Of the total WEEE generated globally in 2016 (44.7 Mt), roughly 25.3% was generated in the Americas, with 6.3 Mt generated in the United States. WEEE generation in Latin-American countries has been on the rise: in 2009, this figure was roughly 2.8 Mt; in 2014, it spiked to 3.9 Mt; and 4.2 Mt in 2016 (GSMA TM and UNU-IAS, 2015). Taking the example of computers, studies have calculated a global WEEE generation of around 0.3 kg/capita per year; however, in countries such as Mexico, Argentina, and Chile, rates are much higher (0.44, 0.49, and 0.42 kg/inhabitant/year, respectively) (Araújo et al., 2012).

19.2.2 Processes

A generic scheme of the EEE and WEEE management process cycle in developing countries is shown in Fig. 19.1. EEE production in countries such as Colombia and Ecuador refers mainly to equipment imports and, to a lesser degree, the import of (foreign) parts and local (domestic) assembly. Likewise, distribution involves large and small retailers and is divided into new and second-hand (donated, repaired, or reconditioned equipment) EEE.

Mining activities negatively impact the environment in the form of ecosystem degradation, pollution of natural resources (air, ground, and water), in addition to public health problems (Brunner, 2011). Consequently, urban mining, which is the term for city dwellers' use of WEEE as a material source, has taken on growing importance for material recovery and decreased primary extraction (Simoni et al., 2015).

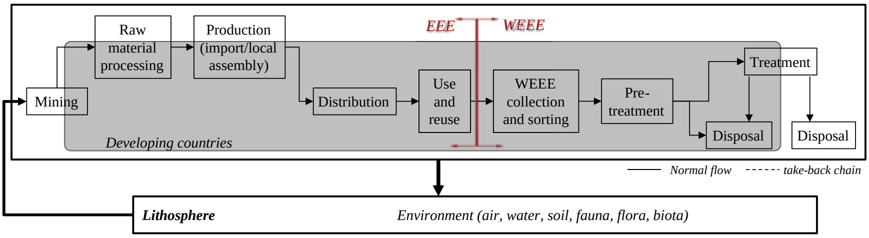


Figure 19.1 Generic WEEE management processes in developing countries.
Source: Adapted from Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. https://doi.org/10.1021/es403506a and Streicher-Porte, M., Marthaler, C., Böni, H., Schluep, M., Camacho, Á., Hilty, L.M., 2009. One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia. J. Environ. Manage. 90, 3498–3511. https://doi.org/10.1016/j.jenvman.2009.06.002.

The smuggling of low-quality equipment represents a part of imports (production) in developing countries, which increases the amount of WEEE generated given that it must be added to the WEEE exports from the developed world to developing countries. The use-reuse phase displayed in Fig. 19.1 includes both new and used equipment, and the generation of WEEE occurs once EEE is declared obsolete by the consumer. At this juncture, it demands pretreatment (either repaired or disassembled), with the option of selling or exporting the whole obsolete equipment, breaking it down into parts, disposing of it in sanitary landfills or introducing it into formal and mostly, informal.

19.2.3 Actors

In order to improve WEEE management, seven Latin-American countries have introduced specific legislation; Colombia is one of these seven countries. In total, eleven Latin-American countries have begun drafting a regulatory framework (Baldé et al., 2017; GSMA TM and UNU-IAS, 2015). The majority of these regulations are based on the EPR principle, which places the responsibility for equipment on its respective producer(s), importers, and distributors including the final disposal of toxic constitutive elements (e.g., heavy metals) and the recovery of materials (e.g., metals and plastics). Main (generic) actors at the national level include the environmental authority, the ICT authority, the import/export authority, the producing industry, distributors, and retailers of new and second-hand equipment, recyclers (formal and informal) and, last but certainly not least, consumers. In countries where EPR has been implemented, and collective take-back schemes are in place, producer responsibility organizations (PRO) serve as the bridge between consumers and producers, thus acting as an essential stakeholder in its own right (Fig. 19.2). In order that a PRO can really function, physical infrastructure is needed; however, studies in various countries reveal the inadequate progress of these strategies in urban areas and their virtual inexistence in rural areas (Chi et al., 2011; Empa and CNPML, 2010, 2008; Espinoza et al., 2008; Ott, 2014; Sinha-Khetriwal et al., 2005).

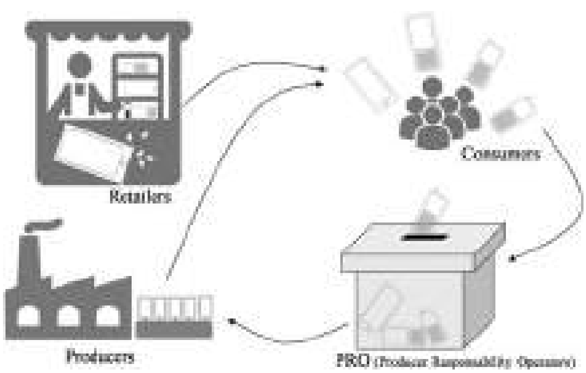


Figure 19.2 Generic actors and producer responsibility organizations (PRO).

One of the main barriers to implement collection and management strategies through PRO in these countries has been the lack of coordination and cooperation among public organizations and between public and private institutions. For example, as shown in Fig. 19.2, cooperation between producers and retailers is needed to physically install the collection device so that consumers could deposit WEEE. In addition, the cooperation between the PRO and recyclers and treatment services is required to assure adequate treatment of the devices. Furthermore, the promulgation of regulations and public policies help to achieve necessary stakeholder participation. However, this needs to be complemented by control instruments by the relevant authorities. Public policies are usually designed (and passed) by only one authority (generally the environmental authority), despite the fact that the complexity of the system demands intersectorial cooperation. In order to assure that the cooperation becomes effective, multisectoral public policies are required (e.g., involving ICT, education, and public health authorities).

19.2.4 Waste electronic and electrical equipment management in Colombia

Colombia has around 49.8 million inhabitants, 74% live in urban areas (DANE, 2018) where the most substantial amounts of WEEE are generated. In 2013, the generation of WEEE was around 120 kt, which includes large household appliances (24%), IT and telecommunications equipment (17%), consumer equipment (38%), lighting equipment (13%), and batteries (8%) (Pronet, 2013). The per capita generation of WEEE in Colombia has increased from 3.7 kg/inhabitant in 2009 to 5.3 kg/inhabitant in 2014 (GSMA TM and UNU-IAS, 2015). To determine urban per capita generation of WEEE, it is important to account for the six different socioeconomic levels in the country: low−low (22.2% of the total population), low (41.2%), medium−low (27.1%), medium (6.4%), medium−high (1.9%), and high (1.2%) (Ministerio de Hacienda y Crédito Público et al., 2005).

Generic WEEE management processes in Colombia are shown in Fig. 19.3, which only includes the formal system or processes authorized by the environmental authority.

Nowadays in Colombia, there are some authorized collection systems. Nevertheless, a high share of obsolete devices is collected and pretreated by informal or nonauthorized workers (Fig. 19.4) and metals are recovered. Informal collectors usually dismantle WEEE by pounding the objects against the ground, increasing health risks and harmful environmental effects due to the toxic elements contained in WEEE (Empa and CNPML, 2010; León, 2010; Streicher-Porte et al., 2005; Widmer et al., 2005).

19.2.4.1 Postconsumer programs as producer responsibility organizations in Colombia

In Colombia different PRO, named as *postconsumer programs*, have emerged in recent years based on EPR. In 2015 there were around 100 authorized programs,

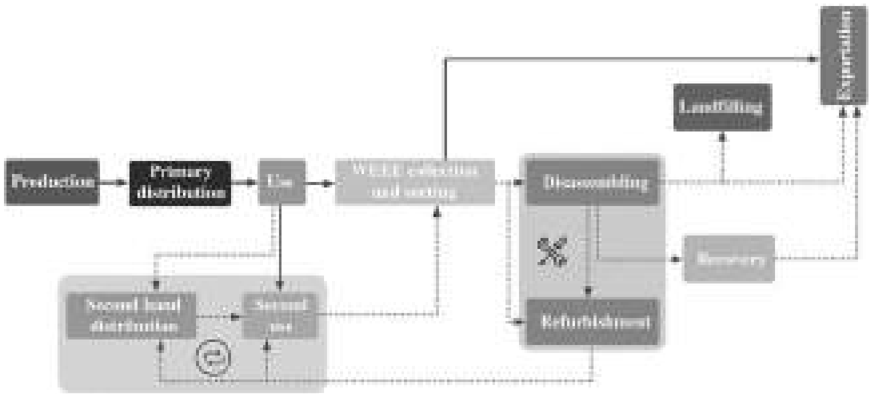


Figure 19.3 Generic waste electrical and electronic equipment (WEEE) management processes in Colombia.
Source: Adapted from Méndez-Fajardo, S., 2016. Systemic Decisions for More Sustainable WEEE (Waste Electrical and Electronic Equipment) Management in Developing Countries. Pontificia Universidad Javeriana, Bogotá D.C and Méndez-Fajardo, S., Böni, H., Hernández, C., Schluep, M., Valdivia, S., 2017a. A practical guide for the systemic design of WEEE management policies in developing countries; Méndez-Fajardo, S., Gonzalez, R.A., & Barros-Castro, R.A., 2017b. Using actor-network theory in agent-based modelling. In: García-Díaz, C., Olaya, C. (Eds.), Social systems Engineering: The Design of Complexity. Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118974414.

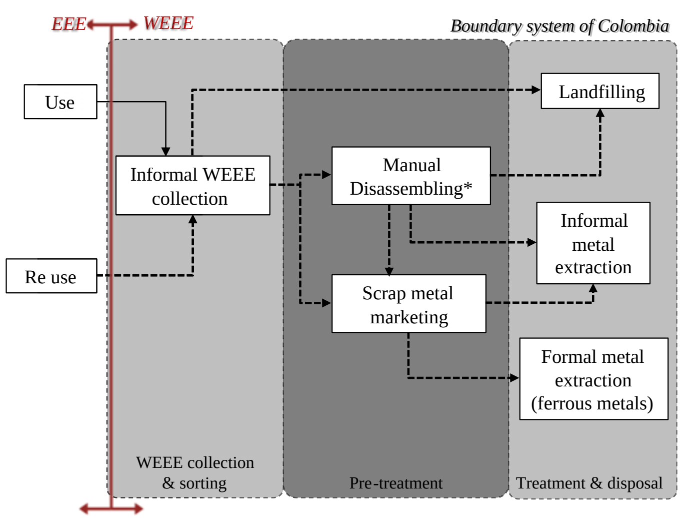


Figure 19.4 Subsystem of informal waste electrical and electronic equipment (WEEE) management processes in Colombia.

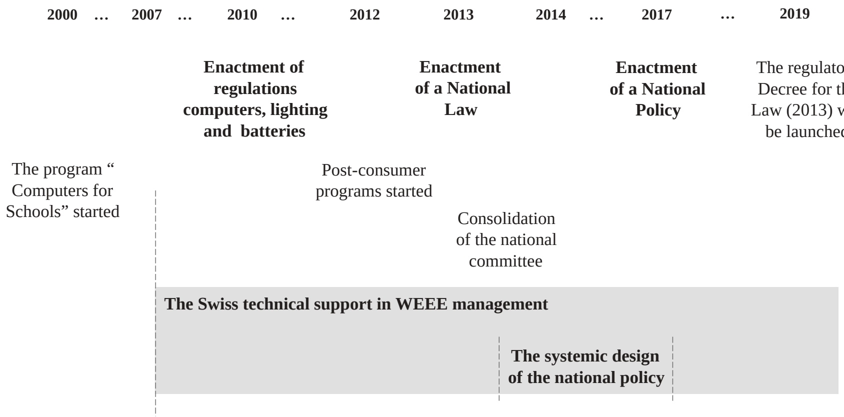


Figure 19.5 Milestones within the waste electrical and electronic equipment (WEEE) management history in Colombia.
Source: Adapted from Méndez-Fajardo et al. (2016).

the main being *Eco-Cómputo* for computers, *Pilas con el Ambiente* for batteries, *Lumina* for lighting equipment, and *Red Verde* for large household appliances such as refrigerators and washing machines. As part of the system, formal organizations of recyclers are known as WEEE managers (*gestores* in Spanish). They are contracted by postconsumer programs like *Eco-cómputo* to treat the WEEE collected.

In addition to producers, postconsumer programs and WEEE managers, other generic actors involved in WEEE management in Colombia can be classified as distributors, consumers, informal (nonauthorized) recyclers or operators, and the government at national, regional, and local levels. Recyclers usually play the supplementary role of collectors. To better identify the relevant actors, we have reviewed the milestones in the history of WEEE management in the country (Fig. 19.5).

The National WEEE Committee (NWC) was created in 2013 to advise policy decisions and follow-up policies, strategies, and programs. As promulgated by the Law 1672/13, the NWC must establish the mechanisms for negotiating with the private sector; identify sources of financial support; and support research and related technological innovations. The NWC is made up of associations that include groups of producers (ANDI—The *Asociación de Industriales de Colombia*) and CCIT—*Cámara Colombiana de Telecomunicaciones* (Colombian Chamber of Informatics and Telecommunications) and distributors (FENALCO—the *Federación Nacional de Comerciantes*), as well as the *Ministerio de Ambiente y Desarrollo Sostenible* (MADS), the *Ministerio de Protección Social* (Ministry of Health and Social Protection), the *Ministerio de TICSs* (Ministry of Communication and Information Technologies), and the *Ministerio de Comercio, Industria y Turismo* (Ministry of Commerce, Industry and Tourism). Two delegates from authorized WEEE recyclers, two advisers and one representative from the *Centro Nacional de Producción Más Limpia*—CNPML (the National Cleaner Production Center) were added to the committee. Last, but not least, the NWC counts on the support of international experts.

In June of 2017, the National Policy for the Integrated WEEE Management in Colombia was launched by the Ministry of Environment and Sustainable Development. Its contents and process of design are explained in Section 19.4.5.

19.2.5 Waste electronic and electrical equipment management in Ecuador

In Ecuador, the governments are divided geographically and in a decentralized way. Hence, the competencies for solid waste management are assigned to each municipality (Asamblea Constituyente, 2008; Asamblea Nacional, 2017, 2012), 221 in total (INEC, 2017). However, WEEE is not considered as Municipal Solid Waste (MSW) but as special waste, if it has not been disassembled; otherwise it is considered as hazardous waste (MAE, 2012). As in Colombia, the Ministry of Environment and Water of Ecuador is in charge of developing legal regulations for WEEE management and authorizes waste managers to operate, but due to operative limitations, these competencies can be delegated to municipal or provincial governments. In 2016, the amount of WEEE generated in Ecuador reached 90 kt 2016 (Baldé et al., 2017); from this, 75.6 t were collected by 24 municipalities (INEC, 2017). Additionally, because in Ecuador WEEE is traded jointly with scrap metal (Beltrán, 2013), the Council of Foreign Trade and Investments and the Ministry of Production, Employment and Competitiveness established regulations to control the exportation of scrap (IRR, 2015; MIPRO, 2010). In three of the biggest cities of Ecuador Quito, Guayaquil, and Cuenca, informal collection of WEEE reaches 5.99 kt and of scrap metal 7.54 kt (IRR, 2015). The informal sector is essential in the WEEE management chain but usually is exposed to poor health and environment conditions.

The Ecuadorian legislation enforces the precautionary principle, and the extended producer responsibility concept (EPR). The precautionary principle implies that even if there are no scientific data about a severe risk or harm to the environment, it is imperative to propose measures to prevent degradation. The EPR principle is related to the responsibility of the producers, importers, or distributors along the life cycle of the products. It means being responsible for material selection, processes, and final disposal (Asamblea Nacional, 2017; MAE, 2013).

19.3 The systemic-design of solutions

The systems approach translated into the systemic-design proposed herein considers WEEE management to be a sociotechnical system. It is constituted by the interaction between human factors like decision-making, interests, or habits, and technical elements such as waste itself, treatment technologies, and infrastructure.

In order to lead the systemic design process of a WEEE management system, the formation of a team is required. This systemic-design team should involve at least three generic actors: one who approves the final design, one who brings in technical

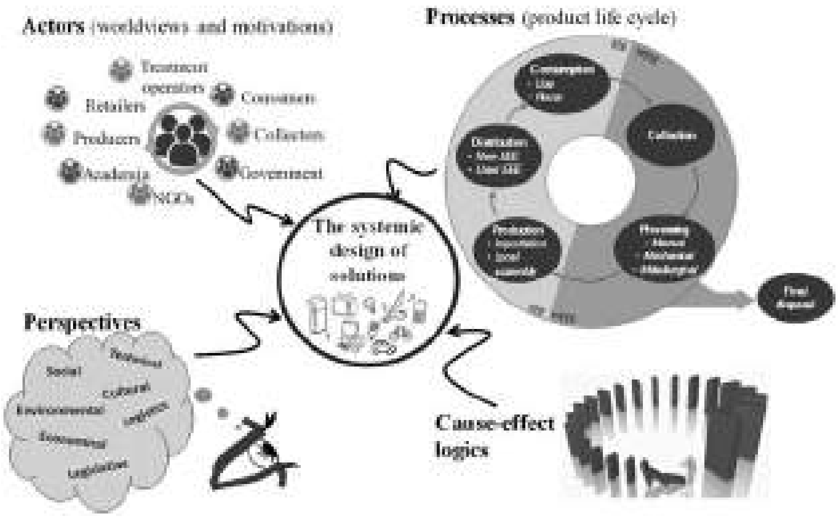


Figure 19.6 PAPC-E, the four elements of the systemic design.
Source: Adapted from Méndez-Fajardo, S., Böni, H., Hernández, C., Schluep, M., Valdivia, S., 2017a. A practical guide for the systemic design of WEEE management policies in developing countries; Méndez-Fajardo, S., Gonzalez, R.A., & Barros-Castro, R.A., 2017b. Using actor-network theory in agent-based modelling. In: García-Díaz, C., Olaya, C. (Eds.), Social systems Engineering: The Design of Complexity. Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118974414.

and logistic support, and one who leads and guides the methodology. In the case of policy design, the first should be the governmental institution in charge of developing related legislation. The technical and logistic support could involve, for example, one national and relevant ONG and/or international advisors, while the methodological support could come from, for example, the academia.

The systemicity of this methodology is evidenced in two ways: the systemic elements PAPC-E (perspectives, actors, processes, cause-effect) that should be applied during the whole design process, and the logic that actors involved follow in the design. To increase the empowerment of actors and the collective knowledge about holistic WEEE management, designers of solutions or policies should include the four elements shown in Fig. 19.6. This scheme includes some examples within each element, but in accordance with the context, there could be less or more parts (e.g., different actors or additional processes).

Cause-effect logic implies considering three-time horizons: the past, the present, and the future. The past refers to what involved actors could learn from past successful and failed actions, while the present is the assessment of the current situation. The systemic-design also brings tools to include the improved future or the idealized design, which is explained within the design journey below.

The design journey is composed by the phases that lead participants to build a holistic policy or solution. Although the phases shown in Fig. 19.7 look like the

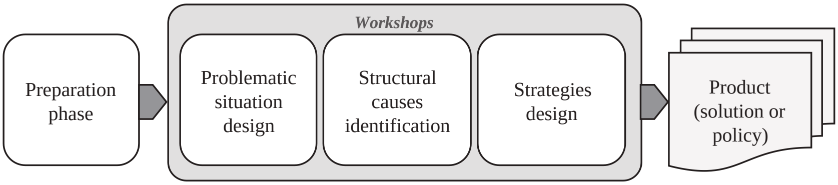


Figure 19.7 The phases that constitute the systemic-design journey.
Source: Adapted from Méndez-Fajardo, S., 2016. Systemic Decisions for More Sustainable WEEE (Waste Electrical and Electronic Equipment) Management in Developing Countries. Pontificia Universidad Javeriana, Bogotá D.C and Méndez-Fajardo, S., Böni, H., Hernández, C., Schluep, M., Valdivia, S., 2017a. A practical guide for the systemic design of WEEE management policies in developing countries; Méndez-Fajardo, S., Gonzalez, R.A., & Barros-Castro, R.A., 2017b. Using actor-network theory in agent-based modelling. In: García-Díaz, C., Olaya, C. (Eds.), Social systems Engineering: The Design of Complexity. Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118974414.

traditional path of design, their specific goals and methods constitute a fundamental difference; in addition, each of these steps should include the PAPC-E elements resulting in high levels of participation and collective learning.

A systemic implementation should follow the systemic design. This implies that high participation of actors, cooperation and coordination is desired. In the same way, activities of the solution or policy implementation should provide feedback to the initial design under a dynamic of adaptation and continuous improvement.

19.3.1 Preparation phase

This phase aims at gathering and analyzing existing information and documents such as assessments, studies, research, news, legislation, among others. The outcomes of this stage help to understand the context and provide the primary material to start the most participatory activities. In this phase, all actors (relevant and secondary) should be identified, and it is suggested to hold interviews with the relevant actors previously to begin engaging them in the design process. The structured interviews could include questions about the past (which actions have been already made, who participated, which elements of failure or success could identify), about the current situation of the WEEE management, and expectations about a better future waste handling.

19.3.2 The pillar of the systemic-design: actor participation through workshops

As Fig. 19.7 shows, the methodology includes three main workshops within which the perspectives, actor's motivation, processes, and cause-effect logic (PAPC-E) are identified. Participants would navigate here from the past to the present until reaching the foundations for the desired future.

Figure 19.8 Paradigms, concepts, and parts of a generic WEEE management system.

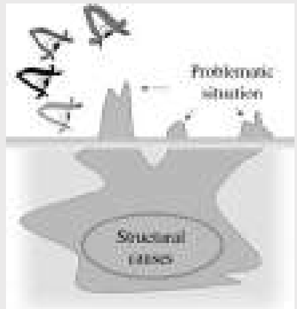
The reasoning for these three steps can be explained with the following example: it is common to identify the "vast vehicle mobility" as the main problem in a huge and congested city. However, if we would ask different citizens about the causes of this problem, we could make a list of additional issues like "the lack of roads," "the bad public transport system," "the excess of cars," "the excess of bicycles or motorcycles," "the lack of transit rules and signs," "the lack of fines," "the high accidentality," among others. At some point, it is difficult to identify the best solution because it is not easy to really point at the most relevant problem to solve.

Applying this on WEEE management, planners or policymakers are immersed in several concepts and paradigms around the topic which includes many tools and theories to solve related problems (Fig. 19.8). Additionally, each actor will have different approaches and interests, but their integration is required. How can decision makers deal with this complexity? What are the most relevant issues to solve? What are the most urgent ones? How to invest resources in more sustainable solutions?

To tackle this, the systemic design couples three main methods to follow the analogy of the iceberg, going in a participatory way from the list of problems related to a focal one, providing solutions to the most relevant or structural issues (Table 19.2). As in the analogy, what each person thinks is the main problem to solve could become just an effect of the deepest (structural) problems. To facilitate discussions, we suggest categorizing as "sub-problem" all possible problems, causes or effects that constitute the problematic situation.

The problem tree method is part of the logical framework for designing and evaluating projects (CEPAL et al., 2005) and has been used to design public policies in Colombia on the basis of the identification of causes and effects constellated around the main problem. This main (focal) problem should encompass smaller

Table 19.2 Methods coupled into the core of the systemic design of solutions.

Problematic situation design		**Structural causes identification**	**Strategies design**
Adapted method	Problems tree (CEPAL, 2005)	Matrix of direct influences (Godet, 2009)	Round Robin (LUMA, 2012)
			
General description	Consensus on the focal problem and identification of causes and effects.	Evaluation of influences between subproblems	Validation of strategic or main policy's (or solution's) goals.
	Identification of relations between them	Prioritization of subproblems through the matrix	Design of strategies to achieve the goals
	Preprioritization	Analysis of the graph of dependency-mobility of subproblems	Strategies prefeasibility

problems in a general statement such a "the infective WEEE management in the country," or "the pollution generated for unhandled WEEE in the country." Then, participants should identify as many subproblems as possible, locating them in the correspondent perspective proposed by the systemic-design team (sociocultural, economic, technical, and environmental). In the logic of the iceberg's analogy, participants could make a preprioritization of subproblems by rating them with points.

There are several methods to do that, among which we suggest using the Godet's matrix of direct influences. Here, actors involved in the design assign weights to the possible relationship between "perceived problems" of 0, 1 or 2, where "0" means not existing influence, "1" weak influence, whereas "2" shows a strong influence (see Fig. 19.9).

	Sub-problem	a	b	c	d	e	Influence Σ	Influence %
	a	-	0	1	1	0	2	25
	b	1	-	1	1	1	4	50
	c	0	0	-	0	0	0	0
	d	0	0	1	-	0	1	12,5
	e	0	0	1	0	-	1	12,5
Dependency	**Σ**	1	0	4	2	1		
	%	12,5	0	50	25	12,5		

Figure 19.9 Matrix of direct influences.
Source: Adapted from Godet, M., 1993. From Anticipation to Action: A Handbook of Strategic Prospective. Unesco Publishing.

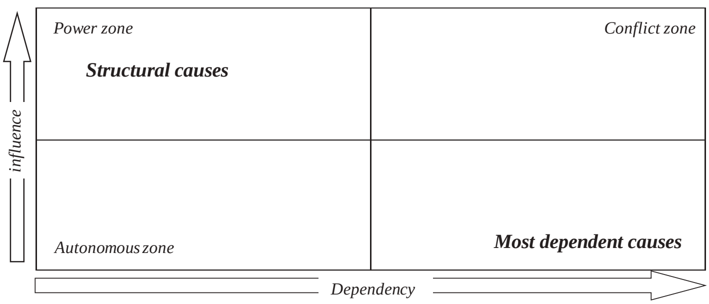


Figure 19.10 Graph of dependency and influenceability between causes (or subproblems).

As shown in this matrix, the highest sum in rows evidences the "perceived issue" that most influences others, while the highest sum in columns shows the most dependent "perceived issue" (or the most impressionable).

Based on this matrix, the graph shown in Fig. 19.10 can be generated. It locates the structural causes as the most dependent and most easily impressionable causes. More direct influences mean a cause is more conflictive. However, if a cause has few dependencies, it can be considered an autonomous cause (if it does not influence several other causes) or a structural one (if it does influence several other causes).

From these results the most relevant inputs to design the strategies can be derived as follows:

- Strategic or main goals are the structural causes written as objectives.
- Means to achieve these goals through the strategies come from current legislation, the main subproblems identified in the first workshops, written as tool or activity. For example, "the lack of infrastructure" as "creation of infrastructure." The systemic design team could also include good practices derived from developed countries which could be adapted to the specific context.

- Relevant actors of the system who have been identified since the preparation phase of the design (see Fig. 19.7).
- To develop the round robin (the method as suggested in Table 19.2) participants will form groups each of which starts by writing a strategy to achieve an assigned goal. In the second round each group has the opportunity to criticize and to improve the strategy written by the neighboring group, based on a preevaluation of its feasibility; this includes questions as "which possible obstacles could have the strategy from an economic (or: logistic, legislative, environmental, technical) point of view?". In the end, the systemic-design team receives a group of strategies preevaluated by participants, additional of an increase in the empowerment of the actors regarding the designed policy (or solution), and higher levels of confidence between them.

Finally, inputs to define the policy action plan or to schedule solution activities come from all previous stages of the systemic design. In the case of a policy, this stage falls more on intern processes of the authority who has been leading the process (e.g., Ministry of Environment, or Ministry of Industry). Usually, this step involves legal and technical offices to verify that goals, strategies, and actions are aligned with current laws, decrees, and regulations.

19.4 The systemic-design of the waste electronic and electrical equipment management policy in Colombia

Colombia has set the legal framework for a national WEEE management system based on the EPR policy principle, which demands the involvement of all actors along the entire take-back process. Therefore the implementation of such a system requires consensual decisions and strategies designed to affect every actor in the reverse supply chain. Additionally, EPR entails the implementation of infrastructure to collect WEEE from consumers with active distributor participation and the design of infrastructure for the transport, storage, and treatment of this waste.

The design of the policy began in 2010 under the leadership of the MADS, with the involvement of some additional actors in the process. Nevertheless, the delay in the alignment of their interests forced the MADS to publish first a national law (2013). Supported by the Swiss development cooperation through the program Sustainable Recycling Industries (SRI), the systemic-design process of the policy developed between February of 2014 and October of 2015 was a cornerstone for reinitiating the policy development process that came to stagnancy before. The results of this process became fundamental for the design of the final policy and action plan launched in June 2017.

As a pillar of the systemic design methodology, workshops and meetings were held with the members of the NWC representing the most relevant actors. The Swiss funded Sustainable Recycling Industry Program through experts from the Swiss Federal Laboratory for Materials Science and Technology (Empa) and the

Figure 19.11 The first workshop of the systemic design to identify causes and effects related to the focal problem.

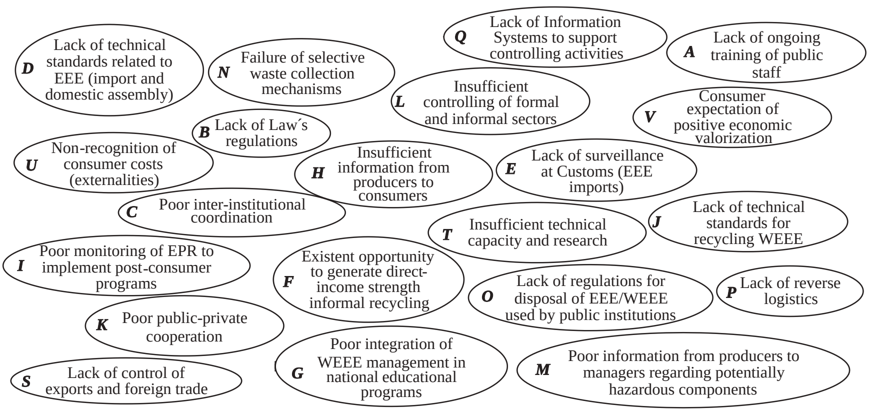


Figure 19.12 Subproblems identified by participants (without prioritization).

World Resources Forum (WRF) supported the process. At some stages, other participants like academy and NGOs were involved.

19.4.1 The design of the problematic situation

The process started by interviewing relevant actors and compiling existing documents like baseline assessments and existing regulations. This information was the main input for the first workshop (October 2014). In order to use the *problem tree*, participants defined the focal problem to be addressed: "the insufficient and inadequate WEEE management in the country" (MADS, 2017). Based on this, actors identified causes and effects through a *think tank*, classifying them into the following dimensions: environmental, sociocultural, economic, technical, and political (Fig. 19.11—in the middle). Additionally, the method of *visualizing the vote* was used to prioritize the identified causes (Fig. 19.11—right).

The list of subproblems identified by the participants (Fig. 19.12) included 21 items. Participant votes traced the leading cause of the focal problem to consumer

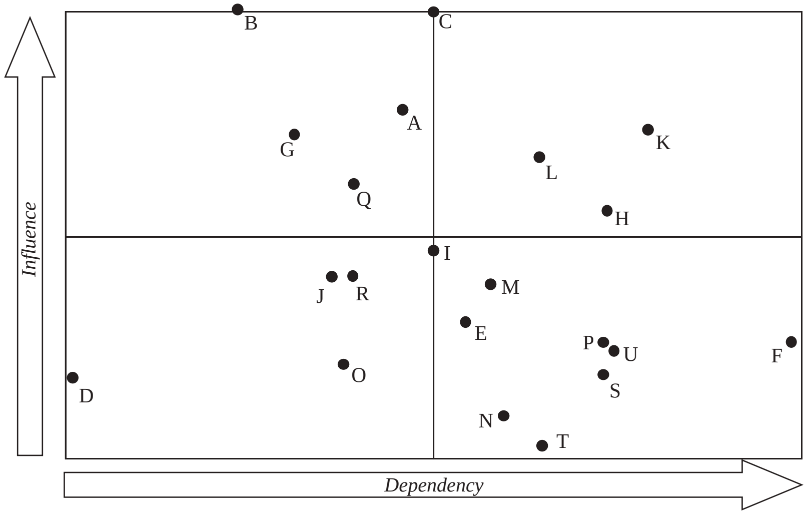


Figure 19.13 The final diagram used visualize cause tendencies.

behaviors, the lack of a systems approach in decision-making, and the lack of monitoring and control by authorities.

19.4.2 Identification of structural causes

As explained in Table 19.2, to identify the deepest causes (or subproblems) as in the *iceberg analogy*, the structural analysis method based on the matrix of influences MDI (Godet, 1993) was used. At the end of this second workshop, actors reached a consensus on the most dependent and influencer facts. Fig. 19.13 depicts in which the conflictive, autonomous, and power (structural) causes were visualized.

The structural causes that emerged as a result of the matrix of influence exercise are shown in Fig. 19.14.

19.4.3 Participatory design of strategies

The third workshop aimed at designing potential strategies to achieve the strategic objectives, which emerged from the main elements: the existing national law and the structural causes of the focal problem. The five identified objectives were the following:

Objective 1: Minimize public health and environmental impacts potentially caused by inefficient WEEE management.

Objective 2: Increase cleaner production and responsible consumption through more sustainable WEEE management by primarily focusing on minimizing generation and offering socioeconomic incentives for properly discarding of WEEE.

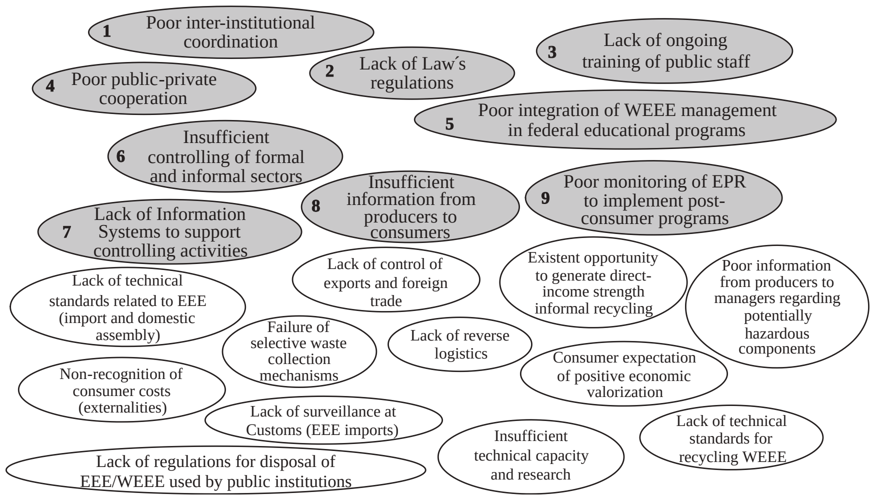


Figure 19.14 Structural (or the more dependent) causes prioritized through the MICMAC method.

Objective 3: Promote the engagement of actors involved in the EEE and WEEE production chain, regarding especially the design and implementation of strategies, plans, and projects related to WEEE management.

Objective 4: Facilitate consumer participation through collection programs and infrastructure to prevent informal activities and the presence of WEEE in public areas and sanitary landfills.

Objective 5: Improve the functional efficiency, transparency, and reliability of EPR systems.

The *round-robin* method included a two-round process that critically engaged the attendees who were arranged into five groups (number of strategic goals). In the first round, participants wrote the strategy and described related responsibilities of the public and private sectors, as well as the civil society. Then, in the second round, each team reviewed a form filled out by a different team to review and subsequently gave their opinion about whether or not they believed the strategy proposed was viable from economic, legal, technical, and institutional points of view. If this last step improved the strategy, specific changes proposed were reported on the form.

At the end of the workshop, a list of strategies was proposed for each strategic goal. These were taken into account in the final design of the policy, a process led by the MADS.

19.4.4 Decision-enhancement studio

An additional activity developed to reinforce the systemic approach of the strategies consisted of a decision-enhancement studio DE-S (Keen and Sol, 2008; Méndez-Fajardo, 2016). This studio entailed the design and use of a computer-based simulation which simulated consumer's behaviors around WEEE management. The technological tools aimed at facilitating an understanding of what it means to adopt a "systems-based approach" about a problem situation, which, in turn, was ultimately geared toward a sparking dialogue among policymakers. The agent-based model named Coop4SWEEEM—Cooperation for Sustainable WEEE Management (Méndez-Fajardo, 2016)—included information from the preparation phase, and a survey replied by 1614 participants.

As an argument to define the main question to solve in the DE-S of "*How to influence consumers to deliver their WEEE to the formal collection system*?," we concluded that the low participation of consumers is the main cause for the low rates of WEEE collection. Two main factors determine the amount of WEEE collected: consumer behavior (Desa et al., 2011; Ongondo and Williams, 2011; Saphores et al., 2012) and the existence of a physical infrastructure, which affects consumer attitudes (which culminate in behavior). The development of a physical infrastructure depends on coordination and cooperation among public and private organizations and the existence of a legal framework. As simulated in Coop4SWEEEM, common consumer attitudes in WEEE management include storage of obsolete items at home, transfer to family members, friends, or informal recyclers or disposal along with ordinary waste (Fernández, 2007). According to the survey developed as part of the Coop4SWEEEM design, 53.3% of the consumers do prefer to deliver their WEEE to postconsumer programs (PCP) located in shops and stores where EEE is sold. Within this population, there were four main motivations to return their WEEE, which were included in the simulation: to receive money (21.7%), to support social projects (70.8%), to find the collection infrastructure or urn to deposit the WEEE (3.7%), and to receive information about WEEE management and the system (3.7%).

The DE-S was developed at the *Pontificia Universidad Javeriana* of Bogota, in 2015 (Fig. 19.15). The 15 attendees (from public institutions, private organizations, or companies), represented the main WEEE management decision makers in Colombia: The MADS, the ANDI (industrial association), the CNPML, two postconsumer programs, eight authorized recyclers, and Empa and WRF from Switzerland.

Using Coop4SWEEEM, the participants simulated different combinations of two PCP by playing with incentives between the following two options: to provide money to the consumers in exchange for their WEEE, and/or to allow consumers to

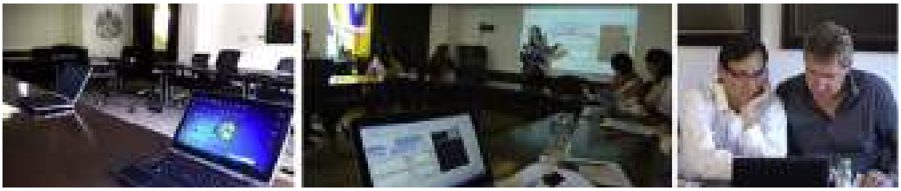


Figure 19.15 Development of the decision-enhancement studio (DE-S).

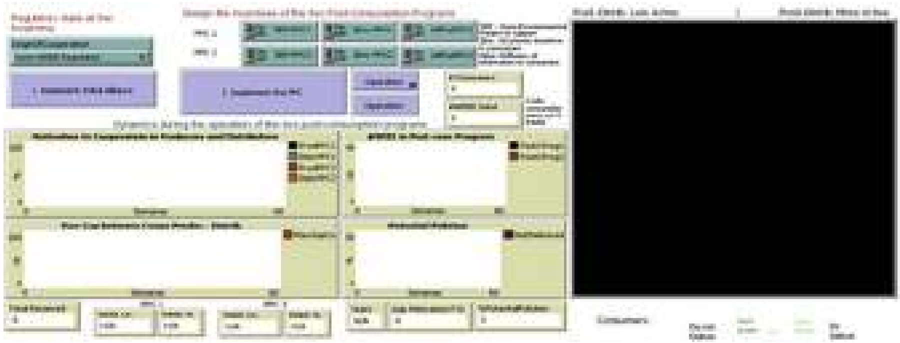


Figure 19.16 Interphase of COOP4SWEEEM in Netlogo (Méndez-Fajardo, 2015).

support social projects in exchange for their WEEE. In addition, each PCP could include or not dissemination activities to spread their existence among consumers.

Coop4SWEEEM was implemented using NetLogo software. The interphase included three display areas: the PCPs configuration area (Fig. 19.16—upper half left), the consumer behaviors (Fig. 19.16—right), and graphs to report the simulation dynamics (Fig. 19.16—lower half left).

The consumer behaviors display also showed the level of cooperation between producers and distributors of EEE (see the detailed display in Fig. 19.16); each pair of producer-distributor was assigned to one of the two PCP. Thus, the level of cooperation directly changed according to the amount of WEEE received in the PCP. This dynamic was also reported in the graph's area of the interphase, as Fig. 19.17 shows.

In the graphs to report display (Fig. 19.18), producer and distributor motivation changed in response to consumer delivery of WEEE, as well as potential pollution (%). Dynamics of delivering WEEE to each PCP is shown in the upper-right graph in Fig. 19.18.

As a result of the DE-S, the best combination of the PCPs included the incentive to support social projects rather than to receive economic incentives; and included media dissemination of the PCP too. This shows that consumers could be attracted not only by receiving explicit economic incentives but also (or even more) by giving social and environmental help.

19.4.5 The policy for integrated waste electronic and electrical equipment management in Colombia

As presented in the introduction to the final policy document launched in June of 2017 by the MADS, the formulation of the policy was approached from a systemic view going into the structural causes to define goals, strategies, and specific actions. Several outcomes from the systemic design were included into the conceptual framework, the assessment, and the strategic framework; and the description of the systemic methodology was explicitly included as annex.

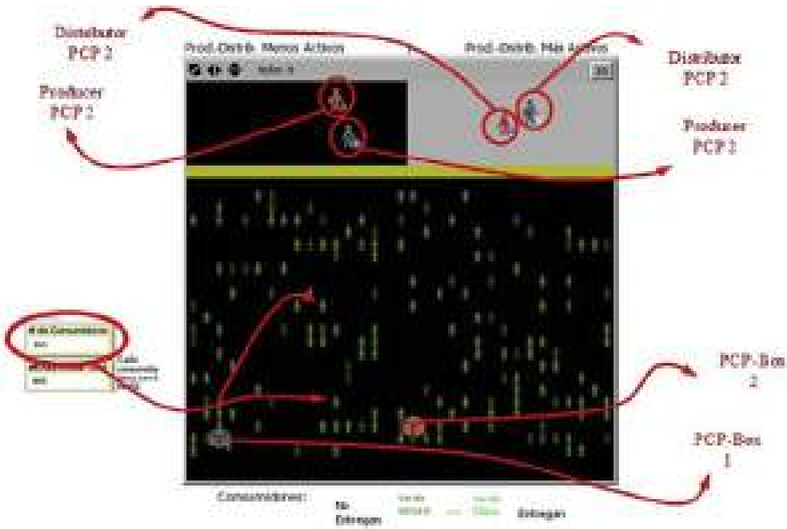


Figure 19.17 Details of the consumer behaviors display in COOP4SWEEEM.

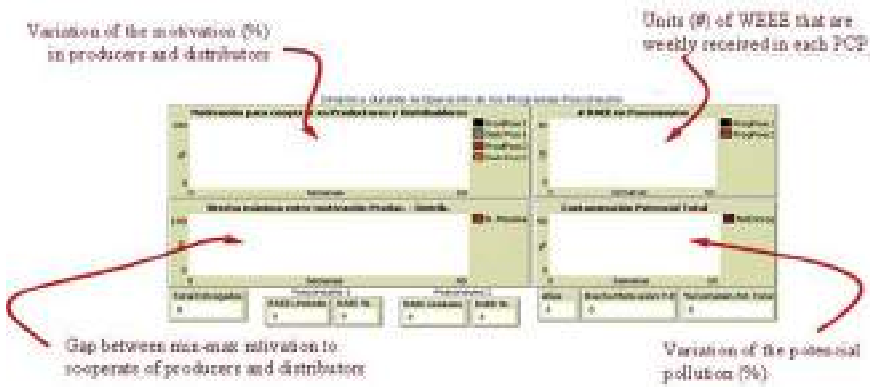


Figure 19.18 Details of the graphs to report the simulation dynamics in COOP4SWEEEM.

The resulting policy focused on meeting the general objective of "promoting the integrated management of waste electrical and electronic equipment (WEEE)" (MADS, 2017; Méndez-Fajardo et al., 2017a,b). The five specific objectives which guided the participatory design of strategies in the case of Colombia (see Section 19.4.3), were translated into four specific objectives formulated in the policy as follows:

- Prevent and minimize the generation of WEEE
- Promote the integrated management of WEEE
- Incentivize the environmentally conscious utilization of WEEE

- Promote the full integration and participation of producers, retailers, users, and consumers of EEE

The strategies included in the final policy aim at involving generic actors (Fig. 19.2), and the perspectives used in the workshops (environmental, sociocultural, economic, technical, and political). In addition, the description of consumer behaviors includes components and concepts discussed between actors during the DE-S, which shows the relevance of this type of participatory spaces.

All actors who participated in the workshops and meetings attended the launching ceremony and referred to the document as "our policy."

19.5 The systemic-design of solutions in Ecuador: applying the methodology in a 3-days workshop

To test the methodology as a short systemic design, the authors developed in Ecuador in July 2018 at the University of Cuenca a workshop titled "WEEE Management: Cooperation and the systemic design of solutions." It was organized and co-financed by CEDIA (the Ecuadorian National Network on Research and Education), the University of Cuenca and the ESPOCH (in Spanish: *Escuela Superior Politécnica del Chimborazo*) of Ecuador, and Empa and Skat Foundation of Switzerland.

The audience of the training included 33 attendees from governmental institutions, producers, and retailers of electronic and electrical equipment (e.g., producers of mobile phones, computers, and home appliances), and treatment operators or recyclers. Other important actors like two Universities, the National Institute of Statistics and Censuses (INEC), and the Ecuadorian Standardization Service (INEN) also participated.

The workshop was developed in 3 days and was methodologically based on the systemic-design of policies (Méndez-Fajardo et al., 2017a,b). Plenary sessions with national and international experts were held during two previous days to provide theoretical and technical inputs to the participants. During the days 3, 4, and 5, participants had the opportunity to apply this information in a practical way in a 3-days workshop, which corresponded to the core of the methodology: the problematic situation design, the identification of structural causes (or subproblems), and the design of strategies.

19.5.1 The design of the problematic situation (workshop 1)

After introducing the systems approach, systems thinking and their application on WEEE management in the design of solutions, participants identified the "focal problem" which served as a basis for the discussions and analysis during the 3-days workshop. As the focal problem was identified: "The lack of a holistic and sustainable system for the management of EEE and WEEE."

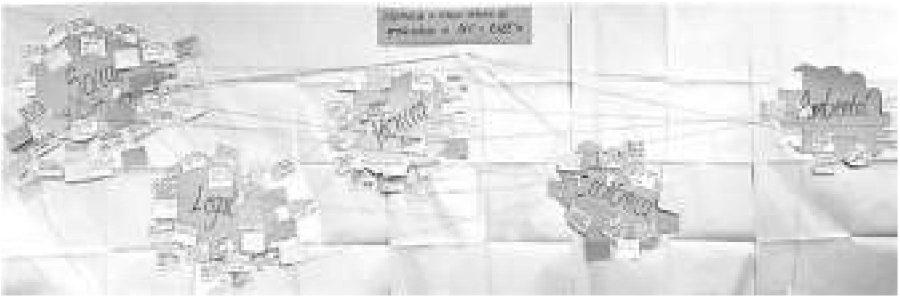


Figure 19.19 Visualized results of the first workshop.

Following this, participants identified possible problems/causes/effects attached to the focal problem, from the social, technical, economic, legal, and environmental perspectives, as shown in Fig. 19.19.

The subproblems can be summarized as Fig. 19.20 shows. The last part of this workshop consisted of making a prioritization of these problems. The most voted were: the lack of an integrative policy, low profitability of the treatment system, the unawareness of environmental impacts, and the lack of assuming responsibility by producers, importers, and wholesalers. Translating a "problem" into a "solution," participants defined the most important solutions in the same vote, as: communication and education and the design of a national policy.

19.5.2 Identifying structural causes (workshop 2)

Based on the resulting matrix of direct influences (MDI), the subproblems identified in the first workshop were located in the graph of dependency versus influenceability (Fig. 19.21). It shows that the most "powerful" or structural (those that are located in the upper left quadrant of the graph) are the lack of an integrative policy (D), insufficient information and education strategies (C), poor territorial integration (J), and low profitability of collection and treatment or recycling systems (B).

19.5.3 Participatory design of strategies (workshop 3)

Based on the problems classified as structural (numeral 4.2), *five Strategic Objectives* through which a "more holistic and sustainable management of EEE and WEEE" could be achieved, were identified as follows:

Objective 1: Design and implement an actor integrating policy, norms, and strategies for holistic and sustainable management of EEE and WEEE, resulting in a sociocultural, economic, and technological development of the country.

Objective 2: Achieve sociocultural changes and technological advancement required for a sustainable EEE and WEEE management system.

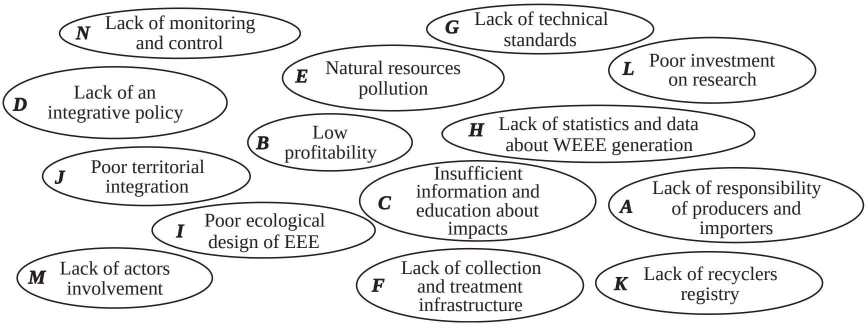


Figure 19.20 Subproblems related to the focal problem: "The lack of a holistic and sustainable system for the management of electrical and electronic equipment (EEE) and waste electrical and electronic equipment (WEEE) in Ecuador."

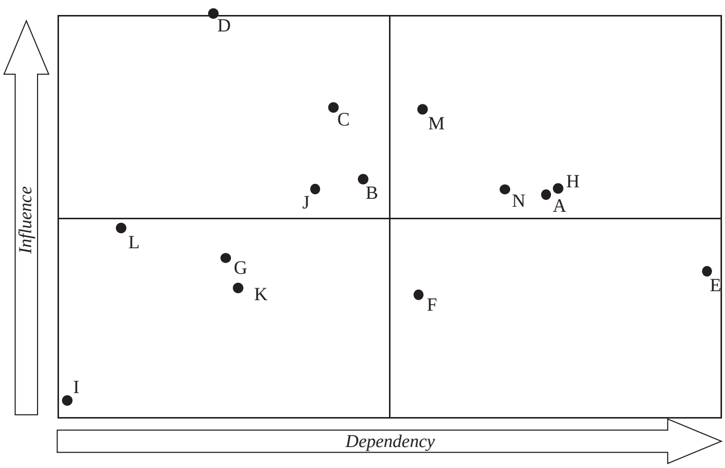


Figure 19.21 Subproblems (problems/causes/effects) related to the waste electrical and electronic equipment (WEEE) management in Ecuador, located in the graph of dependency versus influenceability.

Objective 3: Strengthen the institutional capacity and territorial articulation necessary to successfully implement the sustainable, holistic system of EEE and WEEE, and continuously monitor and improve it.

Objective 4: Have a robust legislative and regulatory framework, coherent and adapted to the dynamics of the management system, which is easy to understand and to implement.

Objective 5: Have a communication and information system which integrates the processes of sustainable holistic management of EEE and WEEE, their dimensions, actors, and responsibilities.

Table 19.3 Strategies designed in the 3-days workshop at the University of Cuenca.

Objectives	Strategy
1	Determining a baseline for government policy design, and generate a participatory process that involves and engages all stakeholders (government, academia, importers, managers, consumers, and society in general) in construction, financing, implementation, control, research, and dissemination of the system of holistic and sustainable management of EEE and WEEE
2	Encouraging education, research, and alliances according to the social, environmental, political, economic, and cultural context of each Territory, to guarantee cultural change and sustainable technological advancement, through public and private initiatives.
3	Improving institutional capacity by establishing a normative framework (supporting national and international experts) and specific competencies for stakeholders in the sustainable management of EEE and WEEE, ensuring the permanent allocation of Human and economic resources that allow the management of decentralized, participatory and control processes, based on the commitment of the actors.
4	Forming a coordinating technical committee that defines strategies for inclusion, participation, and action. Articulating and involving all stakeholders in a participatory manner through the creation of subcommittees for the construction of laws, codes, regulations, and technical norms, which extend the responsibility of producers, importers, and consumers; Contemplating a process of training and diffusion to facilitate the comprehension and implementation of actors involved.
5	Reaching interinstitutional agreements for the generation of information consolidated in an observatory that will be the communication entity of the management of EEE and WEEE.

The solutions identified in the first workshop were included in a list of "means to achieve the goals," as input for the participants. These *strategic objectives* are a direct result of the pilot exercise of the three workshop days. They do not yet reflect a complete policy design process that would take between 1 and 2 years. This implies that in a complete exercise each objective would need more than one strategy; however, in the 3-days workshop, using the method of *Round-robin*, each subgroup endeavored to draft one strategy that would encompass as many means as possible. The results are shown in Table 19.3.

19.6 Results and discussion

As in any participatory process, different tangible and intangible results emerge from the systemic-design. Tangible here refers mainly to documents such as reports, guides, and the policy designed. These include the description of the problematic situation of the WEEE management in each context (Colombia and Ecuador), the identification of relevant actors and their interactions, the assessment of infrastructure and processes, and existing regulations and laws.

The participants of the DE-S in Colombia and the 3-days workshop in Ecuador summarized the achievements of the systemic approach as follows:

- The 16 participants of the DE-S in Colombia stated that the decision agreed upon followed a more systemic approach than known and previously done in similar policy development processes (e.g., it took more than several dimension into account, considered the interests of more than one actor, more than one management phase and considered the logic of cause-effect).
- The 12 participants of the 3-days workshop in Ecuador agreed that the methods and logic applied with the systemic methodology helped them to achieve a holistic understanding of the WEEE management in the country. Respondents also agreed that applying a systemic approach as in the 3-days workshop does increase the involvement and potential cooperation between actors.
- Similarly, they agreed that applying a systemic approach as in the 3-days workshop does increase the involvement and potential cooperation between actors.

As part of the intangible results, the collective knowledge about WEEE management and consumers' participation increased. As examples, two explicit discussions that support this outcome were reported in Méndez-Fajardo (2016) as follows:

- The MADS representative said that "*homo economicus* must be considered when designing incentives, especially since the informal sector takes advantage of this facet of human beings." Nevertheless, "economic incentives might work at first, but, in the long-term, may become unsustainable. Given that people in the Colombian context always expect money, environmental education should be complementary and continually implemented to guarantee sustainability." The representative of one of the formal recycler organizations, echoed the MADS's representative, saying that "the day there isn't any money to buy WEEE, the system will collapse."
- The MADS representative also proposed that "sustainable WEEE management should include strategies to minimize waste generation instead of solely looking at the collection of already generated waste. Strategies could include, for example, both environmental education for children in schools and young people in universities, and economic incentives for adults."
- According to the representative of a PCP, "it is necessary to make it clear to consumers that environmentally responsible management comes with a cost, which means it isn't true that only recyclers earn money." In this sense, "when consumers deliver their WEEE to the system, they are actually contributing to the protection of the environment, instead of just supporting recycling businesses."
- According to the representative of the National Cleaner Production Center, a nationally recognized expert in WEEE management, "the question should not be about how to avoid program costs because implementing more sustainable WEEE management programs necessarily entails financial investment. For that reason, the question should refer to where the money is going to come from and where it will go (within the management processes)."

Table 19.4 summarizes the keywords that arise from workshops, meetings, and the DE-S's discussions and how they could be linked to the four elements of the systemic design, the PAPCP-E.

Table 19.4 Elements of the systems approach to waste electrical and electronic equipment (WEEE) management included as keywords in the showed discussions between decision-enhancement studio (DE-S)' participants.

The four elements of the systemic design (PAPC-E)	**A**	**B**	**C**	**D**
P: Different perspectives of the problem	Economic, cultural	Cultural, economic, social	Environmental, economic, social	Economic, logistic
A: Different actor targets	Consumers, informal recyclers	Consumers, recyclers, academia	Consumers, recyclers	"Who finances the system"
P: Processes within the life cycle	Collection, recycling, management	Generation, collection	Recycling, management	Collection, treatment
C-E: Logics of cause-effect and temporality	"... work the short term but ..."; "... could become unsustainable... "; "continually implemented ..."; "... the system will collapse..."	"... should include ... to minimize ..."; "...then, the strategies should include ..."	"... when consumers deliver ..."; "contributing to the environment ... supporting recyclers..."	"... to implement more sustainable .... It is necessary ..."

Source: Adapted from Méndez-Fajardo, S., 2016. Systemic Decisions for More Sustainable WEEE (Waste Electrical and Electronic Equipment) Management in Developing Countries. Pontificia Universidad Javeriana, Bogotá D.C.

Similar discussions and concepts emerged in the 3-day workshops in Cuenca. Comparing both cases (Colombia and Ecuador), there are common elements that should be observed to approach this field in other Latin-American countries:

- Although informal recycling is one of the most perceived problems, we have found that a lack of regulations, of control, of infrastructure, of awareness, are indeed structural causes of this effect.
- To attract the interest of producers, it is desirable that governments enact laws and regulations that request collection rates.
- A national policy as short- medium- and long-term plan helps government and relevant actors to meet such laws and regulations
- Designing in a participatory systemic way a national policy increase empowerment, motivation, and commitment of relevant actors, which in turn increases the sustainability of strategies and implementation activities.

Real-world problems, in this case, WEEE management, can be tackled in two ways, which can be considered opposing or complementary. One is the preventive approach focused on reducing WEEE generation and, correspondingly, decreasing

EEE consumption. The other is the reactive approach, which guides actions toward the responsible collection and treatment of already generated waste.

Responsible consumption involves both approaches. A responsible consumer should decide to buy or to reuse equipment based on economic and aesthetic criteria *and* environmental and ecological criteria, the latter two being related to the minimization of waste generation. A responsible consumer should also make an informed decision regarding WEEE disposal, through formal systems (part of their behavior). Invariably, emotions play a crucial role in consumer decisions. As a result, these decisions are intimately connected to the consumer characterization performed in this research with the hope of arriving at a profound comprehension of consumers and thereby exploring additional incentives to strengthen the responsible consumption.

To achieve high levels of actor participation, it is suggested first to investigate and analyze all previous actions related to WEEE management in the country, identifying actors who have taken part and the elements that aligned their interests to cooperate. Then, start a pilot process with the most active and gradually involve all other organizations and people. If the country already has some existent regulation or law, this pilot experience should aim to implement its principles.

Finally, education and research are the pillars of cultural changes required to achieve more sustainable WEEE management, then related actions and strategies should be included in the producer' strategies to comply the EPR's goals and should also be appropriated and supported continuously by distributors or retailers, recyclers, ONGs, academy, governments, and all actors involved in the system.

Acknowledgments

The authors thank Skat Foundation of Switzerland for cofunding the 3-day workshop at the University of Cuenca in Ecuador, Eng. Carlos Hernández from the Cleaner Production Center of Colombia, Eng. Ismael Fernando Izquierdo, and Eng. Mario Gustavo Pacheco from the University of Cuenca, for supporting the development of the 3-days workshop in Cuenca and reviewing the chapter.

References

Achillas, Ch, Vlachokostas, Ch, Aidonis, D., Moussiopoulos, N, Iakovou, E., Banias, G., 2010. Optimising reverse logistics network to support policy-making in the case of Electrical and Electronic Equipment. Waste Management 30, 2592−2600. Available from: https://doi.org/10.1016/j.wasman.2010.06.022.

Ackoff, R.L., 1981. Creating the corporate future. Plan or be planned for. John Wiley & Sons, Inc.

Agamuthu, P., Victor, D., 2011. Policy trends of extended producer responsibility in Malaysia RID B-8145-2010. Waste Manag. Res. 29, 945−953. Available from: https://doi.org/10.1177/0734242X11413332.

Ahluwalia, P.K., Nema, A.K., 2007. A life cycle based multi-objective optimization model for the management of computer waste. Resour. Conserv. Recycl. 51, 792–826. Available from: https://doi.org/10.1016/j.resconrec.2007.01.001.

Alves, M.C.M., Lima, B.S.L.P., Evsukoff, A.G., Vieira, I.N., 2009. Developing a fuzzy decision support system to determine the location of a landfill site. Waste Manag. Res. 27, 641–651. Available from: https://doi.org/10.1177/0734242X09103832.

Amoyaw-Osei, Y., Agyekum, O.O., Pwamang, J.A., Mueller, E., Fasko, R., Schluep, M., 2011. Ghana e-Waste Country Assessment.

Antanasijevic, D., Pocajt, V., Popovic, I., Redzic, N., Ristic, M., 2013. The forecasting of municipal waste generation using artificial neural networks and sustainability indicators. Sustain. Sci. 8, 37–46. Available from: https://doi.org/10.1007/s11625-012-0161-9.

Araújo, M.G., Magrini, A., Mahler, C.F., Bilitewski, B., 2012. A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. Waste Manag. 32, 335–342. Available from: https://doi.org/10.1016/j.wasman.2011.09.020.

Asamblea Constituyente, 2008. Constitución del Ecuador. Registro Oficial 449 de 20-Oct.-2008. Retrieved from http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = PUBLICO-CONSTITUCION_DE_LA_REPUBLICA_DEL_ECUADOR.

Asamblea Nacional, 2012. Código Orgánico de Organización Territorial, Autonomía y Descentralización (COOTAD). Retrieved from http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = DESCENTR-CODIGO_ORGANICO_DE_ORGANIZACION_TERRITORIAL_COOTAD.

Asamblea Nacional, 2017. Código Orgánico del Ambiente. Registro Oficial Suplemento 983 de 12-Abr.-2017. Retrieved from http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-CODIGO_ORGANICO_DEL_AMBIENTE.

Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-Waste Monitor 2017. United Nations University (UNU), International Telecommunication Union (ITU) & International Soild Waste Association (ISWA), Bonn/Geneva/Vienna.

Basel Convention Parties, 2006. Nairobi declaration on the environmentally sound management of electrical and electronic waste.

Beltrán, J., 2013. La chatarra sostiene a familias. EL TIEMPO, p. 1. Retrieved from https://www.eltiempo.com.ec/noticias/cuenca/2/la-chatarra-sostiene-a-familias.

Benitez, S.O., Lozano-Olvera, G., Morelos, R.A., de Vega, C.A., 2008. Mathematical modeling to predict residential solid waste generation. Waste Manag. 28, S7–S13. Available from: https://doi.org/10.1016/j.wasman.2008.03.020.

Böni, H., Schluep, M., Widmer, R., 2015. Recycling of ICT equipment in industrialized and developing countries. In: Hilty, L.M., Aebischer, B. (Eds.), ICT Innovations for Sustainability, Advances in Intelligent Systems and Computing. Springer International Publishing, pp. 223–241.

Brunner, P.H., 2011. Urban mining a contribution to reindustrializing the city. J. Ind. Ecol. 15, 339–341. Available from: https://doi.org/10.1111/j.1530-9290.2011.00345.x.

Carter, C.R., Rogers, D.S., 2008. A framework of sustainable supply chain management: moving toward new theory. Int. J. Phys. Dist. & Log. Manage. 38, 360–387. Available from: https://doi.org/10.1108/09600030810882816.

CEPAL, Pacheco, J.F., Ortegón, E., Prieto, A., 2005. Metodología del marco lógico para la planificación, el seguimiento y la evaluación de proyectos y programas.

Chang, N.-B., Pires, A., Martinho, G., 2011. Empowering Systems Analysis for Solid Waste Management: Challenges, Trends, and Perspectives. Critical Reviews in Environmental

Science and Technology 41, 1449–1530. Available from: https://doi.org/10.1080/10643381003608326.

Checkland, P., 1984. Rethinking a Systems Approach. Pergamon Press, Oxford, UK, pp. 43–60.

Chi, X., Streicher-Porte, M., Wang, M.Y.L., Reuter, M.A., 2011. Informal electronic waste recycling: a sector review with special focus on China. Waste Manag. 31, 731–742. Available from: https://doi.org/10.1016/j.wasman.2010.11.006.

Christensen, T.H., Simion, F., Tonini, D., Moller, J., 2009. Global warming factors modelled for 40 generic municipal waste management scenarios. Waste Manage. Res. 27, 871–884. Available from: https://doi.org/10.1177/0734242X09350333.

Churchman, C.W., 1957. Introduction to operations reserach. John Wiley & Sons, Inc.

DANE, 2018. DANE, información estratégica: Proyecciones de población [WWW Document]. URL <https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion> (accessed 2.2.16.).

Desa, A., Kadir, N.B.A., Yusooff, F., 2011. A study on the knowledge, attitudes, awareness status and behaviour concerning solid waste management. Proc. Soc. Behav. Sci. 18, 643–648. Available from: https://doi.org/10.1016/j.sbspro.2011.05.095.

Duan, H., Huang, Q., Wang, Q., Zhou, B., Li, J., 2008. Hazardous waste generation and management in China: A review. Journal of Hazardous Materials 158, 221–227. Available from: https://doi.org/10.1016/j.jhazmat.2008.01.106.

Empa, CNPML, 2008. Gestión de Residuos Electrónicos en Colombia. Diagnóstico de compcomputadores y teléfonos celulares.

Empa, CNPML, 2010. Manejo de los RAEE a través del Sector Informal en Bogotá, Cali y Barranquilla.

Eriksson, O., Bisaillon, M., 2011. Multiple system modelling of waste management. Waste Manag. 31, 2620–2630. Available from: https://doi.org/10.1016/j.wasman.2011.07.007.

Elkington, J., 1994. Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development. California Management Review 36.

Espejo, R., Reyes, A., 2011. Organizational Systems: Managing Complexity with the Viable System Model, first ed. Springer.

Espinoza, O., Villar, L., Villaverde, H., 2008. Diagnóstico del manejo de los residuos electrónicos en el Perú.

Ezeah, C., Roberts, C.L., 2012. Analysis of barriers and success factors affecting the adoption of sustainable management of municipal solid waste in Nigeria. J. Environ. Manag. 103, 9–14. Available from: https://doi.org/10.1016/j.jenvman.2012.02.027.

Fernández P.G., 2007. Estudio sobre los circuitos formales e informales de gestión de Residuos de Aparatos Eléctricos y Electrónicos en Sudamérica.

Forrester, J.W., 1971. World dynamics. Productivity press.

Fuenmayor, R., López Garay, H., 1991. The Scene for Interpretive Systemology. Systems Practice 4. Available from: https://doi.org/10.1007/BF01104459.

Godet, M., 1993. From Anticipation to Action: A Handbook of Strategic Prospective. Unesco Publishing.

GSMA TM, UNU-IAS, 2015. eWaste in Latin America. Statistical Analysis and Policy Recommendations.

Herat, S., Agamuthu, P., 2012. E-waste: a problem or an opportunity? Review of issues, challenges and solutions in Asian countries. Waste Manag. Res. 30, 1113–1129. Available from: https://doi.org/10.1177/0734242X12453378.

Herdiana, D.S., Pratikto, Sudjito, Fuad, A., 2014. Policy of extended producer responsibility (case study). Int. Food Res. J. 21, 873–881.

Hieronymi, A., 2013. Understanding systems science: a visual and integrative approach. Syst. Res. Behav. Sci. 30, 580−595. Available from: https://doi.org/10.1002/sres.2215.

Hilty, L., Aebischer, B., 2014. ICT innovations for sustainability. Springer, New York.

INEC, 2017. Encuesta Nacional de Empleo, Desempleo y Subempleo en Ecuador - ENEMDU.

IPCC, 2007. Cilmate Change 2007: mitigation of Climate Change. http://www.ipcc.ch/publications_and_data/.htm

IRR, 2015. Reciclaje inclusivo y recicladores de base en el Ecuador.

Karak, T., Bhagat, R.M., Bhattacharyya, P., 2012. Municipal Solid Waste Generation, Composition, and Management: The World Scenario. Crit. Rev. Environ. Sci. Technol. 42, 1509−1630. Available from: https://doi.org/10.1080/10643389.2011.569871.

Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F., 2018. What a Waste 2.0. World Bank, Washington. Available from: https://doi.org/10.1596/978-1-4648-1329-0.

Keen, P.G.W., Sol, H.G., 2008. Decision Enhancement Services: Rehearsing the Future for Decisions that Matter. IOS Press.

Klir, G., 2001. Facets of Systems Science, second ed. Springer.

Kollikkathara, N., Feng, H., Yu, D., 2010. A system dynamic modeling approach for evaluating municipal solid waste generation, landfill capacity and related cost management issues. Waste Manag. 30, 2194−2203. Available from: https://doi.org/10.1016/j.wasman.2010.05.012.

Kveselis, V., Farida, E., Masaitis, S., 2017. Analysis of energy development sustainability: the example of the Lithuanian district heating sector. Energy Policy 100, 227−236. Available from: https://doi.org/10.1016/j.enpol.2016.10.019.

León, J., 2010. Modelling computer waste flows in the formal and the informal sector - a case study in Colombia. Swiss Federal Institute of Technology (EPFL)/Swiss Federal Laboratories for Materials Testing and Research (Empa), Lausanne/St. Gallen, Switzerland.

Lindhqvist, T., 2000. Extended Producer Responsibility in Cleaner Production Policy Principle to Promote Environmental Improvements of Product Systems.

LUMA Institute, 2012. Innovating for People Handbook of Human-Centered Design Methods, 1st edition LUMA Institute, Pittsburgh, Pennsylvania.

Maddox, P., Doran, C., Williams, I.D., Kus, M., 2011. The role of intergenerational influence in waste education programmes: the THAW project. Waste Manag. 31, 2590−2600. Available from: https://doi.org/10.1016/j.wasman.2011.07.023.

MADS, 2017. Política Nacional. Gestión Integral de Residuos de Aparatos Eléctricos y Eletrónicos RAEE.

MAE, 2012. Acuerdo Ministerial 142: Listados Nacionales de Sustancias Químicas Peligrosas, Desechos Peligrosos y Especiales. Registro Oficial No 856 de 21-Dic.-2012. Retrieved from http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-LISTADO_NACIONAL_SUSTANCIAS_QUIMICAS_PELIGROSAS_DESECHOS_PELIGROSOS

MAE, 2013. Acuerdo Ministerial 191: Instructivo de aplicación del principio de responsabilidad extendida del productor establecido en el Reglamento para la prevención y control de la contaminación por sustancias químicas peligrosas, desechos peligrosos y especiales,. Registro Oficial Suplemento 881 de 29-Ene.-2013. Retrieved from http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-INSTRUCTIVO_PRINCIPIO_RESPONSABILIDAD_REGLAMENTO_CONTROL_SUSTANCIAS

Marcelino-Sádaba, S., González-Jaen, L.F., Pérez-Ezcurdia, A., 2015. Using project management as a way to sustainability. From a comprehensive review to a framework definition. Journal of Cleaner Production 99, 1–16. Available from: https://doi.org/10.1016/j.jclepro.2015.03.020.
Martens, M.L., Carvalho, M.M., 2015. The Challenge of Introducing Sustainability into Project Management Function: Multiple-Case Studies. J. Cleaner Production. Available from: https://doi.org/10.1016/j.jclepro.2015.12.039.
Mayers, C.K., 2007. Strategic, financial, and design implications of extended producer responsibility in Europe: a producer case study. J. Ind. Ecol. 11, 113–131. Available from: https://doi.org/10.1162/jiec.2007.1228.
McManners, P.J., 2016. Developing policy integrating sustainability: A case study into aviation. Environmental Science & Policy 57, 86–92. Available from: https://doi.org/10.1016/j.envsci.2015.11.016.
Meadows, D.H., 1989. System Dynamics meets the press. Systems Dynamics Review 5.
Méndez-Fajardo, S., González, R.A., 2014. Actor-Network Theory on Waste Management: a university case study. IJANTTI 6 (4). Available from: https://doi.org/10.4018/IJANTTI.
Méndez-Fajardo, S., 2015. Agent-Based Simulation Coop4SWEEEM.
Méndez-Fajardo, S., 2016. Systemic Decisions for More Sustainable WEEE (Waste Electrical and Electronic Equipment) Management in Developing Countries. Pontificia Universidad Javeriana, Bogotá D.C.
Méndez-Fajardo, S., Böni, H., Hernández, C., Schluep, M., Valdivia, S., 2017a. A practical guide for the systemic design of WEEE management policies in developing countries.
Méndez-Fajardo, S., Gonzalez, R.A., Barros-Castro, R.A., 2017b. Using actor-network theory in agent-based modelling. In: García-Díaz, C., Olaya, C. (Eds.), Social systems Engineering: The Design of Complexity. John Wiley & Sons, Ltd, Chichester, UK. Available from: https://doi.org/10.1002/9781118974414.
Menikpura, S.N.M., Santo, A., Hotta, Y., 2014. Assessing the climate co-benefits from waste electrical and electronic equipment (WEEE) recycling in Japan. J. Clean. Prod. 74, 183–190. Available from: https://doi.org/10.1016/j.jclepro.2014.03.040.
Ministerio de Hacienda y Crédito Público, DNP, Ministerio de Ambiente, Vivienda y Desarrollo Territorial, Ministerio de Minas y Energía, Ministerio de Comunicaciones, 2005. Documento Conpes 3386.
MIPRO, 2010. Acuerdo MIPRO 10 464.pdf (p. 4). p. 4. Retrieved from https://www.aduana.gob.ec/archivos/Acuerdo MIPRO 10 464.pdf
Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. Available from: https://doi.org/10.1021/es403506a.
Omran, A., El-Amrouni, A.O., Suliman, L.K., Pakir, A.H., Ramli, M., Aziz, H.A., 2009. Solid Waste Management Practices in Penang State: A Review of Current Practices and the Way Forward. Environ. Eng. Manag. J. 8, 97–106.
Ongondo, F.O., Williams, I.D., 2011. Greening academia: use and disposal of mobile phones among university students. Waste Manag. 31, 1617–1634. Available from: https://doi.org/10.1016/j.wasman.2011.01.031.
Ott, D., 2014. WEEE management in Latin America. Presented at the World Resources Forum, Arequipa, Peru.
Oyoo, R., Leemans, R., Mol, A.P.J., 2011. Future Projections of Urban Waste Flows aand their Impacts in African Metropolises Cities. Int. J. Environ. Res. 5, 705–724.
Pinz, A., Roudyani, N., Thaler, J., 2018. Public–private partnerships as instruments to achieve sustainability-related objectives: the state of the art and a research agenda.

Public Manag. Rev. 20, 1−22. Available from: https://doi.org/10.1080/14719037.2017.1293143.

Pronet, G., 2013. Desarrollo de los elementos técnicos y jurídicos para la definición de un modelo de gestión integral para los residuos de aparatos eléctricos y electrónicos raee en colombia.

Reuter, M., Van Schaik, A., 2012. Opportunities and limits of WEEE Recycling - Recommendations to product design from a recyclers perspective, in: Electronics Goes Green 2012 + (EGG), 2012. Presented at the Electronics Goes Green 2012 + (EGG), 2012, pp. 1−8.

Reynolds, M. (Ed.), 2010. Systems Approaches to Managing Change: A Practical Guide, 2010 Edition. Springer, London; New York.

Saphores, J.-D.M., Ogunseitan, O.A., Shapiro, A.A., 2012. Willingness to engage in a pro-environmental behavior: an analysis of E-waste recycling based on a national survey of U.S. households. Resour. Conserv. Recycl. 60, 49−63. Available from: https://doi.org/10.1016/j.resconrec.2011.12.003.

Simoni, M., Kuhn, E.P., Morf, L.S., Kuendig, R., Adam, F., 2015. Urban mining as a contribution to the resource strategy of the Canton of Zurich. Waste Manag. 45.

Sinha-Khetriwal, D., Kraeuchi, P., Schwaninger, M., 2005. A comparison of electronic waste recycling in Switzerland and in India. Environ. Impact Assess. Rev. 25, 492−504. Available from: https://doi.org/10.1016/j.eiar.2005.04.006.

Streicher-Porte, M., Widmer, R., Jain, A., Bader, H.-P., Scheidegger, R., Kytzia, S., 2005. Key drivers of the E-waste recycling system: assessing and modelling E-waste processing in the informal sector in Delhi. Environ. Impact Assess. Rev. 25, 472−491. Available from: https://doi.org/10.1016/j.eiar.2005.04.004.

Streicher-Porte, M., Marthaler, C., Böni, H., Schluep, M., Camacho, Á., Hilty, L.M., 2009. One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia. J. Environ. Manage. 90, 3498−3511. Available from: https://doi.org/10.1016/j.jenvman.2009.06.002.

Swiss E-waste programme, FEAM, 2009. Diagnóstico da Geração de Resíduos Eletroeletrônicos no Estado de Minas Gerais Belo Horizonte, Brazil.

Tchobanoglous, G., 1994. Gestion Integral de Residuos Solidos, first ed. McGraw-Hill.

Tchobanoglous, G., Theisen, H., Vigil, S.A., 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill.

Thanh, N.P., Matsui, Y., 2011. Municipal solid waste management in Vietnam: status and the strategic actions. Int. J. Environ. Res. 5, 285−296.

The European Parliament, The Council on WEEE, 2012. Directive 2012/19/EU.

Ugochukwu, C.N., Ertel, J., Schmidt, M., 2008. Environmental sustainability and sustainable development issues in the Niger Delta Region of Nigeria. Forum Forsch. 151−156.

U.N., 1993. Agenda 21: Earth Summit - The United Nations Programme of Action from Rio.

United Nations, 1987. Our common future. Report of the World Commission on Environment and Development.

U.N., 2015. Sustainable Development Goals ... Sustainable Development Knowledge Platform [WWW Document]. U.N., Department of Economic and Social Affairs. URL https://sustainabledevelopment.un.org/?menu = 1300 (accessed 2.10.16).

United Nations, 2018a. Goal 13: take urgent action to combat climate change and its impacts [WWW Document]. URL https://www.un.org/sustainabledevelopment/climate-change-2/ (accessed 11.26.18).

United Nations, 2018b. Climate change [WWW Document].

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on E-waste. Environ. Impact Assess. Rev. 25, 436−458. Available from: https://doi.org/10.1016/j.eiar.2005.04.001.

Wilson, D.C., Rodic, L., Scheinberg, A., Velis, C.A., Alabaster, G., 2012. Comparative analysis of solid waste management in 20 cities. Waste Manage. Res. 30, 237−254. Available from: https://doi.org/10.1177/0734242X12437569.

Yeomans, J., 2004. Improved policies for solid waste management in the municipality of Hamilton-Wentworth, Ontario. Can. J. Adm. Sci.-Rev. Can. Sci. Adm. 21, 376−393.

Zero Waste Europe, 2014. Zero Waste is a Climate Solution at the COP20. Zero Waste Europe. URL http://www.zerowasteeurope.eu/2014/12/zero-waste-is-a-climate-solution-at-the-cop20/ (accessed 1.23.16).

Further reading

Armstrong, R., Baillie, C., Cumming-Potvin, W., 2014. Mining and communities: understanding the context of engineering practice. Synth. Lect. Eng. Technol. Soc. 8, 1−148. Available from: https://doi.org/10.2200/S00564ED1V01Y201401ETS021.

Cumming, T.L., Shackleton, R.T., Förster, J., Dini, J., Khan, A., Gumula, M., et al., 2017. Achieving the national development agenda and the sustainable development goals (SDGs) through investment in ecological infrastructure: a case study of South Africa. Ecosyst. Serv. 27, 253−260. Available from: https://doi.org/10.1016/j.ecoser.2017.05.005.

Guerrero, L.A., Maas, G., Hogland, W., 2013. Solid waste management challenges for cities in developing countries. Waste Manag. 33, 220−232. Available from: https://doi.org/10.1016/j.wasman.2012.09.008.

ICR, 2014. Br Environmental Sustainability Agenda Tal.

Khetriwal, D.S., Kraeuchi, P., Widmer, R., 2009. Producer responsibility for E-waste management: key issues for consideration − Learning from the Swiss experience. J. Environ. Manage. 90, 153−165. Available from: https://doi.org/10.1016/j.jenvman.2007.08.019.

Kinyua, R., 2012. Status of Kenya's environmental management and protection. Political, Social and Environmental Issues, Kenya, pp. 119−134.

Koh, S.C., Gunasekaran, A., Morris, J., Obayi, R., Ebrahimi, S., 2016. Conceptualising a circular framework of supply chain resource sustainability. International .

Lu, Y., Geng, Y., Liu, Z., Cote, R., Yu, X., 2017. Measuring sustainability at the community level : an overview of China ' s indicator system on national demonstration sustainable communities. J. Clean. Prod. 143, 326−335. Available from: https://doi.org/10.1016/j.jclepro.2016.12.105.

Network bärkraft.ax, 2017. Development and Sustainability Agenda for Åland. Åland.

PricewaterhouseCoopers PwC, 2008. The sustainability agenda: Industry perspectives.

Radboud Universiteit, 2016. Sustainability Agenda 2016-2020. Nijmegen, Netherlands.

E-waste management in Ecuador, current situation and perspectives

20

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20.1 Introduction

With an annual growth of 2 million tonnes, E-waste is one of the fastest growing waste streams globally (Ignatuschtschenko, 2017; United Nations University, 2014). The global amount generated in 2016 was estimated at 44.7 Mt, from which, 4.2 Mt were generated in Latin America accounting 6.62 kg/inh/year. The top three generators in this region were Brazil (1.5 Mt), Mexico (1 Mt), and Argentina (0.4 Mt). Furthermore, the countries with the highest E-waste generation per capita were Uruguay (10.8 kg/inh), Chile (8.7 kg/inh), and Argentina (8.4 kg/inh). In this context, Ecuador has values below these regional averages, with 90 kt and 5.5 kg/inh, respectively (Baldé et al., 2017). These estimations do not consider undocumented flows of electric and electronic equipment (EEE), that is, smuggling or the so-called "invisible entries," which represents a high percentage of devices entering the region (Cruz-Sotelo et al., 2017), and "aparatos viajeros" (small and middle devices introduced by travelers) (Blaser, 2009) that eventually become E-waste. Latin America faces several challenges toward an integrated sustainable E-waste management, according to Boeni et al. (2008). The most relevant are the lack of specific regulatory frameworks, inappropriate activities performed by the informal sector, and weak E-waste management systems (Boeni et al., 2008).

A crucial element for developing adequate E-waste management strategies, at national and regional levels in Latin America, is the development and implementation of specific regulatory frameworks (Torres et al., 2015; Baldé et al., 2017). Latin American countries have different levels of development on E-waste regulation. Brazil (Veit and Bernardes, 2015), Colombia (MINAMBIENTE, 2017), Costa Rica (Ministerio de Salud, 2018), and Peru (Ministerio del Ambiente, 2012) have aligned their regulatory frameworks with the principle of extended producer responsibility (EPR). However, the adoption of the EPR principle as state policy has faced

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00013-9

difficulties due to particularities of the countries, varying in terms of scope, range, type, and funding mechanisms (Boeni et al., 2008; Torres et al., 2015). Chile approved the law 20920 in 2016, which mandates the application of EPR for waste management, but without a specific law on E-waste (Congreso Nacional, 2016). El Salvador has published a technical guide for E-waste management (Monge et al., 2017). Mexico mentioned E-waste in two general waste management laws (Torres and Accurso, 2015), and Nicaragua presents a general policy where E-waste management is identified as a strategic axis (MARENA, 2018). On the contrary, Argentina (Torres and Accurso, 2015; Escobar, 2017), Guatemala (MARN, 2018), Honduras (MIAMBIENTE, 2018), Panamá (MINSA, 2018), Bolivia (MMAyA, 2017), and Venezuela (Minea, 2018) do not have specific regulations on E-waste enforced. As for Ecuador, it counts on constitutional dispositions about environmental issues, a specific environmental law (Asamblea Nacional, 2017) which incorporates normative of EPR, and ministry agreements on E-waste (MAE, 2013b,c).

In Latin America, initiatives on E-waste management have become social imperative; particularly in the collection phase that represents job opportunities for vulnerable groups in growing economies (Magalini et al., 2015). E-waste collection is typically performed at municipal level, and in most cases, it is left in part to the informal sector (Boeni et al., 2008) which is constituted by groups of collectors, scrap dealers, and traders (Fernández Protomastro, 2013). Informal collectors receive different names, such as "recicladores de base"—base recyclers—(IRR, 2015), "segregadores" (Espinoza et al., 2008), "cachineros," "recicladores" (IPES, 2014), or "recuperadores" (Uribe et al., 2010); in this work the term base recyclers is used. Generally, base recyclers are neither registered nor count on a license to operate. They work under precarious environmental and safety conditions (Magalini et al., 2015), and very often their activities take place on illegal sites (Cruz-Sotelo et al., 2017). There are also semiformal schemes, where base recyclers work under the radar of municipal governments (Solíz Torres, 2015). The activities of the informal sector derive in producers not exercising their legal responsibility (EPR), and consumers getting rid of their EEE without considering the dispersion of pollutants (Fernández Protomastro, 2013). Furthermore, economic interests trigger a fragmentation process, causing the informal sector to collect only valuable items and discarding others with little or no economic value (UNESCO and Plataforma RELAC, 2010; Magalini et al., 2015).

Following collection, base recyclers perform dismantling steps and sell valuable parts to intermediaries, who in turn resell them to E-waste recycling companies. If not sold, these parts are stored inside houses, sharing space with other domestic activities (Uribe et al., 2009, 2010). Typically, the unusable fractions end up on sidewalks, wastelands, or illegal landfills (Cruz-Sotelo et al., 2017). There are also emerging recycling companies with limited capacities, performing mainly dismantling processes (UNESCO and Plataforma RELAC, 2010). Few examples of larger recycling companies also exist in the region. Brazil, Costa Rica, and Mexico have facilities with the R2 certification (Baldé et al., 2015) that deals with protection of people and the environment, protection of data and preservation of resources

(SERI, 2018b). Recently, R2 certified recycling facilities have started operations in Chile, Colombia, and Ecuador (SERI, 2018a). These facilities perform dismantling steps and mechanical treatment of EEE. Final metal refinement is performed at international level by large companies due to its complexity (Hagelüken, 2018), and because of the lack of specialized facilities in the region. In this chapter, the integrated and sustainable waste management (ISWM) framework is used to analyze the E-waste management in Ecuador and to formulate the key challenges and perspectives for the country. Finally, conclusions are drawn highlighting the main findings.

20.2 Integrated and sustainable waste management

In this work, the Ecuadorian E-waste management system is analyzed under the lens of the ISWM framework (Wilson et al., 2015; Ignatuschtschenko, 2017). This framework has been typically used to analyze waste management systems. For instance, Wilson et al. apply the ISWM framework to examine how cities in developing countries have been tackling waste management issues (Wilson et al., 2013). The work of Ignatuschtschenko performs a comparative assessment of the E-waste sector in China, Japan, and Vietnam by examining how those countries comply with the ISWM framework (Ignatuschtschenko, 2017).

The ISWM framework considers the links and overlaps between the three stages of waste management: generation, collection, and disposal. Furthermore, it takes into account the interdependency of these stages with other economic subsystems, for instance, manufacturing, transportation, urban growth and development, and public health (Ignatuschtschenko, 2017). This framework corresponds to three main questions concerning an E-waste management system: Who should be involved?, What should be done?, and How should it be done? (Ignatuschtschenko, 2017). These questions determine the three dimensions of the framework: the *stakeholders*, the *elements*, and *sustainability aspects* of a waste management system.

The *stakeholders* include national and local governments, NGOs, academia, and public or private companies involved in the collection and treatment of waste, as well as formal or informal sectors involved in the waste handling process, and also producers and consumers as waste generators (Anschütz et al., 2004; United Nations Human Settlements Programme, 2010). The *elements* of a waste management system comprise the technical components and the processes relating to removal and safe disposal of waste (generation, collection, and treatment), as well as the actions relating to the valorization of resources (reuse, recycling, and recovery). Finally, the *sustainability aspects* of a waste management system refer to factors that facilitate efficient and sustainable waste management activities, for example, political environment, regulatory frameworks, socio-cultural conditions, environmental and health aspects, as well as financial and economic factors (Anschütz et al., 2004; United Nations Human Settlements Programme, 2010). Fig. 20.1 depicts the ISWM framework proposed by van Klundert and Anschütz.

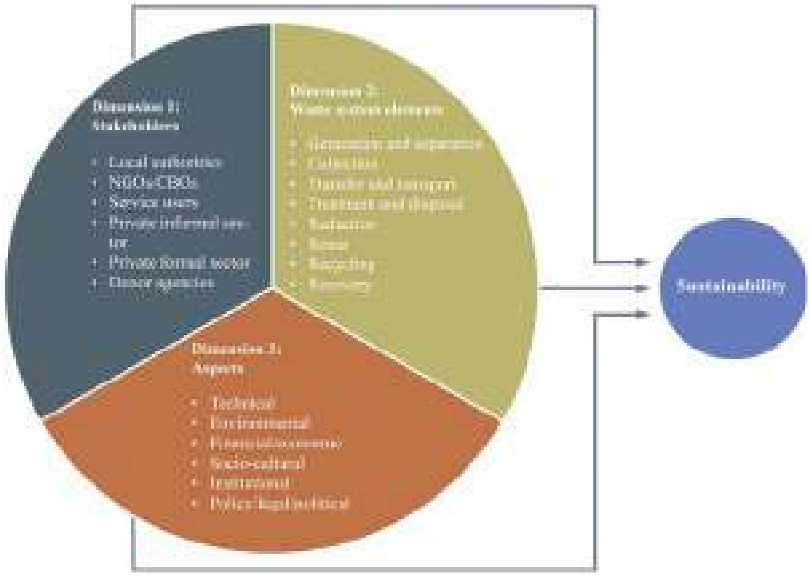

Figure 20.1 The ISWM framework.
Sources: Adapted from van de Klundert, A., Anschütz, J., 2001. Integrated Sustainable Waste Management-The Concept. In: A. Scheinberg (Ed.). Gouda. doi: 90-76639-02-7 and Anschütz, J., IJgosse, J., Scheinberg, A., 2004. Putting Integrated Sustainable Waste Management into Practice - Using the ISWM Assessment Methodology.

20.3 E-waste management in Ecuador

The Republic of Ecuador has an area of 283,561 km^2; it is located in South America, bordering by land with Colombia and Peru, and sharing maritime space with Costa Rica (Nations Online, 2018). Fig. 20.2 shows the location of Ecuador on the American continent. The Ecuadorian population stands at 17.1 million inhabitants in 2018 (INEC, 2018), and presents an annual growth rate of 1.31% (IndexMundi, 2017). According to the last census, 62.77% of people live in urban areas and 37.23% in rural areas (Villacís and Carrillo, 2012). Administratively the country's territory is divided into 24 provinces and 221 cantons. The provinces are grouped into nine Administrative Zones according to their geographical proximity, cultural, and economic characteristics.

The country has a GDP of USD 107.27 billion and a GDP per capita of USD 6300 (IMF, 2018). The Ecuadorian economic activity mainly relies on exports of crude petroleum, bananas, and crustaceans. The primary destinations of these products are the United States, Vietnam, Peru, Chile, and Russia. On the other hand, imports mostly consist of machines (mainly computers and telephones), refined petroleum, coal tar oil, and chemical products (OEC, 2018). According to the STEP initiative, the amount of EEE put on the market in 2012 was 7.2 kg/inh with a total of 110 kt (StEP, 2019). Regarding E-waste, it is estimated that Ecuador generates 5.5 kg/inh, adding up 90 kt in 2016 (Baldé et al., 2017).

Figure 20.2 Geographical location of Ecuador.
Source: Map generated based on material from Porto Tapiquén, C., 2015. Shapefiles (*.shp) de América. Available at: <https://tapiquen-sig.jimdo.com/descargas-gratuitas/américa/> (accessed 08.01.19.).

20.4 ISWM: stakeholders

In this chapter, a stakeholder is defined as any group or individual who can affect or is affected by a decision-making processes (Grimble and Wellard, 1997). A stakeholder analysis, which included an in-depth literature analysis and multistakeholder workshops (Reed et al., 2009), was performed to understand the E-waste management system in Ecuador (Grimble and Wellard, 1997; Mushove and Vogel, 2005).

The key stakeholders and their roles were identified considering the last three stages of E-waste management proposed by UNEP: collection, preprocessing and end-processing (Schluep et al., 2012). Next, the stakeholders were categorized according to their type, that is, the nature of the organization that each one represents (Hare and Pahl-Wostl, 2002). Finally, to understand the importance of each stakeholder, their roles were analyzed in detail. Fig. 20.3 illustrates the set of stakeholders' type identified. Most stakeholders play a role within a specific phase of the life cycle. Nevertheless, some of them such as national government, consumers, NGOs, and academia, are present in more than one stage or are not part of a

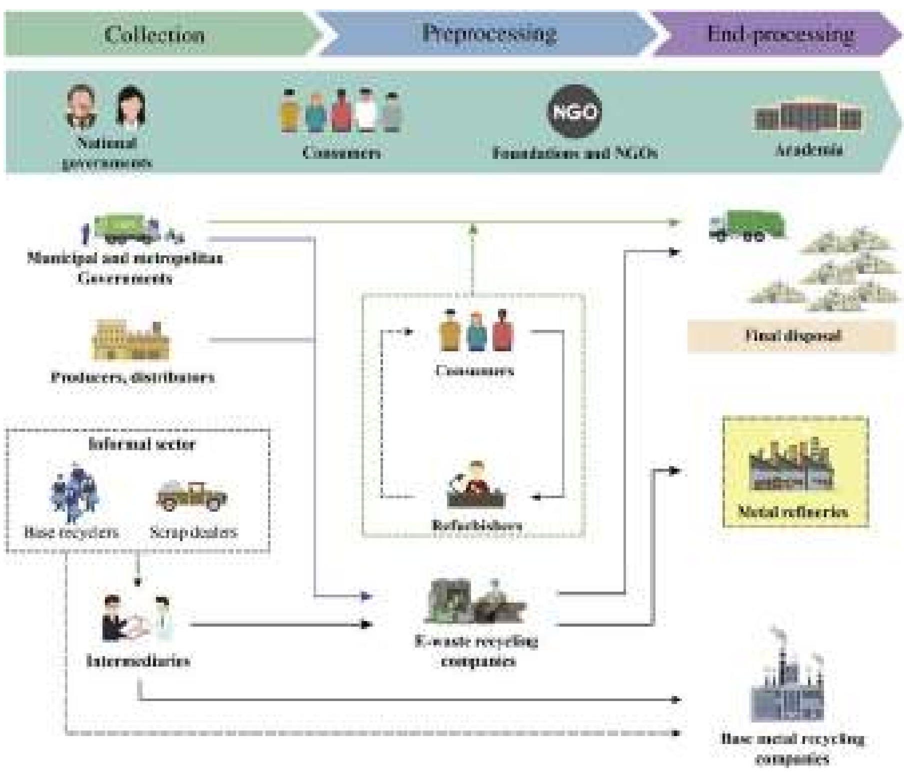

Figure 20.3 Identified stakeholders in the E-waste management system in Ecuador.

specific stage but they are relevant for the entire EEE life cycle. In this work, these stakeholders are referred to as transversal.

20.4.1 Transversal stakeholders

- *The National Government* plays a vital role across the entire EEE life cycle; it is responsible for coordinating, facilitating, and establishing regulations for waste management activities. Ecuador is a unitary state with decentralized administration, so competencies are assigned to different governmental bodies (Asamblea Constituyente, 2008). For instance, the Ministry of Environment(MAE) has the competencies for establishing national policies and developing regulations for waste of electric and electronic products (WEEE/E-waste—RAEE in Spanish) management (Asamblea Nacional, 2017). Besides, this Ministry grants operating permits to E-waste recycling companies (MAE, 2018a) and must promote the formalization, association, strengthening, and capacity building of recyclers at the national and local level (Asamblea Nacional, 2017). Additionally, there are a number of government bodies responsible for activities with a direct impact on E-waste management. For instance, the Council of Foreign Trade and Investments and the Ministry of Production, Employment and Competitiveness led, in 2010, the establishment of regulation to control the export of steel, aluminum, and copper-tin (bronze) scrap (MIPRO, 2010; IRR, 2015). This is relevant because in the country some E-waste, such as refrigerators and stoves, are traded together with scrap metal (Beltrán, 2013). Besides, the Ministry of Industries and Productivity has fostered recycling and scrap dealing initiatives.

  Since E-waste is not yet seen as a critical issue in the country, most of the funding for projects and research on this topic comes from international organizations. For instance, in 2018, the United Nations Industrial Development Organization (UNIDO) and the Global Environment Facility (GEF) in cooperation with the Ministry of Environment of Ecuador launched the program "Strengthening of National Initiatives and Enhancement of Regional Cooperation for the Environmentally Sound Management of Persistent organic pollutants (POPs) in Waste of Electronic or Electrical Equipment (WEEE) in Latin-American Countries" (GEF, 2018; UNIDO, 2018). This project aims to strengthen national and regional E-waste management systems in 13 countries through policies and consumers' involvement (Cueva, 2018).
- *Consumers* in Ecuador do not have a clear and defined role in the waste management system. Moreover, their awareness of the environmental relevance of E-waste is low. The awareness that they are responsible for the generation of E-waste and that should be part of the financing system to treat it properly is rare among consumers. On the contrary, there is the perception that discarded EEE has monetary value, so a regular practice is to trade these devices to informal door-to-door waste collectors. If not traded, EEE at the end of life typically remain at home or are donated to persons with fewer economic resources.
- *Foundations and NGOs* provide support to vulnerable groups involved in waste management activities. There are a number of organizations that support projects focused mainly on social and organizational aspects. For instance, the nonprofit organizations (NPO) "Avina" and "Fundación Alianza en el Desarrollo" supported the creation of the "Red Nacional de Recicladores del Ecuador"—National Network of Recyclers of Ecuador—(RENAREC) in 2008. RENAREC started with 18 associations and currently counts on 40 from 14 municipal governments (IRR, 2015). Other examples are the NPO "Hermano

Miguel" that, through the project "Yo reciclo" collects around USD 15,000/month from sales of recycled products (La Hora, 2018). Additionally, the "Fundación Ecuatoriana para la Protección y Conservación de la Naturaleza" NATURA, within its Solid Waste Management Program, carries out the project Fondo Reciclar. This project focuses on investment models for the recovery of recyclable materials from waste, creating green job opportunities and improving people's living standards (Fundación NATURA, 2018). Other NPOs such as "Fundación ESQUEL," OIKOS, "Fundación para la Gestión de Residuos" (FUNGERES), "Fundación para la Gestión Ambiental" (GEA), have also done relevant work for recyclers (Ojeda, 2009). These NGOs also promote the development of waste management regulation. For example, in the city of Cuenca, the organization "Cuenca, Ciudad para Vivir," together with the municipal waste management company, and the participation of recyclers' associations, academia, and public and private institutions presented a bill on solid waste management and inclusive recycling at the end of 2018 (El Tiempo, 2018).

- In Ecuador, *academia* is perceived by other actors as unbiased and positioned to convene stakeholders. Although E-waste has not yet gained enough traction at Universities there have been a number of related studies. Most of these works center on technical and economic aspects of the end of life treatment of E-waste (Espinoza Echeverría, 2010; Padilla Torres, 2017; Vargas Torres, 2017) or the implementation of recycling facilities (Rojas Matovelle and Román Quevedo, 2012). There are few studies on E-waste generation (Delaunay and Montero, 2013) and on the environmental and social aspects involved in E-waste management. These investigations are mostly undergraduate and master thesis rather than scientific publications. In 2018 KU Leuven, Universidad Andina Simón Bolívar and Universidad de Cuenca launched the research project "Enhancing the Social Value of the Circular Economy in Latin America". This project studies opportunities for incorporating informal recyclers in the circular economy, focusing on two waste streams: PET bottles and E-waste (VLIRUOS, 2018). The research focuses on two case studies in Ecuador, Cuenca, and Portoviejo, in close collaboration with the informal recyclers and other stakeholders. Academia is an important actor that has the capability for performing investigations and technical studies on E-waste management; as well as incorporating related topics in the curriculum, which influences future professionals, thus society.

20.4.2 Stakeholders: collection

- In Ecuador, *municipal and metropolitan governments* operate in a decentralized manner. They are in charge of providing the public service of solid waste management, and developing programs to reduce, recycle, and guarantee the adequate treatment of solid waste (Asamblea Constituyente, 2008; Asamblea Nacional, 2012, 2017). The 221 municipalities perform solid waste management activities under four modalities depicted in Table 20.1. It is worth mentioning that each municipality has its particularities and level of development. Most of them (56.6%) are in transition from open dumps to landfills (INEC, 2017). Special and hazardous solid waste, including E-waste, is not part of the competences of municipal governments but of the Ministry of Environment (Asamblea Nacional, 2017). Nevertheless, 24 municipalities report collection of E-waste (INEC, 2017), and some of them have carried out local initiatives to collect E-waste. For instance, the municipality of Ambato started a collection campaign in 2017, gathering 3.8 t of E-waste until May 2018 (GAD Ambato, 2018). In November 2017 the municipality of Cuenca implemented one E-waste collection point (EMAC, 2017), but no data are yet available on the amounts retrieved.

Table 20.1 Municipal waste management.

Modality	Number of municipalities	Percentage
Direct municipal management	161	73
Public municipal company	14	6
Association of municipalities	22	10
Association of public companies	24	11
Total	221	100

Source: Data from INEC, 2017. Base de Datos de Gestión Integral de Residuos Sólidos 2016. INEC, Quito. Available at: <http://www.ecuadorencifras.gob.ec/documentos/datos/Estadisticas_Ambientales/Municipios_Consejos_Provinciales/Gestion_Integral_Residuos_Solidos_de_Municipios/BaseCSVResiduos2016.zip>.

- One of the most important stakeholders for E-waste collection are *base recyclers*, who make a living by retrieving recyclable materials from discarded products. They usually work under substandard sanitary and environmental conditions, and frequently their activities are restricted or even criminalized. This situation poses a great challenge for the government. In 2014 it was estimated that roughly 20,000 base recyclers operated in the country, of which only 6% was associated (IRR, 2015). In 2015 the presence of base recyclers was reported in 101 out of 221 (46%) municipalities (Solíz Torres, 2015), and the four biggest cities (Quito, Guayaquil, Cuenca, and Manta) counted on 8865 base recyclers. The vast majority, 90%, of base recyclers do not have access to social security, and their average monthly income in 2015 was USD 218, while the national basic income for the same year was set at USD 354 (Ministerio del Trabajo, 2015). Only base recyclers from Quito and Cuenca report having support from municipalities or NGOs (IRR, 2015).

  Base recyclers work under two modalities: in the first one, they walk through the city collecting items of their interest directly from consumers, or containers and garbage bags outside the houses. Base recyclers move in reduced areas due to difficulties of transporting the collected waste (Mentefactura, 2017), most of the time walking or biking. In the second modality, base recyclers separate materials at landfills or dump-sites. There are also *scrap dealers*, who travel by truck across the city, or even provinces, buying items directly from EEE consumers (La Hora, 2008). Following collection, E-waste is sold to intermediaries at a range of USD 0.33 to USD 0.41 per kg (IRR, 2015). In some cases, base recyclers dismantle products to separate components or to recover materials. These operations are often performed without personal protection equipment at streets or at home. Practices such as burning cables, breaking lamps, and recovering of metals through artisanal methods are frequent. These practices are learned by experience and without any awareness on the health and environmental impacts caused by hazardous elements present in E-waste.
- *Intermediaries* constitute the bridge between the informal sector and E-waste recycling companies. They gather whole items, components or materials provided by base recyclers or scrap dealers. Once the amount of E-waste gathered is representative, it is sold to recycling companies. There are no data on the number or location of intermediaries in the country, which hinders E-waste traceability.
- According to the art. 233 of the Environmental Organic Code (CODA) and the Ministry Agreement No. 190, *producers/distributors* are responsible for treating their products at the end of life via a formal management channel (MAE, 2013c; Asamblea Nacional, 2017). To this end, producers/distributors are compelled to be registered as “hazardous waste generators.” However, there is little control to enforce this requirement and not all

the companies comply with it. Few producers/distributors have collection points or offer transportation for large volumes of devices, such as the cases of Xerox and HP, which work in a business to business (B2B) model (HP, 2018; Xerox Corporation, 2018) and Samsung and Computrón that collect electronic waste from public and private companies (Granda, 2014). Most of these initiatives do not keep publicly accessible records.

20.4.3 Stakeholders: preprocessing

- In Ecuador, consumers still tend to send their EEEs to *refurbishers* for extending their lifespan; and there are regulations that ease the importation of spare parts for EEE (e-Comex, 2017; SENAE, 2017). Across the country, there are electrical and electronic product service centers for, among others, refrigerators, TVs, computers, and mobile phones. Typically, these centers are small businesses, while few are authorized centers of international firms. There are no data on the fate of broken components and unusable EEE on the web pages of the refurbishment centers. Although international firms such as Xerox, HP, Samsung, and LG provide refurbishment services, there are no online reports on their E-waste flows.
- In the country, there are 11 private E-waste *recycling companies* with official permits to operate (MIPRO, 2018). They work with the input provided by producers/distributors registered as "hazardous waste generators" and intermediaries of the informal sector. These companies perform storage, primary dismantling and mechanical comminution of discarded EEEs. Following, the valuable fraction of E-waste, containing precious metals and copper, is exported to metal refineries treating WEEE (Wang et al., 2012). For instance, the Ecuadorian company, Vertmonde, reports that 95% of E-waste is sent to further treatment abroad (Vertmonde, 2018, personal communication, 25th September) and the company ReciclaMetal sends Printed Wired Boards (PWBs) to the metal smelter UMICORE in Belgium (Recicla Metal 2019, personal communication, 17th January). There are no data available on the fate of the fractions with low or no value, so it is assumed that they end up at municipal landfills.

20.4.4 Stakeholders: end-processing

- Due to the diversity of elements present in E-waste, there is also a great variety of treatment processes and technologies available for recovering materials (Wang et al., 2012). In the country there are *base metal recycling companies*; for instance, the iron and steel companies ADELCA and NOVACENTRO have implemented smelting processes for treating secondary materials (Visser, 2014; IRR, 2015). ADELCA has supported the creation of storage facilities (about 300 warehouses) (El Telégrafo, 2011) and transport networks (Visser, 2014), and has strengthened the cooperation among base recyclers, as well as supporting the improvement of their working conditions (IRR, 2015).
- *Metal refineries* are International Companies that refine and detoxify outputs from preprocessing through chemical, thermal and metallurgical processes targeting mainly precious metals and copper. In the case of two Ecuadorian E-waste recycling companies, INTERCIA sends preprocessed E-waste to Global Electric Electronic Processing in Canada (El Telégrafo, 2012); and VERTMONDE sends memory modules to Canada for end-processing (Granda, 2014). E-waste that is not treated by metal refineries or base metals recycling companies is sent to municipal waste management systems and disposed of in landfills, controlled dumps, or open dumps.

20.5 ISWM: elements

20.5.1 Generation and separation

In Ecuador, the generation of municipal solid waste (MSW) corresponds mostly to households, accounting for 70%, followed by the commercial-institutional sector with 16%, industry with 8%, and the hospital and healthcare sector with 6% (IRR, 2015). There is an increasing trend in household waste separation and classification; official reports state that in 2010, 25.16% of the Ecuadorian population classified their waste, rising to 41.46% in 2016 (Grupo Técnico DEAGA, 2016). This process considers four categories: organic, paper and cardboard, plastic, and glass (Arias and Seilles, 2014; Seilles, 2015; Grupo Técnico DEAGA, 2016). Regarding municipalities, 82 out of 221 (37.1%) have implemented separation at source (INEC and AME, 2017). Records on E-waste generation are available for the years 2013 (56.46 kt), 2014 (73 kt), and 2015 (76.5 kt), see Table 20.2 (MAE, 2018b).

In the particular case of mobile phones in Ecuador, a recent estimate calculated the number of mobile phones that became E-waste from 2012 to 2018 based on average lifespan, historical records on imports and exports, and stock data from official sources. On average, for the analyzed period, roughly 2 million units become E-waste annually. Considering an average weight of 129 g/device, this quantity represents approximately 0.28 kt of E-waste per year (Sucozhañay and Vidal, 2019).

20.5.2 Collection and transport

The collection service has a 90.9% coverage in urban areas and 57.4% in rural areas (IRR, 2015; Mentefactura, 2017). In 2016 the amount of MSW collected was 4.6 Mt with an *urban* per capita generation of 0.58 kg/inh/day (INEC and AME, 2017), which represents an increment of 0.5 Mt compared to 4.1 Mt documented in 2014 (IRR, 2015). From the collected amount, the organic fraction corresponds to 62%, whereas the inorganic fraction is subdivided as follows: plastics 11%, paper and cardboard 9%, glass 3%, scrap 2%, and "others" 13% (IRR, 2015; Mentefactura, 2017). Although E-waste as such does not appear within this subcategorization, some municipalities retrieve this stream through a differentiated

Table 20.2 Details on imports of EEE, E-waste generation and collection.

	2013	2014	2015
EEE imports (kt)	188.7	194.1	154
E-waste generated (kt)	56.5	73	76.5
E-waste collected (kt)	5.1	6.1	5.9
E-waste collected (%)	9	8	7

Source: Data from MAE, 2018b. Fortalecimiento de Iniciativas Nacionales y Mejora de la Cooperación Regional para el Manejo Ambientalmente Racional de los COPs en Residuos de Aparatos Eléctricos y Electrónicos (RAEE) en los Países de América Latina. Quito, Ecuador.

collection. Specifically, in 2016, 24 municipalities collected 75.6 t of E-waste (INEC, 2017). However, some categories, such as large and small household appliances are typically classified as scrap (Beltrán, 2013; Donoso Carrillo, 2017), so these devices are exported or sold locally as scrap metal, which hinders E-waste traceability. In addition, according to the National Survey on Employment, Unemployment, and Underemployment (ENEMDU), only a small fraction, on average below 5%, of consumers send E-waste to a special container or storage center for further treatment (INEC, 2013; Grupo Técnico DEAGA, 2016). For year 2014, the amount of collected E-waste reached 6.14 kt (MAE, 2018b). In this year the "Iniciativa Regional para el Reciclaje Inclusivo" (IRR) reported data on the quantities of E-waste (5.99 kt) collected by the informal sector in the three biggest cities: Quito, Guayaquil, and Cuenca, which accounted for 98% of the total as depicted in Fig. 20.4 (IRR, 2015). Therefore considering the official quantities reported by MAE, only 8% of the E-waste generated in 2014 was collected. Available records on E-waste collection from 2013 to 2015 are presented in Table 20.2.

There has been only one initiative to set collection targets for E-waste in the country. In 2013 the collection target of 3% of the number of mobile phones placed on market in the previous year was linked to the importation quotas for these devices (MAE, 2013a,c; COMEX, 2012a). From 2013 to 2015, the collection highly surpassed this target (Fig. 20.5). However, in December 2015 the national limit for imports of mobile phones was established in 2,663,762 units regardless of the collected units (PNGIDS, 2018). As a result, collection rates dropped drastically, for example, in 2014 the national collection rate was 14.01%, and in 2016 it reached 3.81% (MAE, 2018b).

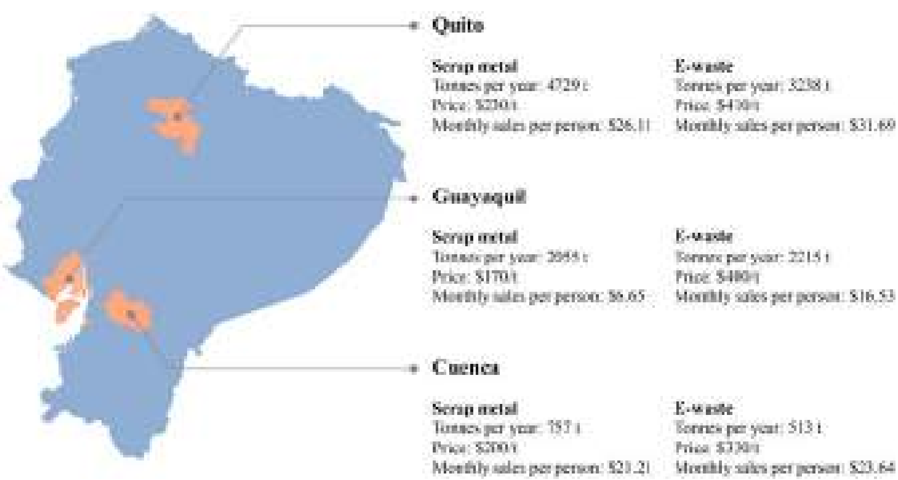

Figure 20.4 Scrap metal and E-waste collected by the informal sector.
Source Data from IRR, 2015. Reciclaje Inclusivo y Recicladores de Base en el Ecuador. Ecuador. Available at: <https://reciclajeinclusivo.org/wp-content/uploads/2016/04/Reciclaje-Inlcusivo-y-Recicladores-de-base-en-EC.pdf>.

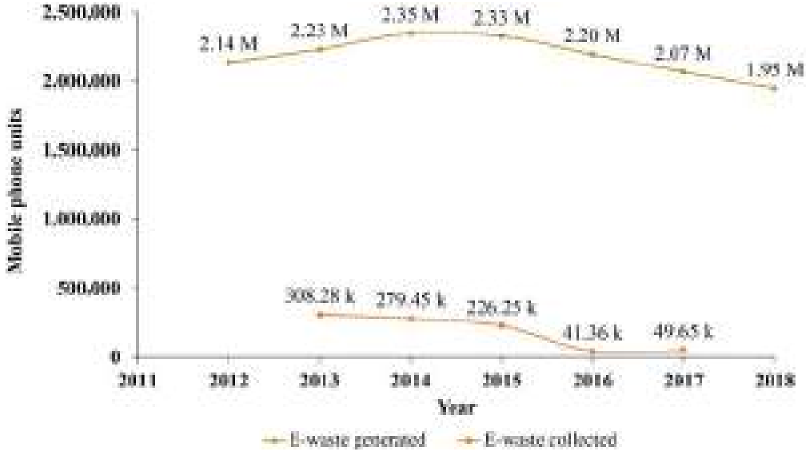

Figure 20.5 Estimations on E-waste generated and collection of E-waste. Case: mobile phones.
Sources: Data from PNGIDS, 2018. Recolección de teléfonos celulares. Quito and Sucozhañay, G., Vidal, I., 2019. Análisis del flujo de materiales y evaluación del impacto ambiental de los residuos de aparatos eléctricos y electrónicos. Caso de estudio: Teléfonos celulares en el cantón Cuenca. Cuenca.

Regarding E-waste transportation, this stage can occur in different ways since this activity can be covered by intermediaries, producers, or by E-waste recycling companies as part of their services. It is worth mentioning that there is a specific procedure for the environmental licensing of hazardous waste transportation. This procedure requires specific elements such as driver certifications, declaration of transportation capacity, and environmental management plans (MAE, 2018a).

20.5.3 Treatment and disposal

The E-waste collected, both formally and informally, is expected to reach an E-waste recycling company, which locally can cover activities such as storage, dismantling, and shredding, and then export components and fractions with precious metals for further treatment (Torres et al., 2015). For 2014, the processing capacity was estimated in 13 kt (MIPRO, 2014, 2016). Assuming that all the E-waste collected in this year reached to these recycling companies, it is noticeable that they work at less than half of the capacity. Following local treatment E-waste is exported to metal refineries, plastic recyclers and base metal recovery companies (Vertmonde, 2018, personal communication, 25th September). Additionally, due to the local demand of recycled scrap, estimated in 588 kt/year (IRR, 2015), recycling processes for base metals take place within the country. For instance, in 2013 MIPRO and the iron and steel company ADELCA signed an agreement with MIPRO to handle 330,000 old refrigerators collected by the National Government and transform them back into steel products (El Telégrafo, 2013; Centrosur, 2016). In compliance with this agreement

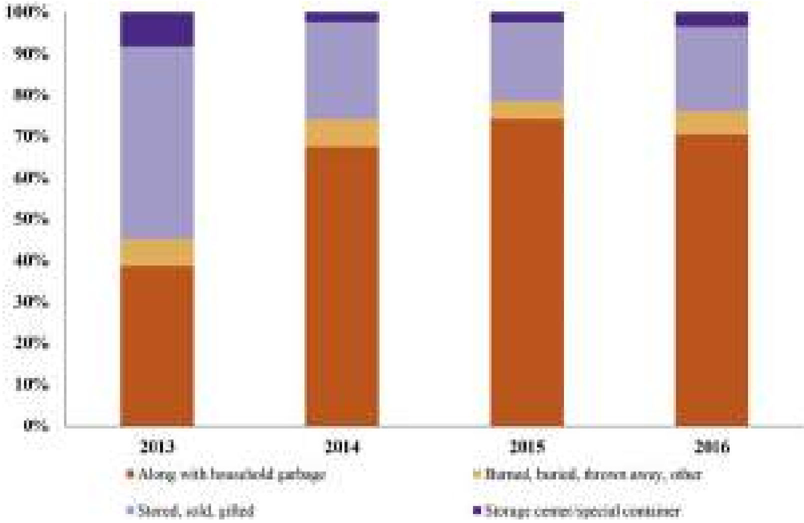

Figure 20.6 E-waste disposal in Ecuadorian households. In 2017, 76% respondents disposed of their E-waste along with household garbage. Other disposal methods were not mentioned. *Sources*: Data from INEC, 2013. Módulo de Información Ambiental en Hogares ENEMDU - Diciembre 2013. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Hogares-2013/201401_EnemduAmbientePresentacion.pdf> (accessed 03.12.18.), Grupo Técnico DEAGA, 2016. Información Ambiental en Hogares. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Hogares/Hogares_2016/Documentotecnico.pdf> (accessed 03.12.18.), and Benavides, R., et al., 2017. Módulo de Información Ambiental en Hogares - Diciembre 2017. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Hogares/Hogares_2017/DOC_TEC_MOD_AMBIENTAL_ENEMDU.2017.pdf> (accessed 03.12.18.).

the program is still ongoing and reports that from 2013 to 2016 the number of refrigerators treated was 92,000 (ADELCA, 2016).

Although disposal is viewed as the last measure in the waste management hierarchy (Ignatuschtschenko, 2017), it is a recurrent practice in Ecuador. On average, from 2013 to 2016, 62.8% of Ecuadorians reported mixing E-waste along with household garbage, see Fig. 20.6 (INEC, 2013; Grupo Técnico DEAGA, 2016). Thus, a high amount of E-waste ends up in final disposal sites such as landfills, emerging cells or open dumps. Furthermore, initiatives encouraging E-waste reduction are rare in the country. As a consequence the amount of E-waste generated in Ecuador has increased from 73 kt in 2014 (Baldé et al., 2015) to 90 kt in 2016 (Baldé et al., 2017).

20.6 ISWM: aspects

Following the ISWM framework, the third dimension comprises the factors that influence the whole waste management system and have impact in terms of efficiency and sustainability (Ignatuschtschenko, 2017). Those factors include political, legislative, and institutional frameworks, socio-cultural conditions, financial and economic factors, as well as technical and environmental aspects.

20.6.1 Socio-cultural conditions

Culture and consumption have an unprecedented relationship in the globalized world. Appadurai (1988) defines consumption as the function of a variety of social practices and classifications, and not so much as a mysterious emanation of human needs. Therefore consumption always assumes cultural forms. In this context, understanding the Ecuadorian culture is important to analyze E-waste management.

Latin American societies have been described as heterogeneous or culturally hybrid, this means, the flow of material and symbolic goods (Brünner, 1988) and the complex articulation of modernities and traditions (Bauman, 1998; García Canclini, 1990). Furthermore, they have been characterized by been moderately collectivistic, this means that social relationships are group-centered; and strongly polychromic, this means that time is seen as cyclical. People in Latin America are strongly relationship-based meaning that there is emphasis on interpersonal relationships and trust; and moderately harmony-oriented which means that focus is on living in harmony with nature and adjusting to the natural and social environment (House et al., 2004; Steers et al., 2010).

Even though in recent years, Ecuadorians have perceived profound changes in their consumer attitudes and practices, it is difficult to compare them with a consumer society such as the North American or European. Ecuador has half of the population living in poverty or extreme poverty. This implies that consumption is not carried out in the same intensity or with the same characteristics as in more affluent societies. For example, low-income populations generally buy second hand or repair appliances for their homes such as refrigerators, TV sets, kitchen appliances, as well as computers and cell phones. Repairing and selling used or refurbished products is an important part of the informal economy. Thus, it is easy to find someone who can repair electronic artifacts and, generally, this service is offered at a competitive price.

20.6.2 Political, legislative, and institutional frameworks

This section focus on policy and legal aspects analyzing the environmental normative in Ecuador related to E-waste management. It describes the Ecuadorian constitutional development according to the international regulatory framework, the secondary normative on solid waste management, and the regulation of the integrated management of hazardous and special waste. Fig. 20.7 shows the constitutional development of the environmental law in Ecuador.

In conformance with the ISWM framework, national legislations should integrate and implement international rules and standards. In this regard, Ecuador participates in most of the international environmental agreements and has formulated its legislation accordingly. The Basel Convention on the Control of Transboundary Movements

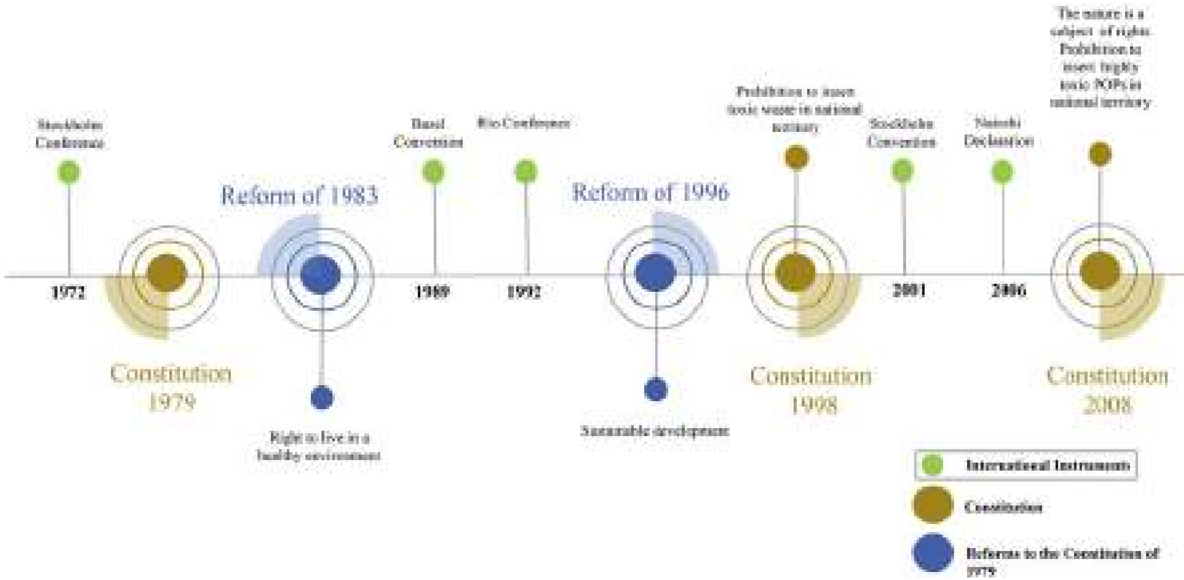

Figure 20.7 Constitutional development of the environmental law in Ecuador.

of Hazardous Wastes and their Disposal (United Nations, 1989) and the Stockholm Convention on Persistent Organic Pollutants (United Nations, 2001) are the most important ones related to E-waste management which influenced the Ecuadorian normative. In addition, there are other international instruments that have shaped the Ecuadorian constitutional development regarding environmental issues and waste management, the most relevant being the Stockholm Conference (United Nations, 1972), the Rio Conference of 1992 (United Nations, 2017), and the Nairobi Declaration on the Environmentally Sound Management of Electrical and Electronic Waste (United Nations, 2006).

The constitution of Ecuador after its return to democracy, established in 1979, along with the reforms of 1983 (Congreso Nacional del Ecuador, 1984) and 1996 (Congreso Nacional del Ecuador, 1996) incorporate the citizen's right to live in a healthy environment free of contamination and the State obligation to guarantee sustainable development. After that, the Constitution of 1998 made the protection of the environment a fundamental duty of the State, the concept of sustainable development turned into a transversal idea and the prohibition to insert toxic waste in the national territory was established (Asamblea Nacional Constituyente, 1998). Later, the Ecuadorian Constitution of 2008 prohibits the development, production, commercialization, importation, transportation, storage, and use of persistent organic pollutants (Asamblea Constituyente, 2008). Moreover, this novel Constitution recognizes the indigenous vision of the relation humans—nature reflected in the concepts of "Pachamama" and "Sumak Kawsay" which are native terms that mean "Mother Earth" and "good living," respectively. In this way, Ecuador changed the traditional anthropocentric view on environmental rights that considers nature as an object (Ávila Santamaría, 2016). Instead of that, a biocentrist perspective is developed in which the "Pachamama" is recognized as a subject of rights to be respected, preserved, and restored according to its life cycle (Asamblea Constituyente, 2008).

Moreover, the Constitution of 2008 and the Environmental Organic Code (CODA) establish a vast list of environmental principles, see Appendix A and B (Asamblea Constituyente, 2008; Asamblea Nacional, 2017). The rights and principles recognized in the Ecuadorian Constitution could be applied directly without the necessity of a secondary normative (Asamblea Constituyente, 2008). Regarding E-waste, two key environmental principles are considered in the Ecuadorian regulations: the *precautionary principle* and the *extended producer responsibility (EPR)*. The former implies that if there is a risk of severe or irreversible harm, the lack of scientific certainty will not be a reason to postpone the measures to prevent the environmental degradation. EPR is related to the duty that the producer or the importer has along the whole life cycle of the product. It includes the impacts related to the selection of the materials, the production process, the final disposal, and the use of them at the end of their useful life (MAE, 2013b; Asamblea Nacional, 2017).

The CODA was enacted in 2018 aiming to unify environmental laws in the country. In this sense, the CODA establishes the general policies for the integral waste management considering EPR and the promotion of the development, exploitation, and appreciation of waste as an economic good with a social purpose. In this sense, the hierarchical principle in waste management must respect the following order: (1) prevention; (2) minimization of the generation in the source; (3) appreciation; (4) elimination; and (5) final disposal (Asamblea Nacional, 2017). In Ecuador E-waste is considered as a hazardous waste (MAE, 2012). The CODA determines that generators and managers of hazardous and special waste must receive an administrative authorization. Then, in agreement to EPR every natural or juridical person that is defined as a generator of special and hazardous waste, is responsible for the environmental management of these waste streams starting from their generation until their elimination and final disposal, according to the hierarchical principle mentioned above. Moreover, the people hired by the generators to manage special and dangerous waste, will share responsibilities in case of accidents that could produce contamination or environmental damage (Asamblea Nacional, 2017).

Most of the fundamental environmental laws are integrated in the CODA; nonetheless, the regulation of special and hazardous waste is still described in a secondary normative. In the case of E-waste, the Ministry of Environment established in 2013 a *National Policy for the Post-consumption of Unused Electric Equipment* that focuses on EPR of importers and producers (MAE, 2013b). In the same way, the Ministry Agreement No. 191 to *Prevent and Control the Contamination by Chemical Dangerous Substances, Dangerous and Special Waste*, regulates the situation of unused cell phone equipment (MAE, 2013c); the Resolution No. 67 of 2012 of the Ministry of Foreign Affairs Commerce that restricts the importation of cell phones (COMEX, 2012b); and the Resolution No. 100 of the same institution of 2012 that establishes a maximum capacity that the importer of cell phones can bring (COMEX, 2012a). Furthermore, there are other vital norms in the field that regulate used batteries (MAE, 2013d) and integral management of plastics (MAE, 2014). In this regard, the Unified Text of Environmental Secondary Normative (TULSMA) regulates the integrated management of dangerous and special waste, which is composed by the following phases: (1) generation; (2) storage; (3) collection; (4) transportation; (5) recover; and (6) final disposal, as shown in Fig. 20.8 (MAE, 2003).

The Ecuadorian legislation recognizes environmental incentives as economic instruments to promote compliance with the environmental law. Mainly two norms regulate this topic: the CODA and the Ministry Agreement No. 140 of 2015 that regulates the institutional chart for environmental incentive. In this sense, the Ministry of Environment has a leading role in this area with the support of the decentralized governments in their territorial division (Asamblea Nacional, 2017). The environmental incentives pretend to promote the sustainable exploitation of biological resources, the culture of prevention and reduction of contaminants and compliance with the environmental law (Asamblea Nacional, 2017). These incentives could be (1) economical or noneconomical; (2) tax or fiscal ones; (3) honorary; and (4) others established by the authority. The environmental incentives promote the implementation of cleaner technologies and integral waste management in the framework of a circular economy. They aim at stimulating sustainable development which

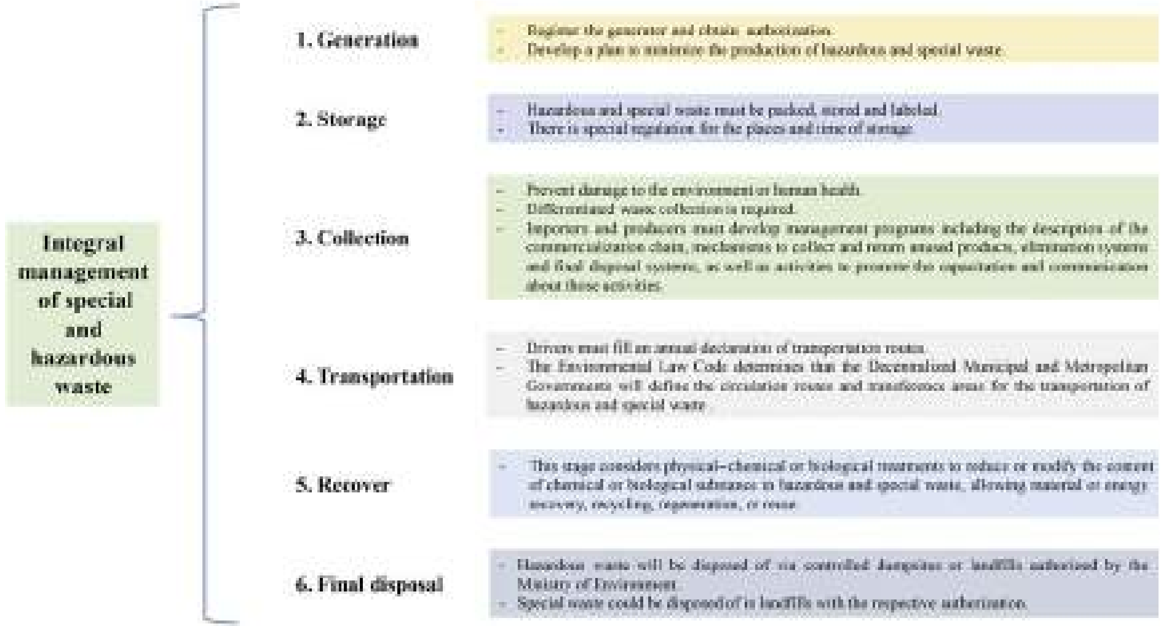

Figure 20.8 Phases of the integral management of special and hazardous waste.
Source: Text of Environmental Secondary Normative, art. 78-147 (MAE, 2003. Texto Unificado De Legislacion Secundaria De Medio Ambiente (TULSMA). Registro Oficial Edición Especial 2 de 31-mar.-2003. Ecuador. Available at: <http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-TEXTO_UNIFICADO_DE_LEGISLACION_SECUNDARIA_DE_MEDIO_AMBIENTE>).

objective is to produce goods and services while reducing the consumption and waste of raw materials, water, and energy (MAE, 2015; Asamblea Nacional, 2017).

20.7 Challenges and perspectives

This section presents the main challenges of the Ecuadorian E-waste management system toward compliance with the ISWM framework. Those challenges were identified in a National Workshop on E-waste management, held in July 2018. This workshop was conducted using the Systemic Design of Solutions (Méndez-Fajardo et al., 2017), previously used to frame the current E-waste National Policy in Colombia (MINAMBIENTE, 2017). The exercise included 51 actors representing most of the interested parties defined in the section of stakeholders. For instance, National and Municipal Government representatives, Manufactures/Importers (e.g., Claro, Indurama), Recycling Companies (e.g., CTIP, Vertmonde), Base Recyclers, Academia (e.g., Universidad de Cuenca, ESPOCH), and International Organizations such as the Swiss Federal Laboratories for Materials Science and Technology (EMPA), the Swiss Resource Centre and Consultancies for Development (Skat), and the United Nations Industrial Development Organization (UNIDO). This broad stakeholder participation contributes to a holistic insight into the E-waste situation in Ecuador.

The absence of E-waste management on the political agenda at the national and local level, together with the lack of budget assignment for this topic are the leading causes that impede the creation of an ISWM system in the country. Only few initiates dealing with E-waste exist, mainly founded by international bodies. The prime limitation associated to the political and legal aspects is the lack of a robust and coherent legislative and regulatory framework, adapted to the dynamics of the management system, which is also easy to understand and operationalize for the actors involved. The regulatory framework for the E-waste management system is composed of Constitutional Norms, the CODA, Ministry Agreements and Resolutions. Hence, the gaps encountered in the Ecuadorian legislation are the result of a dispersed secondary normative and the need for specific E-waste regulation. Aligned with the extended producer responsibility, the country obligates generators of special and hazardous waste to register, obtain authorization, and present a management program including mechanisms to collect and return, elimination systems, and final disposal. However, this normative is not specific for E-waste, but for special and hazardous waste. As a result there is a lack of a technical guide that could recognize the special features of E-waste along their integral management (StEP, 2018). The new "Reglamento al CODA—CODA bylaw" which is currently being analyzed by the President is considered as an opportunity to consolidate the legal framework to regulate WEEE in Ecuador. In this regulation, a special chapter for the Integral Management of Hazardous and Special Waste is considered.

Regarding stakeholders involvement, the main limitation is that their roles and responsibilities are not well-defined. Such uncertainty does not propitiate an environment where stakeholders could assume and develop their roles effectively. The

Ecuadorian environmental competences model is a big challenge because there is too much responsibility of the Central Government. In addition, the country has an enormous financial problem due to an institutional crisis, which derived in a reduction in the number of Ministry Offices from 27 to 20. As a result, the Ministry of Environment was merged with the Ministry of Water (Presidential Decree, 533). This new structure ended up with a Ministry with too many competencies, and fewer resources for the course of action, for example, contracting studies and planning strategies.

Currently the informal sector represents most of the workforce of the E-waste management chain. However, its work is not recognized by the government or society; even an operative model for its socio-economic inclusion does not exist in the country. One way to tackle this informality is guaranteeing a fair price for the provided service and recognizing the critical role the informal sector plays. According to Aparcana (2017) there are different formalization strategies, one of them is to organize waste collectors in associations or cooperatives. Another strategy is to organize waste collectors in community-based organizations or micro and small enterprises and eventually, or to contract them as individual workers by the formal waste management sector (Aparcana, 2017). Formal recognition of their role could decrease the volume of E-waste that goes through an inappropriate channel, that is, ending up at final disposal sites.

In addition, the improvement of the technical capacity of E-waste recycling companies should be considered a priority. For improving their capacities, these companies should aim at complying with technical standards to obtain international certifications. These developments would lead to a higher valorization of the E-waste processed. Currently, only one recycling company complies with an R2 certification. Another point for improvement is the service coverage, considering that the current eleven recycling companies registered by MIPRO have their facilities only in four cities: Quito, Guayaquil, Ambato, and Machala.

In terms of generation and separation, most users in Ecuador do not separate E-waste, and it is most likely to end up in final disposal sites along with household garbage. Therefore it is imperative to support initiatives for classification at source and the implementation of a differentiated collection system to enhance the next steps in waste management. For example, in the urban areas of Cuenca, about 60% of households do not classify their waste, and 35% of them mention that the main reason is the absence of collection points or containers destined for their use. Another 20% mention that they do not have the interest to perform this practice (Mentefactura, 2017). Another critical element for the development and improvement of the Ecuadorian E-waste management system are data. Data contribute with the understanding of E-waste flows and thereby allows the local and national government to take the corresponding actions for the correct treatment of E-waste. However, registered operators do not make data available, neither the amount of E-waste processed nor their processing capacity. Furthermore, E-waste operators and institutions are required to document the flows of unusable state goods received and delivered, but such data are not readily available. Therefore one of the main challenges is to design a proper plan for data collection at municipal and national level. In this regard, StEP (2014) indicates that recycling companies require to document the inputs they receive from their suppliers. Besides, StEP mentions the necessity of stating what information is expected from each participant within the E-waste management chain. Finally, the exchange of information and knowledge, open access data, and well-documented processes are essential. One option to achieve this is by developing a multistakeholder platform that ensures the implementation of a proper E-waste management system where strategic decisions are jointly taken based on an open dialogue and are accepted by all participants.

20.8 Conclusion

This work presents an analysis of the current situation of the Ecuadorian E-waste management system. The assessment is performed under the lens of the Integrated and Sustainable Waste Management framework. It assesses the Ecuadorian situation with respect to the three dimensions proposed in the ISWM, that is, stakeholder's involvement, political and socio-cultural aspects, and the technical elements and procedures that constitute the E-waste management system in Ecuador.

The analysis of the Ecuadorian situation, regarding E-waste management, revealed the shortcomings that hinder the creation of a National ISWM system. The most relevant being, E-waste in Ecuador is not part of the political agenda neither at national nor at local level. The national government should lead the develop of an integral policy and an effective E-waste management system with the participation of key stakeholders. Furthermore, the Ecuadorian regulatory framework has dispersed secondary normative, which lacks coherency and it is not robust. Most of E-waste regulation are built on Ministry Agreements and Resolutions related to Hazardous and Special Waste. This exhibits a need for specific E-waste regulation. Nevertheless, there are ongoing governmental initiatives to consolidate this legal framework in the CODA bylaw.

Roles and responsibilities of stakeholders involved in E-waste management are not well-defined so there is uncertainty on the competences that each one has to assume. In addition, the current financial and institutional situation of the country hampers a proper management, only few resources are assigned to develop new projects on environmental topics. A couple of initiates dealing with E-waste are presently carried out, mainly founded by international bodies. The implementation of formalization strategies for the informal sector needs to be addressed by the government. There exist several alternatives to include the informal sector in the E-waste management chain, which will contribute to improve their well-being as well as to increase the recycling rate of this waste stream. These initiatives should go along with the improvement of E-waste recycling companies. The government should encourage international certifications to assure that best available techniques are in place.

Furthermore collection systems and data gathering schemes must be deployed through alliances between the central government and municipalities. The reverse logistic, statistics and proper treatment can be financed via the EPR system. Currently EPR is mentioned at different levels of legislation but it is not implemented for E-waste. In addition, the limited awareness about E-waste in Ecuador is another problem that limits its proper treatment. National and municipal government must develop actions to increase environmental awareness. They must promote the reuse of EEE, inform consumers about the prohibition to dispose E-waste together with household waste, and create authorized collection points through municipal governments.

Despite the current flaws and challenges in the Ecuadorian E-waste management practices, the country has a strong chart of fundamental rights and principles that enforces the duty of the State to guarantee, through public policies and normative, the creation of an integrated and sustainable E-waste management system.

List of abbreviations

Abbreviations	Spanish	English
AM	Acuerdo Ministerial	Ministry Agreement
AME	Asociación de Municipios del Ecuador	Association of Municipalities of Ecuador
Basel Convention		Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal
CCCV	Cuenca, Ciudad para Vivir	
CE	Constitución del Ecuador	Constitution of Ecuador
CODA	Código Orgánico del Ambiente	Environmental Organic Code
COMEXI	Consejo de Comercio Exterior e Inversiones	Council of Foreign Trade and Investments
COOTAD	Código Orgánico de Organización Territorial, Autonomía y Descentralización	Organic Code of Territorial Organization, Autonomy and Decentralization
EMPA		Swiss Federal Laboratories for Materials Science and Technology
E-waste		Electronic waste
e-Comex	Comercio Exterior	Foreign Trade
EEE		Electric and Electronic Equipment
EMAC	Empresa Pública Municipal de Aseo de Cuenca	Municipal Cleaning Company of Cuenca.
ENEMDU	Encuesta Nacional De Empleo, Desempleo Y Subempleo	National Survey on Employment, Unemployment and Underemployment

(*Continued*)

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Abbreviations	Spanish	English
EPR		Extended Producer Responsibility
FUNGERES	Fundación para la Gestión de Residuos	Foundation for Waste Management
GEA	Fundación para la Gestión Ambiental	Foundation for Environmental Management
GEF		Global Environment Facility
IMF		International Monetary Fund
INEC	Instituto Nacional de Estadística y Censos	National Institute of Statistics and Census
IRR	Iniciativa Regional para el Reciclaje Inclusivo	Regional Initiative for Inclusive Recycling
ISWM		Integrated and Sustainable Waste Management
MAA	Ministerio del Ambiente y Agua	Ministry of Environment and Water
MARENA	Ministerio del Ambiente y los Recursos Naturales de Nicaragua	Ministry of Environment and Natural Resources of Nicaragua
MARN	Ministerio de Ambiente y Recursos Naturales	Ministry of Environment and Natural Resources of Guatemala
MEER	Ministerio de Electricidad y Energía Renovable	Ministry of Electricity and Renewable Energy
MIAMBIENTE	Secretaría de Recursos Naturales y Ambiente de Honduras	Secretariat of Natural Resources and Environment of Honduras
MICPEC	Ministerio de Coordinación de la Producción, Empleo y Competitividad	Ministry of Production, Employment and Competitiveness
MINAMBIENTE	Ministerio del Ambiente de Colombia	Ministry of Environment of Colombia
Minea	Ministerio del Poder Popular para Ecosocialismo y Aguas de Venezuela	Ministry of People's Power for Ecosocialism and Waters of Venezuela
MINSA	Ministerio de Salud de la República de Panamá	Ministry of Health of the Republic of Panama
MIPRO	Ministerio de Industrias y Productividad	Ministry of Industries and Productivity
MMAyA	Ministerio de Medio Ambiente y Agua de Bolivia	Ministry of Environment and Water of Bolivia
MSW		Municipal Solid Waste
Nairobi Declaration		Nairobi declaration on the environmentally sound management of electrical and electronic waste

(*Continued*)

(Continued)

Abbreviations	Spanish	English
NATURA	Fundación Ecuatoriana para la Protección y Conservación de la Naturaleza	Ecuadorian Foundation for the Protection and Conservation of Nature.
NGOs		Non-Governmental Organization
NPO		Non-Profit Organizations
OEC		The Observatory of Economic Complexity
PNGIDS	Programa Nacional para la Gestión Integral de Desechos Sólidos	National Program for the Integral Management of Solid Waste
POM		Placed on Market
POPs		Persistent organic pollutants
RELAC	Plataforma Regional de Residuos Electrónicos en Latinoamérica y el Caribe	Regional Platform for Electronic Residues in Latin America and the Caribbean
RENAREC	Red Nacional de Recicladores del Ecuador	National Network of Recyclers of Ecuador
SENAE	Servicio Nacional de Aduana del Ecuador	National Customs Service of Ecuador
SERI		Sustainable Electronics Recycling International
SKAT		Swiss Resource Centre and Consultancies for Development
SRI		Sustainable Recycling Industries
Stockholm Convention		Stockholm Convention on Persistent Organic Pollutants
TULSMA	Texto Unificado de Legislación Secundaria de Medio Ambiente	Unified Text of Environmental Secondary Normative
UNEP		United Nations Environment Programme
UNESCO		United Nations Educational, Scientific and Cultural Organization
UN-Habitat		United Nations Human Settlements Programme
UNIDO		United Nations Industrial Development Organization
VLIR-UOS		Flemish Interuniversity Council—University Development Cooperation
WEEE	Residuos de Aparatos Eléctricos y Electrónicos	Waste of Electric and Electronic Products

References

ADELCA, 2016. MEMORIA DE SOSTENIBILIDAD 2016. Available at: <https://www.unglobalcompact.org/system/attachments/cop_2018/451621/original/MEMORIA_2016_COMUNICACION_DE_PROGRESO_PACTO_MUNDIAL_04.01.17.pdf?1515445103> (accessed 09.01.19.).

Anschütz, J., IJgosse, J., Scheinberg, A., 2004. Putting Integrated Sustainable Waste Management into Practice - Using the ISWM Assessment Methodology.

Aparcana, S., 2017. Approaches to formalization of the informal waste sector into municipal solid waste management systems in low- and middle-income countries: review of barriers and success factors. Waste Manag. 61, 593–607. Available from: https://doi.org/10.1016/j.wasman.2016.12.028.

Appadurai, A., 1988. The Social Life of Things: Commodities in Cultural Perspective. Cambridge University Press.

Arias, P., Seilles, M., 2014. Información Ambiental en hogares. Available at: <http://www.ecuadorencifras.gob.ec/sistema-integrado-de-estadisticas-ambientales-siea/> (accessed 03.12.18.).

Asamblea Constituyente, 2008. Constitución del Ecuador. Registro Oficial 449 de 20-oct.-2008. Ecuador. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = PUBLICO-CONSTITUCION_DE_LA_REPUBLICA_DEL_ECUADOR>.

Asamblea Nacional, 2012. Código Orgánico de Organización Territorial, Autonomía y Descentralización (COOTAD). Ecuador: <http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = DESCENTR-CODIGO_ORGANICO_DE_ORGANIZACION_TERRITORIAL_COOTAD>. Available at: <http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = DESCENTR-CODIGO_ORGANICO_DE_ORGANIZACION_TERRITORIAL_COOTAD>.

Asamblea Nacional, 2017. Código Orgánico del Ambiente. Registro Oficial Suplemento 983 de 12-abr.-2017. Quito. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-CODIGO_ORGANICO_DEL_AMBIENTE>.

Asamblea Nacional Constituyente, 1998. Constitución Política del Ecuador. Registro Oficial 1 de 11-ago.-1998. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = CONSTITU-CONSTITUCION_POLITICA_DE_LA_REPUBLICA_DEL_ECUADOR_1998>.

Ávila Santamaría, R., 2016. El neoconstitucionalismo andino. Universidad Andina Simón Bolívar; Huaponi Ediciones, Quito.

Baldé, C.P., et al., 2015. The Global E-Waste Monitor 2014. United Nations University, Bonn, IAS-SCYLE. Available at: <https://i.unu.edu/media/unu.edu/news/52624/UNU-1stGlobal-E-Waste-Monitor-2014-small.pdf>.

Baldé, C.P., et al., 2017. The Global E-Waste Monitor 2017. United Nations University (UNU), International Telecommunication Union (ITU) & International Soild Waste Association (ISWA), Bonn/Geneva/Vienna. Available at: <https://www.itu.int/en/ITU-D/Climate-Change/Pages/Global-E-waste-Monitor-2017.aspx>.

Bauman, Z., 1998. On glocalization: or globalization for some, localization for some others. Thesis Eleven 54 (1), 37–49.

Beltrán, J., 2013. La chatarra sostiene a familias. EL TIEMPO, p. 1. Available at: <https://www.eltiempo.com.ec/noticias/cuenca/2/la-chatarra-sostiene-a-familias> (accessed 21.12.18.).

Benavides, R., et al., 2017. Módulo de Información Ambiental en Hogares - Diciembre 2017. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Hogares/Hogares_2017/DOC_TEC_MOD_AMBIENTAL_ENEMDU.2017.pdf> (accessed 03.12.18.).

Blaser, F., 2009. Diagnóstico de Electrodomésticos y de Aparatos Electrónicos de Consumo. Colombia.

Boeni, H., Silva, U., Ott, D., 2008. E-Waste Recycling in Latin America: Overview, Challenges and Potential.

Brünner, J.J., 1988. Un espejo trizado: ensayos sobre cultura y políticas culturales FLACSO. Santiago de Chile.

COMEX, 2012a. Resolución 100: Parámetro cuantitativo de reciclaje de celulares. Registro Oficial 875 de 21-en.-2013. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/ImageVisualizer/ImageVisualizer.aspx?id = 5F1E992623D4F8D0A9D1BC72C1E75B324F406203&type = RO&pagenum = 27>.

COMEX, 2012b. Resolución 67: Restricción cuantitativa anual para la importación de teléfonos celulares. Registro Oficial Suplemento 725 de 15-jun.-2012. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = TRIBUTAR-RESTRICCION_CUANTITATIVA_ANUAL_IMPORTACION_TELEFONOS_CELULARES>.

Centrosur, 2016. NOTICIA, Centrosur. Available at: <http://www.centrosur.gob.ec/?q = node/511> (accessed 02.01.19.).

Congreso Nacional, 2016. Ley 20920. Santiago. Available at: <https://www.leychile.cl/N?i = 1090894&f = 2016-06-01&p = >.

Congreso Nacional del Ecuador, 1984. Constitución Política de la República del Ecuador (Codificación 1984). Registro Oficial 763 de 12-jun.-1984. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = CONSTITU-CONSTITUCION_POLITICA_DE_LA_REPUBLICA_DEL_ECUADOR_CODIFICACION_1984>.

Congreso Nacional del Ecuador, 1996. Constitución Política de la República del Ecuador (Codificación 1996). Registro Oficial 969 de 18-jun.-1996. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = CONSTITU-CONSTITUCION_POLITICA_DE_LA_REPUBLICA_DEL_ECUADOR_CODIFICACION_1996>.

Cruz-Sotelo, S., et al., 2017. E-waste supply chain in mexico: challenges and opportunities for sustainable management. Sustainability 9 (4), 503. Available from: https://doi.org/10.3390/su9040503.

Cueva, A., 2018. Proyecto GEF-ONUDI sobre la Gestión de los RAEE en América Latina. Quito.

Delaunay, N., Montero, R., 2013. Estimación de la Generación de Residuos Electrónicos en el Ecuador. RECICLAMETAL. Retrieved from http://www.reciclametal.com/index.php/noticias/investigacion/96-invest-citic.

Donoso Carrillo, J.C., 2017. EL IMPACTO DE LA INDUSTRIALIZACIÓN EN EL PROCESO DE FABRICACIÓN DE PRODUCTOS INTERMEDIOS DE HIERRO O ACERO SIN ALEAR COMO MECANISMO DE SUSTITUCIÓN DE IMPORTACIONES EN EL CONTEXTO DE CAMBIO DE LA MATRIZ PRODUCTIVA DE LA INDUSTRIA SIDERÚRGICA DEL ECUADOR. Universidad

Internacional del Ecuador. Available at: <http://repositorio.uide.edu.ec/bitstream/37000/2104/1/T-UIDE-1544.pdf>.

e-Comex, 2017. Buscador de Aranceles Ecuador. e-Comex. Available at: <http://arancelesecuador.com/resultados.html?search = repuestos + electronicos&page = 1> (accessed 02.01.19.).

EMAC, 2017. EMAC EP presenta Punto Limpio e Iglú de Reciclaje. Available at: <http://www.emac.gob.ec/?q = content/emac-ep-presenta-punto-limpio-e-iglú-de-reciclaje> (accessed 30.12.18.).

El Telégrafo, 2011. Más de 3 mil chatarreros mejoran su vida laboral. El Telégrafo, Available at: <https://www.eltelegrafo.com.ec/noticias/economia/1/mas-de-3-mil-chatarreros-mejoran-su-vida-laboral> (accessed 21.12.18.).

El Telégrafo, 2012. Intercia envía el primer contenedor de desechos electrónicos a Canadá. El Telégrafo. Available at: <https://www.eltelegrafo.com.ec/noticias/economia/8/intercia-envia-el-primer-contenedor-de-desechos-electronicos-a-canada> (accessed 30.12.18.).

El Telégrafo, 2013. $ 200 millones ahorra el país con el reciclaje de chatarra. El Telégrafo. Available at: <https://www.eltelegrafo.com.ec/noticias/economia/1/200-millones-ahorra-el-pais-con-el-reciclaje-de-chatarra> (accessed 02.01.19.).

El Tiempo, 2018. Resumen de noticias suscitadas en Cuenca. El Tiempo. Available at: <https://www.eltiempo.com.ec/noticias/cuenca/2/resumen-noticias-cuenca> (accessed 01.01.19.).

Escobar, P., 2017. Argentina tiene pendiente el debate por una ley específica de gestión de residuos electrónicos. Misiones Online. Available at: <https://misionesonline.net/2017/06/16/argentina-pendiente-debate-una-ley-especifica-gestion-residuos-electronico/> (accessed 12.12.18.).

Espinoza, O., et al., 2008. Diagnóstico del Manejo de los Residuos Electrónicos en el Perú. Peru. Available at: <http://www.residuoselectronicos.net/archivos/documentos/Diagnosticoperu.pdf>.

Espinoza Echeverría, V.S., 2010. Recuperación de metales de las tarjetas de circuito de celulares descartados. Escuela Politécnica Nacional. Available at: <http://bibdigital.epn.edu.ec/bitstream/15000/2485/1/CD-3188.pdf>.

Fernández Protomastro, G., 2013. Minería urbana y la gestión de los residuos electrónicos, first ed. Grupo Uno, Buenos Aires.

Fundación NATURA, 2018. Natura Nacional. Available at: <http://www.ecuanex.net.ec/natura/nacional/info.htm> (accessed 30.12.18.).

GAD Ambato, 2018. La Municipalidad busca un Cantón saludable y responsable con el ambiente. Available at: <https://www.ambato.gob.ec/la-municipalidad-busca-un-canton-saludable-y-responsable-con-el-ambiente> (accessed 30.12.18.).

García Canclini, N., 1990. Culturas híbridas: estrategias para entrar y salir de la modernidad. México.

GEF, 2018. Strengthening of National Initiatives and Enhancement of Regional Cooperation for the Environmentally Sound Management of POPs in Waste of Electronic or Electrical Equipment (WEEE) in Latin-American Countries, Global Environment Facility. Available at: <https://www.thegef.org/project/strengthening-national-initiatives-and-enhancement-regional-cooperation-environmentally> (accessed 31.12.18.).

Granda, A., 2014. El 90%de las partes de una PC en desuso se puede reutilizar. El Comercio. Available at: <https://www.elcomercio.com/tendencias/quito-computadoras-reciclaje-dico-duro.html> (accessed 02.01.19.).

Grimble, R., Wellard, K., 1997. Stakeholder methodologies in natural resource management: a review of principles, contexts, experiences and opportunities. Agric. Syst 55 (2), 173–193. Available from: https://doi.org/10.1016/S0308-521X(97)00006-1.

Grupo Técnico DEAGA, 2016. Información Ambiental en Hogares. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Hogares/Hogares_2016/Documentotecnico.pdf> (accessed 03.12.18.).

Hagelüken, C., 2018. Recycling of WEEE – Status and New Developments. Munich. doi: 10.13140/RG.2.2.15490.17603.

Hare, M., Pahl-Wostl, C., 2002. Stakeholder categorisation in participatory integrated assessment processes. Integr. Assess. 3 (1), 50–62. Available from: https://doi.org/10.1076/iaij.3.1.50.7408.

House, R.J., Hanges, P.J., Javidan, M., Dorfman, P.W., Gupta, V., 2004. Culture, Leadership, and Organizations: The GLOBE Study of 62 Societies. SAGE Publications.

HP, 2018. Programa de reciclaje. Available at: <https://www8.hp.com/ec/es/ads/planet-partners/index.html> (accessed 26.12.18.).

Ignatuschtschenko, E., 2017. Electronic waste in China, Japan, and Vietnam: a comparative analysis of waste management strategies. Vienna J. East Asian Stud. 9, 29–58.

IMF, 2018. World Economic Outlook (October 2018). Available at: <https://www.imf.org/external/datamapper/NGDPDPC@WEO/OEMDC/ADVEC/WEOWORLD/ECU> (accessed 26.12.18.).

IndexMundi, 2017. Ecuador Tasa de crecimiento. Available at: <https://www.indexmundi.com/es/ecuador/tasa_de_crecimiento.html> (accessed 26.12.18.).

INEC, 2013. Módulo de Información Ambiental en Hogares ENEMDU - Diciembre 2013. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Hogares-2013/201401_EnemduAmbientePresentacion.pdf> (accessed 03.12.18.).

INEC, 2017. Base de Datos de Gestión Integral de Residuos Sólidos 2016. INEC, Quito. Available at: <http://www.ecuadorencifras.gob.ec/documentos/datos/Estadisticas_Ambientales/Municipios_Consejos_Provinciales/Gestion_Integral_Residuos_Solidos_de_Municipios/Base CSV Residuos 2016.zip>.

INEC, 2018. Contador Poblacional. Available at: <http://www.ecuadorencifras.gob.ec/estadisticas/> (accessed 25.12.18.).

INEC, AME, 2017. Estadística de Información Ambiental Económica en Gobiernos Autónomos Descentralizados Municipales. Available at: <http://www.ecuadorencifras.gob.ec/documentos/web-inec/Encuestas_Ambientales/Gestion_Integral_de_Residuos_Solidos/2016/Presentacion Residuos Solidos 2016 F.pdf> (accessed 21.09.18.).

IPES, 2014. Diagnostico Situacional del Manejo de Residuos de Aparatos Eléctricos y Electrónicos en la Ciudad de Cusco. Cusco. doi: 10.1016/j.apcata.2005.04.020.

IRR, 2015. Reciclaje Inclusivo y Recicladores de Base en el Ecuador. Ecuador. Available at: <https://reciclajeinclusivo.org/wp-content/uploads/2016/04/Reciclaje-Inlcusivo-y-Recicladores-de-base-en-EC.pdf>.

La Hora, 2008. Chatarreros los recicladores del metal. La Hora. Available at: <https://lahora.com.ec/noticia/781070/chatarreros-los-recicladores-del-metal> (accessed 21.12.18.).

La Hora, 2018. Vocación para apoyar a los guerreros Ambientalistas. La Hora. Available at: <https://www.pressreader.com/ecuador/la-hora-quito/20180710/282157882010873> (accessed 26.12.18.).

MAE, 2003. Texto Unificado De Legislacion Secundaria De Medio Ambiente (TULSMA). Registro Oficial Edición Especial 2 de 31-mar.-2003. Ecuador. Available at: <http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-TEXTO_UNIFICADO_DE_LEGISLACION_SECUNDARIA_DE_MEDIO_AMBIENTE>.

MAE, 2012. Acuerdo Ministerial 142: Listados Nacionales de Sustancias Químicas Peligrosas, Desechos Peligrosos y Especiales. Registro Oficial No 856 de 21-dic.-2012. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-LISTADO_NACIONAL_SUSTANCIAS_QUIMICAS_PELIGROSAS_DESECHOS_PELIGROSOS>.

MAE, 2013a. 89% de la meta anual de reciclaje de celulares se cumplió en siete meses. Ministerio del Ambiente. Available at: <http://www.ambiente.gob.ec/89-de-la-meta-anual-de-reciclaje-de-celulares-se-cumplio-en-siete-meses/> (accessed 02.01.19.).

MAE, 2013b. Acuerdo Ministerial 190: Política Nacional de Postconsumo de Equipos Eléctricos y Electrónicos en Desuso. Registro Oficial Suplemento 881 de 29-ene.-2013. Quito. Available at: <http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-POLITICA_DE_POST_CONSUMO_EQUIPOS_ELECTRICOS_EN_DESUSO_MIN_AMBIENTE>.

MAE, 2013c. Acuerdo Ministerial 191: Instructivo de aplicación del principio de responsabilidad extendida del productor establecido en el Reglamento para la prevención y control de la contaminación por sustancias químicas peligrosas, desechos peligrosos y especiales. Registro Oficial Suplemento 881 de 29-ene.-2013. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-INSTRUCTIVO_PRINCIPIO_RESPONSABILIDAD_REGLAMENTO_CONTROL_SUSTANCIAS>.

MAE, 2013d. Acuerdo Ministerial 22: Instructivo para la gestión integral de pilas usadas. Registro Oficial 943 de 29-abr.-2013. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-INSTRUCTIVO_PARA_LA_GESTION_INTEGRAL_DE_PILAS_USADAS>.

MAE, 2014. Acuerdo Ministerial 19: Políticas generales para la gestión de plásticos en el Ecuador. Registro Oficial 218 de 03-abr.-2014. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-POLITICAS_PARA_GESTION_INTEGRAL_DE_PLASTICOS_EN_EL_ECUADOR>.

MAE, 2015. Acuerdo Ministerial No. 140: Marco institucional para incentivos ambientales. Registro Oficial Edición Especial 387 de 04-nov.-2015. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-MARCO_INSTITUCIONAL_PARA_INCENTIVOS_AMBIENTALES>.

MAE, 2018a. Acuerdo Ministerial 26: Procedimiento para registro de generadores de desechos peligrosos. Registro Oficial Suplemento 334 de 12-may.-2008. Available at: <http://www.silec.com.ec/Webtools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-PROCEDIMIENTO_PARA_REGISTRO_DE_GENERADORES_DE_DESECHOS_PELIGROSOS>.

MAE, 2018b. Fortalecimiento de Iniciativas Nacionales y Mejora de la Cooperación Regional para el Manejo Ambientalmente Racional de los COPs en Residuos de Aparatos Eléctricos y Electrónicos (RAEE) en los Países de América Latina. Quito, Ecuador.

Magalini, F., Kuehr, R., Baldé, C.P., 2015. E-Waste in Latin America: statistical analysis and policy recommendations. Available at: <http://www.gsma.com/latinamerica/wp-content/uploads/2015/11/gsma-unu-ewaste2015-eng.pdf>.

MARENA, 2018. Fortalecimiento de Iniciativas para la Gestión Ambientalmente Racional de los Residuos de Aparatos Electrónicos o Eléctricos (RAEE). Quito, Ecuador.

MARN, 2018. Fortalecimiento de iniciativas nacionales y mejoramiento de la cooperación regional para la gestión ambientalmente racional de los COP en residuos de aparatos electrónicos o eléctricos (RAEE) en países latinoamericanos. Quito, Ecuador.

Méndez-Fajardo, S., et al., 2017. Guía práctica para el diseño sistémico de políticas para la gestión de RAEE en países en vía de desarrollo. Sutainable Recycling Industries, St. Gallen, Suiza.

Mentefactura, 2017. Plan de Reciclaje Inclusivo de Cuenca. Cuenca.

MIAMBIENTE, 2018. Gestión de RAEE en Honduras. Quito, Ecuador.

MINAMBIENTE, 2017 Política Nacional: Gestión Integral de Residuos de Aparatos Eléctricos y Electrónicos. Bogotá, p. 104. Available at: <http://www.residuoselectronicos.net/wp-content/uploads/2017/07/Política-de-RAEE-31-05-2017-Versión-Publicación.pdf> (accessed 06.12.18.).

Minea, 2018. Proyecto Plan de Gestión Integral de Residuos de Aparatos Eléctricos y Electrónicos (PGI-RAEE). Quito, Ecuador.

Ministerio de Salud, 2018. Normativa vigente para los residuos electrónicos en Costa Rica. Quito, Ecuador.

Ministerio del Ambiente, 2012. Reglamento Nacional para la gestión y Manejo de los residuos de aparatos eléctricos y electrónicos. Available at: <http://raee-peru.pe/pdf/reglamento.pdf> (accessed 06.12.18.).

Ministerio del Trabajo, 2015. El salario básico para el 2015 será de 354 Dólares – Ministerio del Trabajo. Available at: <http://www.trabajo.gob.ec/el-salario-basico-para-el-2015-sera-de-354-dolares/> (accessed 03.01.19.).

MINSA, 2018. Proyecto Fortalecimiento cooperación regional para la gestión ambientalmente racional de los COP en Residuos de Aparatos Electrónicos o Eléctricos Países Latinoamericanos (Panamá). Quito, Ecuador.

MIPRO, 2010. Acuerdo MIPRO 10 464.pdf. Quito, Ecuador, p. 4.

MIPRO, 2014. Proceso de chatarrización de bienes del estado: empresas registradas y gestores ambientales. Available at: <https://www.industrias.gob.ec/wp-content/uploads/2014/11/Empresas-Chatarrizadoras-Registradas-WEB-modificadas-2013-3-xls-actualizar-oct-27-2014.pdf> (accessed 17.12.18.).

MIPRO, 2016. Proceso de chatarrización de bienes del estado: empresas registradas y gestores ambientales. Available at: <https://www.industrias.gob.ec/wp-content/uploads/downloads/2016/12/empresas-registradas-chatarra.pdf> (accessed 17.12.18.).

MIPRO, 2018. Proceso de chatarrización de bienes del estado: empresas registradas y gestores ambientales. Ministerio de Industrias y Productividad, Quito, Ecuador. Available at: <https://www.industrias.gob.ec/wp-content/uploads/2018/09/Copia-de-Copia-de-Xl00004891.xlsGES.-AMB.-Septiembre-2018-1-2.pdf>.

MMAyA, 2017. Diagnóstico de la gestión de residuos de aparatos eléctricos y electrónicos en Bolivia y análisis estadístico. Available at: <https://www.kioscoverde.bo/wp-content/uploads/2018/10/DIAGNOSTICO-RAEE-BOLIVIA.pdf> (accessed 10.12.18.).

Monge, C., et al., 2017. Guía técnica para la gestión integral de los residuos de aparatos eléctricos y electrónicos en El Salvador. San Salvador. Available at: <www.marn.gob.sv> (accessed 11.12.18.).

Mushove, P., Vogel, C., 2005. Heads or tails? Stakeholder analysis as a tool for conservation area management. Global Environ. Change 15 (3), 184−198. Available from: https://doi.org/10.1016/J.GLOENVCHA.2004.12.008.

Nations Online, 2018. Political Map of Ecuador and the Galapagos Islands. Nations Online. Available at: <https://www.nationsonline.org/oneworld/map/ecuador-political-map.htm> (accessed 25.12.18.).

OEC, 2018. Ecuador: Exports, Imports, and Trade Partners. Available at: <https://atlas.media.mit.edu/en/profile/country/ecu/> (accessed 25.12.18.).

Ojeda, J., 2009. Elaboración de un plan de negocio para la creación de una empresa de consultoría en gestión de residuos en Ecuador. Universidad Autónoma de Madrid.

PNGIDS, 2018. Recolección de teléfonos celulares. Quito.

Padilla Torres, F.L., 2017. Propuesta de una guía de procedimientos sobre el manejo de desechos electrónicos en el distrito metropolitano de Quito. Universidad Politécnica Nacional. Available at: <http://bibdigital.epn.edu.ec/bitstream/15000/17545/1/CD-8052.pdf>.

Porto Tapiquén, C., 2015. Shapefiles (*.shp) de América. Available at: <https://tapiquen-sig.jimdo.com/descargas-gratuitas/américa/> (accessed 08.01.19.).

Reed, M.S., et al., 2009. Who's in and why? A typology of stakeholder analysis methods for natural resource management. J. Environ. Manag. 90 (5), 1933−1949. Available from: https://doi.org/10.1016/J.JENVMAN.2009.01.001.

Rojas Matovelle, F.d.P., Román Quevedo, D.C., 2012. Análisis de las tecnologías de información verdes y diseño de una planta de tratamiento de desechos electrónicos. Universidad Politécnica Nacional. Available at: <http://bibdigital.epn.edu.ec/bitstream/15000/4771/1/CD-4387.pdf>.

Schluep, M., Müller, E., Rochat, D., 2012. e-Waste Assessment Methodology Training & Reference Manual. p. 106. Retrieved from http://www.basel.int/Portals/4/download.aspx?d = UNEP-CHW-EWASTE-MANUA-EwasteAssessmentMethodology.English.pdf.

SENAE, 2017. Para Importar, Servicio Nacional de Aduana del Ecuador. Available at: <https://www.aduana.gob.ec/para-importar/> (accessed 01.01.19.).

SERI, 2018a. Find a Recycler. Available at: <https://sustainableelectronics.org/recyclers> (accessed 28.12.18.).

SERI, 2018b. R2 Standard. Available at: <https://sustainableelectronics.org/r2-standard/r2-document-library> (accessed 07.12.18.).

Seilles, M., 2015. Información Ambiental en hogares. Available at: <http://www.ecuadorencifras.gob.ec/sistema-integrado-de-estadisticas-ambientales-siea/> (accessed 03.12.18.).

Solíz Torres, M.F., 2015. Ecología política y geografía crítica de la basura en el Ecuador Political ecology and critical geography of waste in Ecuador. Letras Verdes. Revista Latinoamericana de Estudios Socioambientales 17, 4−28. Available from: https://doi.org/10.17141/letrasverdes.17.2015.1259.

StEP, 2014. Recommendations for Standards Development for Collection, Storage, Transport and Treatment of e-Waste. Available at: <http://www.step-initiative.org/files/_documents/whitepapers/StEP_WP_Standard_20140602.pdf> (accessed 06.12.18.).

StEP, 2018. Developing Legislative Principles for e-Waste Policy in Developing and Emerging Countries. Available at: <http://www.step-initiative.org/files/_documents/whitepapers/Step_White_Paper_7_180221_low_compressed.pdf> (accessed 06.12.18.).

StEP, 2019. Ecuador, StEP E-waste World Map. Available at: <http://www.step-info.org/Overview_Ecuador.html> (accessed 04.01.19.).

Steers, R.M., Sanchez-Runde, C.J., Nardon, L., 2010. Management Across Cultures: Challenges and Strategies. Cambridge University Press.

Sucozhañay, G., Vidal, I., 2019. Análisis del flujo de materiales y evaluación del impacto ambiental de los residuos de aparatos eléctricos y electrónicos. Caso de estudio: Teléfonos celulares en el cantón Cuenca. Cuenca.

Torres, D., et al., 2015. Gestión Sostenible de Residuos de Aparatos Eléctricos y Electrónicos de América Latina. Geneva. Available at: <http://www.residuoselectronicos.net/wp-content/uploads/2015/05/ITU2015.pdf>.

Torres, D., Accurso, M., 2015. Gestión responsable de residuos de aparatos eléctricos y electrónicos (e-waste) en la industria de telefonía móvil en América Latina. Available at: <https://www.gsma.com/latinamerica/wp-content/uploads/2015/12/GSMA-LA-EWASTE-Position-Paper-final-SPA.pdf> (accessed 09.12.18.).

UNESCO, Plataforma RELAC, 2010. Los residuos electrónicos: Un desafío para la Sociedad del Conocimiento en América Latina y el Caribe. https://doi.org/10.1017/CBO9781107415324.004.

UNIDO, 2018. Cooperación regional en gestión de residuos electrónicos en países de América Latina, Unido.org. Available at: <https://www.unido.org/cooperacion-regional-en-gestion-de-residuos-electronicos-en-paises-de-america-latina> (accessed 31.12.18.).

United Nations, 1972. Report of the United Nations Conference on the Human Environment (Stockholm Conference).

United Nations, 1989. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. Available at: <https://www.basel.int/portals/4/basel.convention/docs/text/baselconventiontext-e.pdf> (accessed 31.12.18.).

United Nations, 2001. Stockholm Convention on Persistent Organic Pollutants. Available at: <http://untreaty.un.org> (accessed 31.12.18.).

United Nations, 2006. Nairobi Declaration on the Environmentally Sound Management of Electrical and Electronic Waste. Available at: <http://www.basel.int/portals/4/basel.convention/docs/meetings/cop/cop8/nairobideclaration.pdf>.

United Nations, 2017. United Nations Conference on Environment and Development (Rio Conference), United Nations System. Available at: <https://www.unsystem.org/content/united-nations-conference-environment-and-development-unced-1992> (accessed 31.12.18.).

United Nations Human Settlements Programme, 2010. Solid Waste Management in the World's Cities, Earthscan. UN-HABITAT, London and Washington, DC.

United Nations University, 2014. One Global Definition of E-waste, Step Initiative. Bonn. Available at: <http://www.step-initiative.org/files/_documents/whitepapers/StEP_WP_One.Global Definition of E-waste_20140603_amended.pdf> (accessed 27.11.18.).

Uribe, L., Wolfensberger, M., Ott, D., 2009. Manejo de los RAEE a través del sector informal en Medellín. Medellín.

Uribe, L., et al., 2010. Manejo de los RAEE a través del Sector Informal en Bogotá, Cali y Barranquilla. Colombia.

van de Klundert, A., Anschütz, J., 2001. Integrated Sustainable Waste Management-The Concept. A. Scheinberg (Ed.). Gouda. doi: 90-76639-02-7.

Vargas Torres, M.E., 2017. Estudio de la recuperación de indio a partir de pantallas de cristal líquido descartadas. Escuela Politécnica Nacional. Available at: <http://bibdigital.epn.edu.ec/bitstream/15000/17346/1/CD-7844.pdf>.

Veit, H.M., Bernardes, A.M., 2015. In: Veit, H.M., Moura Bernardes, A. (Eds.), *Electronic Waste*, *Electronic Waste: Recycling Techniques.*. Springer International Publishing

(Topics in Mining, Metallurgy and Materials Engineering), Cham. Available from: https://doi.org/10.1007/978-3-319-15714-6.

Vertmonde, 2018. Gestión Integral de Residuos Eléctricos y Electrónicos - Inicio. Available at: <https://vertmonde.com/index.html> (accessed 03.12.18.).

Villacís, B., Carrillo, D., 2012. País atrevido: la nueva cara sociodemográfica del Ecuador. Edición es. Quito, Ecuador: INEC. Available at: <http://www.ecuadorencifras.gob.ec/wp-content/descargas/Libros/Economia/Nuevacarademograficadeecuador.pdf>.

Visser, W., 2014. Closing the loop on steel: what we can learn from a manufacturer in Ecuador. The Guardian. Available at: <https://www.theguardian.com/sustainable-business/2014/nov/20/steel-recycling-circualr-economy-manufacturer-ecuador-adelca> (accessed 21.12.18.).

VLIRUOS, 2018. Enhancing the Social Value of the Circular Economy in Latin America. VLIRUOS. Available at: <https://www.vliruos.be/en/projects/project/22?pid = 3907> (accessed 02.01.19.).

Wang, F., et al., 2012. The best-of-2-worlds philosophy: developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag 32 (11), 2134−2146. Available from: https://doi.org/10.1016/j.wasman.2012.03.029.

Wilson, D.C., et al., 2015. "Wasteaware" benchmark indicators for integrated sustainable waste management in cities. Waste Manag. 35, 329−342. Available from: https://doi.org/10.1016/j.wasman.2014.10.006.

Wilson, D.C., Velis, C.A., Rodic, L., 2013. Integrated Sustainable Waste Mangement in Developing Countries 2, 52−68. Available from: https://doi.org/10.1680/warm.12.00005.

Xerox Corporation, 2018. HOW: Programa de Sustentabilidad. Available at: <https://www.office.xerox.com/campaigns/ec_recycling_return/esec.html> (accessed 26.12.18.).

Further reading

EcoCómputo, 2018. Informe de Gestión 2017. Available at: <http://ecocomputo.com/sites/default/files/InformeDeGestion2017InformeAutoridadNacional.pdf>.

MAE, 2016. Acuerdo Ministerial 121: Regulación para la gestión de residuos de botellas de vidrio en el Ecuador. Registro Oficial Suplemento 903 de 15-dic.-2016. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = AMBIENTE-REGULACION_PARA_LA_GESTION_DE_RESIDUOS_DE_BOTELLAS_DE_VIDRIO>.

MAE, MIPRO, 2017. Acuerdo Ministerial 120: Normativa para el uso de R - PET para la fabricación de botellas plásticas para bebidas. Registro Oficial Suplemento 75 de 08-sep.-2017. Available at: <http://www.silec.com.ec/WebTools/LexisFinder/DocumentVisualizer/FullDocumentVisualizerPDF.aspx?id = TRIBUTAR-NORMATIVA_PARA_USO_DE_R_PET_EN_LA_FABRICACION_DE_BOTELLAS_PLASTICAS>.

Appendices

Appendix A Constitutional environmental principles in Ecuador

Principle	Content	Constitutional norm
Sustainable Development	Find a balance between environment and development as linked concepts.	Art. 395.1
In Dubio Pro Natura	In case of doubt about the environmental normative, it must be applied in the most favorable sense to the protection of the nature.	Art. 395.4 Art. 71 in relation with art. 11.5
Precautionary	The authorities must adopt measures to protect the environment, even though the cause-effect relation between the activity and the harm have not been scientifically proven.	Art. 396, 73
Prevention	It takes place when there is certainty about the harm or the danger of the activity.	Art. 396.1
Solidarity and Integral Responsibility	It links everyone who is part of the production, commercialization and consume chain with the environmental responsibility. It is also known as "cradle to grave."	Art. 396
Integral Regulation	Environmental management policies must be applied integrally, and those will be mandatory for the authorities in general and every person.	Art. 395.2
Effective Judicial Protection and the Inversion of the Burden of Proof	The possibility to claim to authorities and judges to obtain effective judicial protection in environmental issues. It includes preventive measures that could stop the threat or the environmental damage, invert the burden of proof that is an exception of the principle of the presumption of innocence, so who has to proof is the person that alleges that there was not environmental damage.	Art. 397.1 Art. 87
Actions and Sanctions for Environmental Damage are Imprescriptible	The actions or sanctions never lapse.	Art. 395

(*Continued*)

(Continued)

Principle	Content	Constitutional norm
Prior Consultation	Every decision or governmental authorization that could affect the environment will be consulted to the community.	Art. 398 Art. 424

Appendix B Environmental principles in the environmental organic code of Ecuador

Principle	Content
Integral Responsibility	Who promotes the activity, generates or could generate environmental impact must be responsible.
Best Available Technology and Environmental Practices	The State must promote the development and use of clean environmental technologies and low impact alternative no contaminative energies.
Sustainable Development	The process in which the economic, social, cultural, and environmental aspects are linked to satisfy generational necessities.
Who Contaminates Must Pay	Who contaminates is obligated to integrally repair and to compensate those adversely affected.
In Dubio Pro Natura	In case of doubt about, it must be applied in the most favorable sense to the protection of nature.
Access to Information, Participation And Justice In Environmental Issues	Every person, community, nationality or collective, according to the law, has the right to the opportune and adequate access to information related with the environment.
Precautionary	If there is no scientific certainty of the environmental impact, the State must adopt opportune and effective measures to eliminate, avoid, reduce, mitigate and stop the affectation.
Prevention	If there is scientific certainty of the harm, the State must require to whom it corresponds measures to eliminate, avoid, reduce, mitigate and stop the affectation.
Integral Reparation	Group of actions, processes and measures to revert the impacts and environmental harm, to avoid their recurrence and facilitate the restitution.

(*Continued*)

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Principle	Content
Subsidiarity	The State must intervene in a subsidiary and opportune form to repair the environmental damage, when the person that promotes the activity does not assume the responsibility about the integral reparation.

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The Chilean regulation of waste electrical and electronic equipment (WEEE): some of the challenges and opportunities to incorporate informal E-waste recyclers

21

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21.1 The international commitments of Chile in the management of WEEE

Two landmarks at the international level have defined the agenda for management of waste electrical and electronic equipment in Chile. One was the country's ascription to the Basel Convention in 1992, which establishes the principles for cross-border transit of hazardous waste, which must be consistently reduced to the minimum with appropriate environmental management. Hazardous wastes should be treated and disposed of spatially, as close as possible to the source of generation, given that they are expected to be reduced and minimized at the source.

Chile's entry into the OECD Organization for Economic Co-operation and Development in 2010 has been another important affiliation for Chile, to promote policy processes in relation to environmental policy, and specifically to the proper treatment of waste in the country. To become a member, Chile undertook commitments in line with the recommendations delivered in a first environmental performance assessment in 2010.

At the time, it was recommended to develop and strengthen the regulatory frameworks to improve environmental health and comply with Chile's international commitments. For the second environmental performance assessment in 2016, the OECD acknowledges the normative advances and specifically recommended strengthening waste management, particularly that of hazardous chemicals and substances under international treaties. In general, among other things, it is recommended to apply more stringent environmental regulations and to respond to the needs of infrastructure development (ECLAC/OECD, 2016).

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00020-6

21.2 Some background prior to the enactment of the Law

The first constitutional process is carried out in August 2013, where the first version of the draft law enters the chamber of deputies, to establish a national legal framework. Prior to this, waste electrical and electronic equipment (WEEE) was regulated under instruments referred mainly to solid waste. The competence of their management was the responsibility of the Ministry of Health, under Supreme Decree No. 148/2004, establishing the Health Regulations on the Management of Hazardous Waste.

The application of this decree did not adequately consider the social and economic potential of WEEE, because the standards requested did not correspond to the necessary conditions for the specific treatment of the devices. Therefore material recovery was costly. These requirements enabled only a limited number of companies to respond to these conditions, usually with a closed system of business between companies.

This situation was far from an adequate solution for this type of waste management, as OECD countries were solving it, particularly the member states of the European Union. Since 2002, the member countries of the European Union had a policy that combined environmental and social concerns, where electrical and electronic waste was included. This means that Latin American laws, including the Chilean one, have been nurtured on the European integrated system for waste created 14 years earlier.

Two years after the European provisions, in 2004, the Regional Latin American and Caribbean Platform for Electronic Waste (RELAC) proposed to work on the digital gap, which, according to their diagnosis, contributed to increase the lag in waste management in the region. To this end, it was proposed to investigate and raise awareness about the link between Information and Communication Technologies (ICTS) and electronic waste.

In this line, the RELAC Platform has contributed to giving urgency and visibility to this problem in public and private spaces of the region. In parallel it has also worked in finding solutions in Chile, a country where its headquarters is located and from where regularly participates with the Ministry of Environment.

The government was sensitive to the proposal and called for a Voluntary Agreement of Management of Electronic Waste in 2010, which, although not implemented, served to establish the issue of WEEE management as a potential public−private task. This agreement was made among five companies of electronic products, the former National Commission for Environment (CONAMA) and the RELAC/SUR Platform. The latter provided for the first study in Chile on volumes of waste from computers and generation of electronic waste, which included an analysis of the current situation. It also included an estimate of present and future waste volumes of computers, using the model of the flow of materials (Silva, 2007; CyV Environment, 2009) and a model of inclusion of the Informal Sector in the sustainable management of WEEE in Chile (Wolfensberger, 2009).

All these results have been encouraging alliances to discuss regulations for theses residues that require special treatments. In practice, the concern of formalizing their revaluation requires that the regulatory vision be broadened. Most are sanitary regulations and consider residue to be hazardous solid waste within international health regulations and the regulation on basic safety and sanitary conditions in landfills, thus decreasing the diversity of WEEE and their respective life cycles (Alarcón, 2012).

21.3 The national movement of waste pickers (MNRB)

With urban life, people collecting and making use of waste have historically been identified. They are identified and named according to the type of waste they work with. Although garbage is not synonymous with waste, their work has made them socially stigmatized and undervalued. In Chile, current waste recyclers acknowledge their work since the late 19th century. Their identity has required of collective work, supported by the construction of its historical memory.

Currently, the National Movement of Waste Pickers (MNRB) is one of the most visible, which we could consider in terms of collective action, as an interest group for the formation of national and even regional public policies.

The beginning of this movement may be traced back to the early 1990s, when the first collective gatherings were held in order to eliminate the persecution by the police and to achieve better prices for their materials. At the beginning of this decade, the first formal organizations were identified in the country, and the first Association of Independent Collectors, together with the first meeting between the association and entrepreneur waste recyclers took place.

In the year 2000, the environmental public policy recognizes the work of the waste recyclers in environmental management, and they begin to internationalize their associative work and networks in Latin America. There is no doubt that the fire that cost the lives of the entire family of waste recyclers on May 23, 2007 triggered the formation of the MNRB.

Their demands include fairer working conditions and dignity, in addition to the need for appropriate places and sanitary conditions for the collection of the material, thus preventing catastrophes in their own homes.

In 2010, the MNRB was formalized as the Association of the National Movement of Independent Waste Pickers of Chile, which allows them to participate in discussions on the national law for waste management. Additionally, with the support of the International Labor Organization and the Avina Foundation, this association, participates in the follow-up of national public and regional public policies. A public–private interweaving that strengthens the framework of principles of inclusive is being developed through the Regional Initiative for Inclusive Recycling (IRR) for Latin America and the Caribbean. This initiative is led by regional public–private partnerships, where the association participates with the financing of the Inter-American Development Bank (IDB), Fundación Avina, Coca Cola, Pepsi-cola, and the Latin American Network of Waste Pickers (Red LACRE).

The association of waste pickers−recyclers project inclusion more directly on the state and the market, and more culturally in civil society. Their vision includes for them to become professional providers of environmental and public services. They also propose to modify their isolated and undervalued work, for one that is linked to differentiated collection systems in communal recycling centers, in formalized association modalities of cooperatives, companies, and associations.

The incidence of the association in national policy discussions on residue has highlighted the inclusive principles they demand in terms of recognition, dignity, and equity. Through this construction of identity, MNRB postulate to increase public recognition and the social and environmental contribution of their work.

Now, regarding the regulation of WEEE, as its president Ezekiel Estay says, there are many challenges to face in the handling, transport, and packaging of WEEE that need to be addressed in terms of prevention of health and environmental risks (Fig. 21.1) (Yohannessen et al., 2019).

Their concern is still not to hide the work that exists and has been carried out for years by these workers, with standardization directed exclusively toward the large producers. In particular, they are concerned that this treatment is exclusively for large retail stores. There are different electrical and electronic products that waste recyclers are willing to reconsider in handling and certification of competencies.

21.4 National law of waste and extended producer responsibility (REP) (Law 20920)

On June 1, 2016, Law 20920 was issued in Chile as the "framework law for waste management, extended producer responsibility, and the promotion of recycling." This standard aims to reduce waste generation and to promote reuse, recycling, and other types of recovery, through establishing extended producer responsibility and other instruments for waste management, in order to protect human and environmental health.

The provisions incorporated into the waste electrical and electronic equipment (WEEE) included as one of six priority products, considered so by the characteristics that these products share: the large volume of waste they produce, their components, the high level of replacement, among others.

Various studies show the exponential growth of these residues, which are currently under the label of appliances and are the ones that produce the highest volumes of waste, more than any other product, between countries from the North to the Global South (Davis and Herat, 2008; Puckett, 2005).

To this situation, we add the quality of its components, which increases their importance and makes it complex to regulate their management (Bakhiyi et al., 2018). By norms, it is known that these devices coexist with toxic and hazardous materials (lead, mercury, and cadmium) with tradable materials such as gold, silver,

Figure 21.1 Voluntary recruitment of waste pickers of WEE in August in Temuco 2017. Pictures of team research and main results in Yohannessen et al. (2019).

and copper (FCPy MNRCh, 2015) and with global health challenges for vulnerable populations (Heacock et al., 2016). These particularities require a waste management system to ensure adequate treatment so hazardous materials have a safe final destination and that materials of value are recovered. In addition, all these procedures must protect the health of workers and the general population. To this end, the enactment of Law 20820 aims to promote integrated management and to promote specific regulations for these residues.

Chile is one of the few countries in Latin America that are beginning a legislative process that responds to the challenges and opportunities offered by the management of electrical and electronic waste, taking into account the characteristics of the countries of the region.

In that sense, the Law 20920 opts for a series of provisions that are new in the regulatory system relating to WEEE. One of these precepts has been to identify this standard, stating it as extended producer responsibility, more commonly known as the REP Law, for its name in Spanish. There it is established that the extended producer responsibility is the specific system to regulate the management of WEEE. This means that producers are responsible for the organization and the funding of these products which are marketed in the country. This is the system chosen, considering that it will ensure compliance with the proper management of these wastes.

Another of the peculiarities of this law is the introduction of new actors such as the municipalities and their active role in various stages of management, mainly in the inverse production chain management systems, recycling management, and environmental education. Municipalities can be considered a hinge, that enables articulating the participation of other actors such as managers, and very especially including waste recyclers, who will be able to access certain benefits through municipalities.

Certainly one of the most important measures, related to the issue of this chapter, is the principle of inclusion, which Law 20920 is defined as the set of mechanisms and instruments for training, funding, and formalization aimed at enabling the integration of waste pickers in the management of waste, including the management systems in the context of extended producer responsibility

From this principle, a series of provisions are established, which allow the integration of waste pickers—recyclers, formalizing their presence and participation in the management systems of the REP Law in Chile. It is important to note that this is the only law in Latin America that includes waste recyclers in the waste management system in its contents. The specific way of incorporating these actors will be set to the specific decree for WEEE, which, because of its complexity, will be the last to be published. However, according to the provisions of Law 20290, the structure of their actions is designed.

Although the proclamation of this law is a response to international demands, as well as an update of the national environmental policies, through legislation and regulation, its implementation is relative to each product. In this way, waste electrical and electronic equipment, given their complexity, are expected to be the latest products to have regulated norms through a specific decree. It is necessary to emphasize that the process concerning the publication of the decrees has been slow, more than expected at the time the law was presented, which includes six priority products: (1) tires, (2) containers and packaging, (3) lubricating oils, (4) dry cell batteries, (5) batteries, and (6) electrical and electronic equipment. Without the promulgation of decrees, the implementation of the law for WEEE is not feasible. The expectations designed in 2017 of developing targets for most priority products for 2019 have not yet been met, except the tires. Currently, there is work on the regulation for packaging. Following the previous order, four more decrees would have to pass before the decree that regulates the implementation and management goals for waste electrical and electronic equipment is issued.

This does not mean that there is no progress at the policy level about the implementation of this law. This proclamation has given way to a series of tools that have been the support mechanism and have prepared the proper regulatory context for its implementation. Since 2016, the following regulations have developed:

- National Waste Policy 2008–2030
- The regulation governing the procedure for the elaboration of the supreme decrees established in Law 20920 (November 2017)
- Amendments to the Regulation of Pollutant Release and Transfer Register RECT (June 2017)
- Regulation Fund for recycling (March 2017)
- Regulation governing the Cross-border Movement of Waste (March 2017)

This law, from its constitution, has initiated a prolific and extensive process of including actors on the one hand, and of creating tools and instruments, on the other. In line with the principles of inclusivity, the participation of waste recyclers is an achievement, which has not been fortuitous and, for this group of actors, it has been a difficult and permanent task which continues to the present. Given the entire process of what it means to regulate the implementation of the law in connection with the participation of recyclers, questions to be solved in this regard are opened. Their participation in the management of electrical and electronic waste is mentioned in various areas of the law and specific ways in which they will be reflected.

21.5 Including waste pickers as recyclers in Law 20920

As mentioned, the Chilean REP Law is the only one in Latin America that includes waste pickers as recyclers in its system of management of priority waste in its text. The specific way of incorporating these actors will be established in the future decree of WEEE; however, by the regulations of Law 20290, the structure of their actions may be interpreted from the definitions expressed.

All the normative instruments referred to have means to facilitate the participation of recyclers in the integral management of priority waste.

In summary Law 20920

- Acknowledges them as waste managers. Thus, they should respond to the same requirements as recycling companies.

- They must be registered with the National Pollutant Release and Transfer Register (PRTR) to participate as authorized managers in the fulfilment of targets for collecting stipulated in waste management.
- Must be certified within the framework of the National Certification System of Labor Competencies established by Law No. 20267.

Article 3 establishes that a waste recycler is a natural person who, through the use of manual and semi-industrial techniques, participates directly and habitually in the selective collection of domestic or absorbable waste, and in the management of reception and storage facilities of such waste, including its classification and pre-treatment. Notwithstanding the above, waste recyclers are also natural persons registered as waste recyclers, by article 37.

The activities set out in this article are similar to those performed by formal managers on any solid residue, specifically selective collection, and classification. However, waste pickers as recyclers may be excluded from some activities due to the hazardous components. This may be the case of storage procedures that involve specific conditions of protection of these residues and include pretreatment, such as for some electrical and electronic waste. In this way, the implementation of this law may be at risk in terms of inclusivity because marginalizing or fractioning the activities that are being conducted within the law, could mean a ban on them and therefore significant reduction in their income, given that they would only be able to perform the easier work with less pay (Fig. 21.2).

To understand the pathway by which waste pickers as recyclers of WEEE could prove to be excluded from some activities set out by law, it is necessary to detail how they are considered part of it. The first phase is the recording. These waste recyclers are required to be duly certified within the framework of the National System of Labor Competence Certification (SNCCL) established in Law No. 20267.

This SNCCL, in turn, considers waste recycling people as human capital that require recognition and strengthening, by incorporating them in Law 20920, according to four job profiles. These profiles defined in collaboration with the Movement of Informal Waste Recyclers in Chile. Thus it is possible to establish performance standards on these activities, skills, and roles they may assume and fulfil later (Fig. 21.3).

As it is foreseeable, this instrument, on the one hand, is the first barrier of entry, where a percentage of waste recyclers will be excluded. On the other hand, it enables the inclusion of another percentage of waste picker's recyclers, offering them a formative plan that identifies their possibilities of work development.

This way, SNCCL allows for different participative areas and tools, which enable or restrict workers of the informal sector to respond to the procedures and requirements of the WEEE management system, which cannot overlook safe management for health and the environment, at all stages of reverse management.

It is important to highlight that to date, the study of reference for these topics is that of Foundation Chile Valora, jointly with the Ministry of Environment (2017), which does not include electric and electronic residue, because it only considers

Figure 21.2 Collecting, dismantling, and repairing WEEE. Pictures of team research, August 2017.

Figure 21.3 A waste picker leader showing the certification of competencies of waste pickers in a free market in Maipú. Picture of team research January 2018.

nonhazardous inorganic residue. So far, this also excludes the four occupational profiles on which the training plans for workers were based. In short, none of the specific procedures required for waste from electrical and electronic equipment are officially considered in the law for waste recyclers.

Although these certification systems recover part of the knowledge of the workers, in this case of recyclers, they reflect only a portion of their activities. Otherwise, this set of activities are the most accessible ones to incorporate standardized management systems, given that they still do not consider the complexity and degree of danger of some elements incorporated into waste. Added to this is the trend of producers of reducing costs of materials in the production process of these devices, which has decreased the recovery of higher priced materials for informal waste recyclers.

Both the complication in identifying the categories of WEEE and the trend of the devaluation of their waste leads to a greater probability for each informal waste recycler to become invisible in an official reverse value chain. In summary, these complications and uncertainties can increasingly nurture speculations on the value of these residues, thus increasing the informal and illegal circuits of valorization, with its implications for human health and the environment.

One of the entry restrictions for the certification of informal recyclers is academic training. They are required to have completed secondary education in order to receive certification. In Chile, the level of schooling of informal waste recyclers is concentrated on primary education; only 15% has completed secondary education. Also, the certification has a cost.

How to enter WEEE is pending, along with the inclusion of these waste pickers as recyclers into WEEE, within the waste recyclers in general in the competency profiles. It seems unrealistic to marginalize formal and informal waste recyclers from participation given the history, discussion, diversity, and dangerousness of WEEE.

Below we list some expected challenges and opportunities for the inclusion of waste recyclers within the provisions considered for them by the law.

Article 6 of the Law 20920 sets out the obligations of waste managers. Moreover, is a state that "Each manager must handle waste in an environmentally sound manner, applying the best available techniques and the best environmental practices, in accordance with the current regulations and the corresponding authorizations.

Additionally, each manager must declare, through the National Pollutant Release and Transfer Register, at least, the type, quantity, costs, service fee, origin, treatment, and destination of waste, by the provisions of the Regulation referred to in article 70, Letter p of Act No. 19300."

One of the transitory provisions of law establishes that during the first 5 years, waste pickers as recyclers will be able to register without the required certification. However, after this period without having been accredited, their registration will expire. Then, the conditions and requirements on the possibilities of including waste recyclers are brought together in the certification above processes, together with the National Pollutant Release and Transfer Register, ETC, and their corresponding statements.

The 5 years of the exception of record for waste pickers as managers will be fulfilled by 2021. Three years have already passed without much information on the development of instruments for inclusion to facilitate the participation of the waste managers in the management of WEEE. It is conceivable and expected for the legal proposals to be ready by that time, but the processes for real inclusion of the managers requires training, information, and infrastructure. It is important to clarify that all these aspects of implementation are more laborious to achieve and require greater preparation and time.

On the other hand, one of the more serious offenses established by this law is not enrolling in the registry established in article 37. If the requirements are difficult to achieve, a possible future scenario is the inclusion of a limited number of waste managers in the area of WEE, and that the informal sector continues to work, with the precarious conditions of labor, health risks, and with low income.

One of the relevant actors in this law are the municipalities. These institutions have historically dealt with waste collection in the cities. However, this new law, in article 30, also gives new roles to these institutions that extend their tasks, including the celebration of agreements with waste pickers as recyclers.

In line with the above, this act establishes a recycling fund that finances projects, programs, and actions to prevent the generation of waste and promote recycling and reuse of another type of recovery implemented by municipalities or their associations. This fund will be composed of various sources of economic income and technical assistance. In this chapter, it is particularly noteworthy that the inclusion of waste recyclers should be considered within their field. This would enable the participation of this sector, through project application, access to programs or actions that may favor them (Fig. 21.4).

This waste pickers as recyclers require this type of support in different areas, for example, looking into the skills of these recyclers, it has been proven that need

Figure 21.4 Repairing and storage activities. Right workers of Emaus in Temuco and Corcolén Storage in Temuco local government. Pictures of Amaranta Agost.

technical strengthening and knowledge, that is, on the treatment of different equipment and devices (a reference to the study). Another area that they realize they require support is in the marketing of products and materials they obtain. Negotiations are usually with other mediators, which reduces their profit (FCPy MNRCh, 2015).

Municipalities can certainly facilitate spaces to materialize the collection of WEEE.

Generally, for this work, recyclers use their own houses, in the yards or parking spaces. However, this type of storage neither meets the security conditions this type of waste requires, nor safeguards the family of these workers from long periods of exposure to toxic elements. In this regard, the municipality can provide storage space that meets all the safety requirements.

Municipalities could also support waste pickers as recyclers in their training to work collectively. Generally, the work of the waste recyclers is individual or by family. If you require a higher level of professionalism, which is the aim of including them in this law, collective labor must be created. This would open up all the possibilities that come with forms of social and solidarity economy, such as cooperatives, associations, and foundations. While this would mean a change from the individual to the cooperative in the conception of their work, it would also open up the possibilities for strengthening their previous work as a collective action, which has made them known as another trade union, requiring comprehensive inclusion.

21.6 Conclusions

As mentioned above, the exclusiveness of the Chilean law, within the environmental frameworks, is in the fact of considering principles of economic valuation, in the context of extended producer responsibility together with the principles of inclusion. Both frameworks exist and may become problematic in their implementation. Given the specificity of waste electrical and electronic equipment, a collective conversation about ways of including informal sectors recyclers in the integral management of this type of waste is still pending. In particular, what is missing is how the implementation of the provisions of the law will be designed.

The needs of the waste pickers as recyclers in the areas of training, organization, infrastructure, and economics, among others, are very broad. The specificities and history of waste recyclers should be considered when the decrees are being designed—acknowledging them as managers are not enough because they cannot compete with the formal managers who have worked with WEEE until now.

Instruments of inclusion are designed primarily for solid waste. They do not have alternatives for the equipment that contains hazardous elements, as in the case of WEEE. Thus, the law would be including waste pickers as recyclers mainly in terms of collection and their technical achievements, displacing all dimensions of environmental health and that of their workers.

The role of the municipalities stands out in articulating the processes of inclusion of these recyclers, in terms of financing certification processes, opening up possibilities in storage, and management as well.

The transition toward sustainability of waste in the country has been linked to the collective action of waste recyclers, as an influential interest group in its design and discussion. This specificity is expected to remain productive, and that electric and electronic residues are not the exception.

Finally, the commitments it has assumed the government of Chile in the 20292 law implies a series of opportunities and challenges that can give an account of an exemplary experience, particularly in the principles of inclusion refers, for the Latin American region.

21.7 Acknowledgments

This study was funded by the special agreement between Platform RELAC and Instituto de Estudios Avanzados of the Universidad de Santiago de Chile and the University of Michigan Graham Sustainability Institute, United States. The authors appreciate the participating workers, without whom this study would not have been possible and to Dr. Richard Neitzel who is leader of this environmental study.

References

Alarcón, K.S., 2012. Gestión y Tratamiento Jurídico de los Residuos de Aparatos Eléctricos y Electrónicos, en el Contexto de la Regulación Genérica de los Residuos Sólidos en Chile. University of Chile, Santiago, Chile, 136 pp.

Bakhiyi, B., Gravel, S., Ceballos, D., Flynn, M.A., Zayed, J., 2018. Has the question of E-waste opened a Pandora's box? An overview of unpredictable issues and challenges. Environ. Int. 110, 173−192.

Comisión Económica para América Latina y el Caribe (CEPAL)/Organización para la Cooperación y el Desarrollo Económicos (OCDE), 2016. Evaluaciones del desempeño ambiental. CEPAL ediciones, Santiago, 275 pp.

Chile Valora, 2017. Subsector Servicios de Reciclaje y Eliminación de Residuos. Proyecto de competencias laborales. Santiago Chile, 144 pp.

CyV Medioambiente, 2009. Diagnóstico, Producción, Importación y Distribución de Productos Eléctricos y Manejo de los Equipos fuera de Uso. RELAC/GTZ/Gobierno de Chile, Santiago de Chile, 155 pp.

Davis, G., Herat, S., 2008. Electronic waste: the local government perspective in Queensland, Australia. Resour. Conserv. Recycl. 52 (8-9), 1031−1039.

FCPy MNRCh. Fundación Casa de la Paz y Movimiento Nacional de Recicladores de Chile, 2015. Catastro Sociolaboral de Recicladores de la Región Metropolitana. Iniciativa Regional para el Reciclaje Inclusivo. Santiago: Sodfa Törey ed., 78 pp.

Heacock, M., Kelly, C.B., Asante, K.A., Birnbaum, L.S., Bergman, Å.L., Bruné, M.-N., et al., 2016. E-waste and harm to vulnerable populations: a growing global problem. Environ. Health Perspect. 124, 550−555.

Puckett, J., 2005. The Digital Dump. Exporting Re-Use and Abuse to Africa. The Basel Action Network, Seattle, 85 pp.

Silva, U., 2007. Gestión de Residuos Electrónicos en América Latina. Ediciones SUR, Santiago, 299 pp.

Wolfensberger, M., 2009. Modelo de inclusión del Sector informal en una gestión sustentable de RAEE en Chile. Plataforma RELAC, EMPA, 39 pp.

Yohannessen, K., Pinto-Galleguillos, D., Parra, D., Agost, A., Valdés, M., Smith, L., et al., 2019. Health assessment of electronic waste workers in Chile: study design and participant characterization. J. Environ. Res. Public Health 16 (386). Available from: https://doi.org/10.3390/ijerph16030386.

Further reading

GIZ, 2017. Building the Link: Leveraging Formal-Informal Partnerships in the Indian E-Waste Sector, Eschborn, 54 pp.

UE Unión Europea, 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE) Text with EEA Relevance, 34 pp.

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Electronic waste management in Romania: pathways for sustainable practices

22

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22.1 Introduction

Electronic waste (E-waste) or waste electrical and electronic equipment (WEEE) is an emerging waste stream which poses serious challenges in sustainable waste management practices for both developed and developing countries while consumer of electronic goods is expected to increase in following years. At the global level, there are huge disparities in E-waste generation rates and E-waste management activities while specific E-waste legislation is still missing in several countries (Mihai et al., 2019). The Countering WEEE Illegal Trade (CWIT) project found that in Europe, only 35% (3.3 million tons) of all the E-waste discarded in 2012 are covered by collection reporting systems while the other 65% (6.15 million tons) was either exported (1.5 million tons), recycled under noncompliant conditions in Europe (3.15 million tons), scavenged for valuable parts (750,000 tons), or simply thrown in waste bins (750,000 tons) as shown by Huisman et al. (2015). These findings point out some serious gaps in E-waste management activities among EU countries. Former Soviet countries try to reduce such gaps by transposing EU legislation and to develop better treatment activities supported by improved E-waste collection schemes.

This chapter aims to examine such challenges in case of a new EU Member State like Romania, where some progress is made in the right direction. The chapter points out the route from unsound E-waste disposal activities (e.g., illegal dumping or landfill of E-waste) toward the sustainable collection, treatment, and recycling practices among various stakeholders (EEE producers, waste operators, recycling companies, public institutions, and local authorities, and civil society). The best E-waste management practices are outlined in the chapter. To make an easier transition toward a circular economy in Romania such activities must be further supported.

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00024-3

22.2 E-waste disposal activities

22.2.1 Illegal dumping of the E-waste stream

Smaller urban areas and rural communities are still exposed to illegal dumping activities associated with the lack of proper waste management facilities. In the latter case, the rural population still lacks waste collection services; therefore the E-waste stream generated by rural population is susceptible to illegal dumping practices. However, poorer socio-economic conditions increase the lifespan of electronic products and there is a low purchasing power compared to larger urban areas which reduce the magnitude of this practice. Wild dumps and open burning activities were the main waste disposal options across rural communities prior to 2010. Frequently, each village from commune to town had an open dump to dispose of the household wastes (Orlescu and Costescu, 2013). E-waste stream contains toxic pollutants (e.g., heavy metals) contaminating the soil and water bodies. The closure of rural dumpsites was performed by local authorities and supervised by the National Environmental Guard. These actions comply with the obligations assumed by the EU Landfill Directive transposed by Government Decision no 345\2005 regarding the landfill of waste. These actions obliged rural municipalities to seek solutions for waste collection services and transport the wastes to urban landfill sites. The delays in the implementation of regional integrated waste management systems cause gaps in the current waste collection schemes favoring illegal waste disposal practices around urban and rural areas (Mihai, 2018). Despite the closure of wild dumps and expansions of waste operators coverage areas the collection efficiency is not 100%, particularly in less developed areas, thus, there is an uncollected waste flow (including E-waste fraction) which is dispersed on the surroundings or burnt. Also, individuals focus to recover valuable items from electronic scraps and the rest of the items are prone to littering behavior.

In 2015, every Romanian (urban area) has in average 72 kg of EEE of which 7.35 kg became E-waste which is further managed as follows: 30% is collected by formal E-waste activities, 21% reused by friends/family, and 49% are improperly managed via informal sector, municipal bins, or illegal dumping practices (Ecotic, 2015). These findings confirm that illegal dumping is a possible route for E-waste flow uncollected by the formal sector. This situation could be worse in rural areas where waste management facilities are scarcely seen. Best practices should be promoted and supported by awareness campaigns.

These are necessary steps to combat illegal dumping practices or bad situations where individuals keep the E-waste in their households in unsafe conditions and are not motivated to take such wastes to collection centers (Recycling4Regions, 2014).

22.2.2 Open burning of the E-waste stream

Open burning of E-waste release harmful pollutants in the air threatening the public health, particularly in transition and developing countries with a less developed waste management infrastructure (Mihai and Gnoni, 2016). In Romania, this bad practice sporadically occurs in rural areas without access to proper waste collection schemes. The rural population is still unaware of public health risks associated with open burning activities of this E-waste stream. The burning process of household waste is performed in open piles which could contain electronic items beside agricultural waste fraction. There are some recommendations of the Inspectorate for Emergency Situation regarding the burning of agricultural and organic fraction of MSW stream in special conditions as seasonal cleaning activities (mainly in spring and autumn). Burning of hazardous items (such as E-waste, batteries, and spray) is forbidden and a special permit from the local council is required for each individual in the case of open-fire activities. Better law enforcement is needed to eradicate such bad practices among inhabitants.

22.2.3 Landfill of the E-waste stream

Prior to EU accession E-waste stream was regarded mainly as part of the municipal solid waste flow (including bulky items) managed by public or private waste operators as residual waste.

The mixed municipal waste collection prevailed through collection points or "door to door" schemes, including E-waste fraction of private households or commerce sector. The presence of E-waste stream in urban landfills increases the in situ and/or nearby pollution risks through the leachate contaminants or direct contact with soil.

In Europe, around 750,000 tons of mainly small appliances end up in the waste bin, with varying amounts per country of between 1 and 2 kg per inhabitant per year, while waste management systems are still landfill-based (Huisman et al., 2015).

In the last two decades, most of the urban landfills were noncompliant with EU regulations and such sites should be closed until 2017. However, the delays in building and operating activities of the new regional sanitary landfill sites (supported by EU funds) lead to temporary dumpsites where mixed municipal waste is disposed of, including E-waste streams which are not source-separated by population or economic agents, thus, these are discharged either on dumps or in mixed residual waste bins or containers. The E-waste represents around 5%–6% of the total amount of waste in a community and Romania household has EEE products older than 5 years (Region4recycling, 2014). Landfill of E-waste is often used in Romania while recycling work is done in small plants based on manual dismantling (Ciocoiu et al., 2016).

The correct source-separated of dry recyclables and special waste streams (such as E-waste, oils, batteries, construction and demolition waste, and tires) are key challenges to avoid contamination of residual wastes with hazardous items which are further sent to landfill sites. Low amounts of E-waste were found in WEEE in household waste composition in Cluj-Napoca city as a result of separate collection scheme and E-waste collection campaigns since 2011 (Pop et al., 2015). Environmental awareness of citizens is crucial in this regard and further campaigns must be implemented in both urban and rural areas.

22.3 E-waste collection practices

22.3.1 EU collection targets

Source separate collection and special treatment activities are required in the EU, which updated new legislation dedicated to this waste fraction such as *Directive 2012/19/EU* which entered into force on August 13, 2012 and it had to be transposed into national law of Member States by February 14, 2014. The old Directive 2002/96/CE imposed the EU Member States a per-capita collection target of 4 kg per capita year valid for 2012–15. This flat collection rate was difficult to be achieved in a country like Romania with limited E-waste management infrastructure, particularly in towns and rural areas combined with lower purchasing power at EU level and greater lifespan of electronic goods in less developed regions.

Thus, Romania reported a value of around 1.5 kg of E-waste per capita per year (taking into consideration private households and other sectors) which is the lowest among EU countries (UNU-IAS, 2015). In fact, the total amount of E-waste collected in Romania during 2006–10 is 4.3 kg per capita of which 2.7 recycled or recovered (Popescu, 2015). Cyprus, Croatia, Estonia, Italy, Latvia, Malta, Poland, Romania, and Slovakia did not achieve this collection target in 2014 (Kling et al., 2017). The new Directive changes this approach based on a flat per-capita basis toward economic market conditions associated with EEE products. This new requirement is to collect 45% of the total amount of EEE put on the market (as an average of the last 3 years) starting from 2016 and increasing to 65% in 2019 or to collect 85% of the total E-waste generated. There are countries which already fulfilled the new targets for 2016 in 2014 such as Austria, Bulgaria, Denmark, Hungary, Ireland, Lithuania, the Netherlands, Portugal, and Sweden (Kling et al., 2017). Romania, as other new EU countries, has the possibility to apply for a derogation for these new collection targets. In 2014, E-waste collection rate is only 24% of EEE put on the Romanian market supported mainly by retailers while municipalities do not provide adequate collection schemes (Kling et al., 2017). There is a proposal to collect the equivalent amount of 40% EEE introduced on the market during 2016–10 then this rate will increase to 65% in 2021 or collect 85% of the total E-waste generated (as an average of the last 3 years) according to UNU-IAS (2015). The main contributors are industry sectors (EEE producers) and consumers (private households, offices, public institutions, shops, and hotels) which feeds this E-waste flow.

Table 22.1 shows the amounts of EEE put on market and E-waste collected breakdown per each major category as follows: (1) large household appliances; (2) small household appliances; (3) IT&C equipment; (4) consumer equipment; (5) lighting equipment; (6) electrical and electronic tools; (7) toys, leisure, and sport equipment; (8) medical devices; (9) monitoring and control instruments; and (10) automatic dispensers.

In 2008, the largest amount of EEE was put on the market (before the economic crisis) compared with 2011 with a slight increase in 2014. On the opposite side, the amount of E-waste collected is largest in 2014 (after the economic crisis) due to

Table 22.1 Amounts of EEE put on the market (tons) compared to WEEE collected (tons) per each category.

Category	EEE_ 2008	WEEE_2008	EEE_2011	WEEE_2011	EEE_2014	WEEE_2014
1	161,964.55	8923.68	69,456.21	9987.33	84,995.17	20,465.24
2	18,080.61	735.82	14,422.82	673.18	10,466.12	1021.16
3	19,715.01	6252.69	14,349.97	5446.3	13,400.46	4803.3
4	22,659.92	5175.38	13,348.15	3199.49	14,832.53	3513.27
5	3926.90	206.20	5747.56	291.95	5350.9	1140.05
6	9918.45	321.83	6728.90	743.07	7727.25	815.37
7	466.23	32.80	744.09	94.57	999.47	65.6
8	5605.49	16.49	472.57	20.51	394.51	34.07
9	934.14	39.66	2981.97	464.17	938.16	236.42
10	457.48	13.85	261.21	87.69	482.54	64.51
Total	*243,728.78*	*21,718.40*	*128,513.45*	*21,008.26*	*139,587.1*	*32,158.99*

Source: National Environmental Protection Agency (National Environmental Protection Agency, 2017. WEEE Management Status in Romania. <http://www.anpm.ro/documents/12220/2023847/Informatii + privind + gestionarea + DEEE_10.01.17.pdf/26d81c92-8250-4ccc-8020-94fe30b02594> (accessed 05.06.19).

improvements made in E-waste collection schemes. However, there are huge differences between amounts of EEE put on the market and WEEE collected and registered in official statistics. The collection targets assumed by Romania could not be achieved because of several factors: the greater lifespan of EEE products, low purchasing power (particularly in rural areas), insufficient E-waste collection points, large informal sector, landfill of E-waste, poor awareness of citizens related to E-waste management issues, and improper monitoring activities.

The category 1 or large household appliances (e.g., refrigerators and washing machines) are the largest flow both EEE and WEEE during 2008 and 2014. Other key categories are small household appliances (category 2) and IT&C equipment (category 3). The total amount of E-waste collected is almost the same for 2008 and 2011 (around 21,000 tons) but much lower in comparison with 2014 (32,158 tons).

In fact, there are some E-waste categories with a strong increase compared to previous years such as large household appliances (category 1) and lighting equipment (category 5) as shown in Table 22.1. A decreased level in 2014 compared to 2011 is specific to categories 3, 7, 9, and 10. In such cases, more efforts need to be made to increase collection rates to fulfill the overall EU targets. The chapter further examines the E-waste collection challenges in urban and rural areas.

22.3.2 E-waste collection in urban areas

Collection centers are required in each large urban area for each 50,000 inhabitants and local authorities need to organize in each year E-waste collection events. Unfortunately, such collection points cover only 10% of the urban population and these are almost not existing in rural areas (Kling et al., 2017). Retailer's E-waste collection points play an additional key role in formal E-waste management sector in urban areas. "Buy-back" practices represent around 30% of the total E-waste sales in Romania, but some retailers have the tendency to use such initiative for marketing purpose offering good rates only for the electronic goods which are not well sold (Regions4Recycling, 2014). There are over 2,000 collection points in commercial networks in Romania, with adequate infrastructure for weekly or monthly collection (Păceşilă et al., 2016). However, the necessary of municipal E-waste collection points are less than the number of authorized collectors in most of the Romanian counties (Ciocoiu et al., 2016).

Fig. 22.1 depicts the discarded patterns of E-waste flow in Romania considering a total E-waste generation of 7.35 kg per person where retailers and municipal collection points catch only 20 % of E-waste flows (Magalini, 2017).

This figure points out the role of life extension and bad habits (e.g., mixed with household waste) as key factors for a limited performance of separate E-waste collection schemes.

22.3.3 E-waste collection in rural areas

Prior to EU accession, the household E-waste stream was associated with municipal waste which (in most cases) had been mixed collected by a waste operator and sent

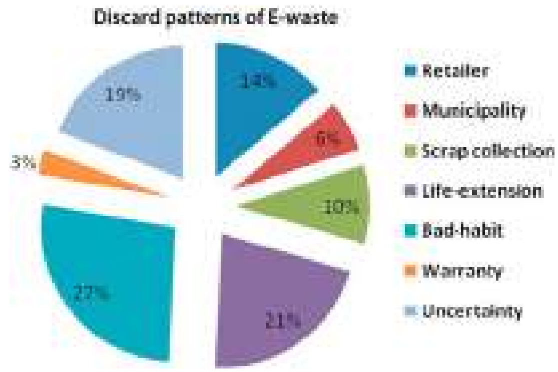

Figure 22.1 Discard patterns of E-waste in Romania.
Source: Magalini, F., 2017. All WEEE Flows: Study in the Netherlands, Italy and Romania. <http://ec.europa.eu/environment/waste/weee/pdf/WEEE%20workshol%20february%202017/All%20WEEE%20flows_F_Magalini.pdf> (accessed 03.11.19).

to an urban landfill site without any pretreatment activities. The E-waste diversion from wild dumps or open burning activities is related to the development stage of municipal waste collection schemes across rural communities. There are some collection campaigns dedicated to E-waste or obsolete electronic products in rural areas, but with poorer results in terms of per-capita collection rates. Romania is facing a prolonged life of large appliances 13−17 years (even 50-year-old appliances in some rural households) compared to Europe (8−10 years) which makes more difficult to achieve collection targets (Toretta et al., 2013). However, the benefits of such initiatives were noticed in Buzau county where 20 tons E-waste were collected across Patarlage and Pogoanele towns and Berca, Maracineni, Sapoca, Vadu Pasii, Valea Ramnicului, Cochirleanca, and Zarnesti communes in 2009 (Ecotic, 2009). Some informal collectors could operate in periurban areas in searching for scrap electronics. In 2010, Ecotic organization expanded awareness campaigns for E-waste collection in rural communities from Salaj, Vrancea, Bacau, Iasi, Ialomita, Valcea, Dambovita, and Cluj which cover over 500 communes (Ecotic, 2010). This campaign proposes an exchange a sack of wood briquettes for 10 kg E-waste resulting 60 tons of total E-waste collected during this event. Rural areas are the most exposed to open dumping or even open burning activities until the new integrated regional waste management systems (at each county level) will be fully operational.

22.3.4 Informal sector and illegal E-waste trade

Scrap metals are the most valued items among informal urban street collectors in Romania. Large E-waste appliances and electric tools rich in metals are susceptible to be managed by individuals who sell such scrap items to recycling companies. Frequently, the E-wastes are mixed with scrap metals which are further improperly treated and few E-waste items are sent from scrap recycling sites to proper E-waste treatment facilities (UNU-IAS, 2015). In this context, a certain fraction of E-waste treated is out of official statistics and included in the scrap metal stream (NWMP, 2017). The role of the informal sector in the collection process of scrap metals (including E-waste fraction) could be significant in the context of improper local municipal waste management systems and the lack of reliable E-waste collection schemes. Frequently, people go from house to house and collect WEEE and other recyclables before these waste fractions enter into the formal waste management system (Tartiu, 2011). In fact, industry stakeholders claim a high informal collection sector and competitive disadvantages for certified treatment facilities due to substandard informal E-waste treatment (Kling et al., 2017). Few EU Member States have implemented conclusive reporting and monitoring of depollution and up-to-standard treatment conditions and knowledge gap in E-waste flows is one of the largest in Romania around 60% (Huisman et al., 2015).

However, there are no data about illegal E-waste trade in Romania, but such knowledge gap could be explained by the poor reporting systems and the unknown impact level of the informal sector on E-waste flows at local, regional, and national levels.

22.4 E-waste recycling and recovery practices

In Romania, the amount of WEEE available for proper collection and treatment activities is around 20% (70 ktones) compared to total E-waste resulted from households in 2015 (UNU-IAS, 2015). The same study reveals that around 22% of E-waste is reused by extending the lifespan of electronic goods from holders to relatives, friends, or other individuals. This fact could explain the low collection rate of E-waste fraction across Romanian regions. However, the new National Waste Management Plan (NWMP) stipulates that total treatment capacity in Romania is around 120,000 tons/year which should be sufficient in the following years. Despite this fact, E-waste collected is assumed to be properly treated only by some facilities (Kling et al., 2017). The main issue is to feed such treatment facilities by improved E-waste collection schemes. The average rate for recycling/preparation for reuse of E-waste was relatively high in all the Member States, ranging from 76% to 96% and Romania is on top 10 countries besides Croatia, Finland, Hungary, Italy, Latvia, Luxembourg, Poland, and Slovakia (Kling et al., 2017). This situation is also supported by Table 22.1 where national targets are fulfilled during 2008–14 breakdown by the main 10 E-waste categories. The only exception is the year 2008 in the case of category 5 where the valorization rate is under 80% threshold, 63%, respectively (Table 22.2).

These data are based on reports submitted by E-waste collection and treatment facilities. Their reliability is questionable compared to E-waste flows in Romania since the E-waste collection schemes are insufficiently developed across Romanian counties and the informal sector is considered to be widespread. Informal recycling is the result of interactions between economic incentives legislative gaps, industrial

Table 22.2 E-waste valorization rate in Romania.

E-waste category	Recycling and reuse target	2008	2009	2010	2011	2012	2013	2014
1	**80**	84	93	93	91	89	93	93
2	**70**	76	84	84	89	88	89	88
3	**75**	77	84	86	86	86	85	87
4	**75**	88	86	89	87	87	88	88
5	**80**	63	84	88	85	84	92	93
6	**70**	75	85	87	90	89	88	91
7	**70**	68	71	73	84	83	84	84
8	**NA**	NA	NA	NA	NA	NA	NA	NA
9	**70**	77	85	85	86	86	86	88
10	**80**	89	90	91	91	90	92	92

(1) Large household appliances; (2) small household appliances; (3) IT&C equipment; (4) consumer equipment; (5) lighting equipment; (6) electrical and electronic tools; (7) toys, leisure, and sports equipment; (8) medical devices; (9) monitoring and control instruments; and (10) automatic dispensers. *NA*, not available.
Bold values indicates to point out the recycling and reuse targets stipulated by NEPA.
Source: National Environmental Protection Agency.

interdependence, and socio-economic conditions (Ciocoiu et al., 2011). Overall, waste statistics data rely on the one hand, to waste operators honesty and on the other hand, depend on volumetric estimations due to the improper weighing systems.

22.5 Pathways for sustainable practices related to E-waste management activities in Romania

Fig. 22.2 highlights the main steps for a reliable transition toward a sustainable E-waste management system in Romania under the circular economy approach promoted by the EU. The left side points out the need to reduce the unsound E-waste disposal practices as previously discussed in Section 24.2 and to provide better statistics and improved monitoring activities under environmental authorities supervision. E-waste management infrastructure needs to be further developed involving all key actors such as EEE producers, municipalities, and environmental NGOs with particular focus to E-waste collection schemes including smaller urban areas and rural communities.

The right side supports the current best E-waste management practices in Romania which are further examined in this section. Best European standards should be applied in treatment activities related to E-waste fraction by recycling companies. E-collection events and information campaigns about E-waste management challenges need to be further expanded (schools, mass media, social networks, and local authorities) to stimulate environmental awareness of citizens. Furthermore, good cooperation between stakeholders can lead to innovative projects

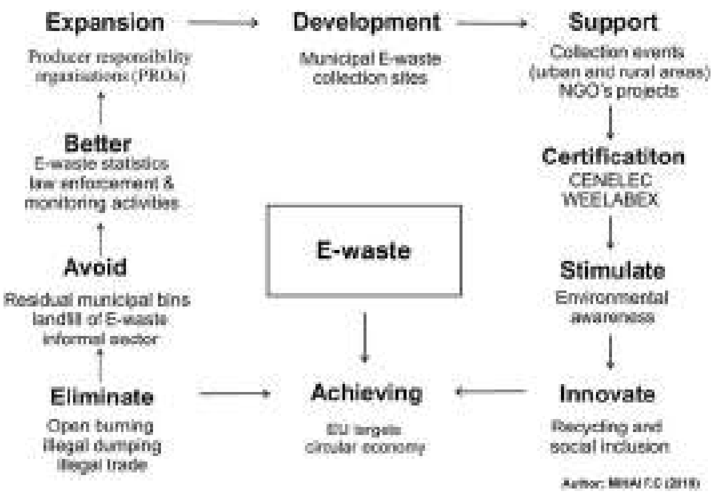

Figure 22.2 Pathways for sustainable E-waste management practices in Romania.

which promote both social inclusion and suitable E-waste recycling activities. Achieving EU targets related to E-waste management sector is possible by combining these both sides as pathways for sustainable practices in Romania.

22.5.1 Monitoring the EEE flows placed on the national market and improved E-waste statistical data

Any company that manufactures/imports electrical or electronic equipment is required to register with the National Environmental Protection Agency and to participate, through a collective or individual system, in the financing of WEEE management as stipulated by national regulation (GEO 5/2015). Romania is obliged to report on the achievement of the targets for E-waste collection, reuse, recycling, and/or recovery on the basis of Commission Decision 2005/369/EC. A common methodology for the calculation of the quantity of E-waste generated in each Member State and the weight of EEE placed on the national market is provided by EU (on the basis of the Commission Implementing Regulation 2017/699) are found at http://ec.europa.eu/environment/waste/weee/data_en.htm. The key issue is providing reliable data at national and regional (county) levels combined with E-waste statistics data for urban areas and rural communities if possible. Diverse geographical coverage of statistical data will enable a pertinent analysis of E-waste flows in Romania.

22.5.2 Better inspection and monitoring of E-waste management activities

In Belgium, Estonia, and Romania the inspection plan does not cover the entire territory or does not include both collection and treatment and in five Member States

(Cyprus, Greece, Italy, Romania, Slovenia) no information was available about the existence of effective, proportionate and dissuasive penalties (Kling et al., 2017). In Romania, the National Environmental Guard supervises the implementation of waste related legislation by business sector and monitor the illegal practices throughout the County Commissariats. At the local level, illegal activities associated with unsound E-waste disposal activities (illegal dumping, open burning) could be supervised by local police. The responsibilities and obligations derived from environmental legislation are generally not known and individuals interests in improving E-waste management practices must be further stimulated (Regions4Recycling, 2014). Also, significant amounts of E-waste are lost in scrap collection or treatment activities due to the poor enforcement of legislation (Kling et al., 2017). Therefore better inspection and control of collection and treatment activities are required to improve the current situation.

22.5.3 Expansion of "producer responsibility organizations" (PROs)

The WEEE Forum (www.weee-forum.org) is a European not-for-profit association representing 32 electrical and electronic equipment waste (WEEE) producer compliance schemes—(alternatively referred to as "producer responsibility organizations" PROs) including from Romania via Ecotic, Environ, and Rorec organizations. In 2014, its member organizations reported collection, proper depollution, and recycling of more than 1.7 million tons of E-waste (Huisman et al., 2015). In Romania, there are eight authorized PROs by the Ministry of Environment which play a key role in E-waste collection and treatment activities across Romania.

1. Ecotic—is the first Romanian "producer responsibility organization" related to E-waste management (founded in 2006) covers the interests of over 600 EEE producers and importers (https://www.ecotic.ro/despre-noi/). This organization introduced the "Green Stamp" (2007) which later became remuneration to cover the cost of WEEE collection, reuse, recycling, recovery and disposal, and consumer awareness costs based on a fee in the sale of EEE products. These activities need to be funded by EEE producers, according to national legislation (art 28−32 of GEO 5/2015). The amounts of E-waste have increased since 2013, from 8978 tons to 23,390 tons in 2018 (of which 1300 tons of hazardous compounds were extracted from E-waste) according to their last activity report (Ecotic, 2018). The same report points out that the main contributors in E-waste collection flow supervised by this organization are retailers/shops (49%) and E-waste operators (43%) compared to public authorities/sanitation operators (1%). Washing machines (35.1%) and refrigerators (29.6%) are dominant categories of E-waste collected followed by IT&C (12.9%) and TV and monitors (11.5%) as revealed by the Ecotic report (2018).
2. Recolamp—a nonprofit organization which supports the collection and recycling activities of E-waste derived from the used lighting equipment (category 5) in Romania since 2007 (https://recolamp.ro/). This association is a member of Eucolight, the European network of organizations engaged in E-waste management activities associated with lighting equipment, promoting the principles of the circular economy. Recolamp has over 13,000 collections points varying from companies, retails networks to local authorities and institutions.

Recolamp collected 946.97 tons of lighting equipment E-waste (48.57% of producers sales in the last 3 years) in 2017 and 3650 tons during 10 years of activity in this sector (Recolamp, 2017). Individuals could consult a list of locations for each county/city where the used lighting equipment can be collected in a safe manner (https://recolamp.ro/locatii-colt-verde/).

3. Environ—is a member of WEEE Forum which manages legal responsibilities associated with the E-waste fraction for over 600 EEE producers and importers. This nonprofit organization supervises 4000 E-waste collection points (companies, retailers, supermarkets, schools, local authorities, and other institutions). The 10 years activity report of this organization points out some key figures: 50,000 tons of E-waste collected (average 25 tons/day); served over 700 companies and performed over 100 awareness and collection events; ecological education activities in 1100 schools (Environ, 2017).
4. EcoPoint aims to the development of an E-waste collection system that allows selective storage E-waste items generated by households. Thus, special recipients were placed in proximity areas of end-users—networks of shops, educational institutions, administrative institutions, commercial companies with specific activities, and housing assemblies (https://eco-point.ro/).
5. RoRec association initiate the campaign "Recycling Patrol" a widespread national education program in schools (90,000 preschooler children, pupils, students, 3000 teachers) collecting 2500 tons of E-waste (https://www.rorec.ro/despre-noi/realizari/).

Eco-one and Ecolighting collect are another two nonprofits organizations besides CCR Logistics Systems RO S.R.L. (company) involved in E-waste management activities as licensed PROs.

22.5.4 Municipal source-separated E-waste collection points

Cities should be more responsible in providing separate waste collection centers where household E-waste flow could be brought by inhabitants, otherwise, the collection targets of this waste fraction will not be achieved only based on retailers and producer responsibility organizations efforts. There is some pilot project in this direction which must be further expanded in other cities and towns. Piatra Neamt city has two civic amenity sites (CAS) located in two districts (Darmanesti and Maratei) as part of an integrated municipal waste management system funded by the ISPA program. These sites offer a proper collection infrastructure for diverse items of household waste including E-waste, oils, batteries, construction and demolition wastes, furniture, and other bulky items.

Ecoviron association implemented in 2011 the project "Ecorampa" a separate waste collection center, which is exclusively powered by an alternate energy source in Bucharest city (Sector 1). The 10 waste streams that can be collected at this center are paper and cardboard, plastic, white glass, colored glass, ferrous and nonferrous metals, tires, E-waste, bulbs, and lamps, used batteries, and textiles (Environ, 2011). Iasi city has a modern facility (since March 2016) for separate collection items resulted in households (small and bulk E-waste fractions, lamps, batteries, and metals) as shown in Fig. 22.3 with a diverse range of other waste types (garden waste, construction and demolition waste, papers and cardboard, plastics, glass, aluminum cans, textiles, oils, detergents, paints, adhesives) free of charge for

Figure 22.3 E-Waste collection facilities within collection center of Iasi City.

individuals. This facility was financed via Green Industry Innovation Programme (Norway Grants) with a partnership between Ecotic organization, City Hall and Salubris SA (public urban waste operator).

A particular focus is given to E-waste fraction as part of the project “Steps for WEEE” co-financed by Norway grants (covering 90% of costs) and implemented by Ecotic organization during 2015−16. This project provided 15 street E-waste collection points in Bucharest city (Sector 3) to increase the population responsibility for proposal disposal of smaller E-waste items (more info https://www.ecotic.ro/proiecte/steps-for-weee-proiect-al-organizatiei-ecotic-cofinantat-de-norway-grants/).

SIGUREC network—https://www.sigurec.ro/—this is a modern collection system using smart and easy to use automatic containers for dry recyclables and E-waste types (e.g., batteries, light bulbs, and neons) as well as a waste pick-up service from households for larger items. The recyclables are sorted, counted, and weighed automatically and users receive a bounty depending on the types of waste and their quantities. The wastes collected are further sent to specific recycling companies. This system derived from a collaboration of various stakeholders such as private sectors (retailers, Green Group, Econpaper, Romcarbon SA), Ministry of Environment, local authorities, and recycling companies. Sigurec Prime is a smart collection station for recyclables (plastic bottles, plastic bags, paper and cardboard, polystyrene, and another packaging) which include also the ESCALE machine for E-waste (lighting bulbs and batteries).

Sigurec In—These are interior machines, which can be found in large retail outlets where some E-waste items could be also collected.

SIGUREC systems collected 14,136.81 tons of E-waste so far and these collection stations are available in several urban areas (https://www.sigurec.ro/ro/locatii-sigurec).

22.5.5 Support for special E-waste collection events and environmental awareness

Local authorities should be responsible to initiate or support several E-waste collection events in both smaller urban areas and rural communities due to the precarious current waste management facilities. These events increase the awareness toward separated E-waste collection behavior among individuals and on the other hand, to support E-waste diversion from municipal waste bins (which ultimately are disposed of in landfills) and to combat illegal dumping practices. A survey shows that 42.29% of interviewed people responded that dispose of WEEE using the formal system, while 29.25% dispose of in the informal system so the formal system needs to be further expanded (Colesca et al., 2014).

The Ecotic organization launched in 2018 a new event named "Clean communes" dedicated for E-waste collection in rural areas. Thus, 23 tons of E-waste were collected across 36 communes in 9 collection events while 25 campaigns in urban areas collected 42 tons of E-waste associated with "Clean cities" program (Ecotic, 2018). The number of the educational and informing campaign has considerably grown in the latter years stimulating E-waste collection from households (Lates and Moica, 2015).

There is a web map of E-waste collection points in Romania (see https://undereciclam.ro/map/?county = &city = AIUD) for each county and the urban area where reliable information can be found by interested individuals or economic agents. Also, organizations like Ecotic developed applications for mobile phones (e.g., ECO RADAR) to know where are the closest E-waste collections are located (see https://www.ecotic.ro/puncte-de-colectare/) with national coverage. Such tools help individuals to take quick decisions where and when to dispose of their E-waste items.

22.5.6 Certified treatment facilities

The European Standardization Organizations defines European standards relevant for E-waste flow concerning the collection, transport, and treatment activities which are listed at the following the link: http://ec.europa.eu/environment/waste/weee/standards_en.htm. The implementation of such standards will provide a homogenous set of sustainable practices related to E-waste management activities. A recent study at EU level suggests the adoption of such quality standards (WEEELABEX, European standards on WEEE collection, transport, and treatment) and strictly enforce the requirements for proper treatment as given by Article 8 and Annex VII of the WEEE Directive (Kling et al., 2017).

CENELEC is the European Committee for Electrotechnical Standardization and is responsible for standardization in the electrotechnical engineering field (https://www.cenelec.eu) which could help the EEE producers to provide suitable, resource-efficient, and environmentally friendly design products and sustainable E-waste treatment practices.

CENELEC or WEEELABEX standards are legally required in one form or another (Belgium, France, the Netherlands, Ireland, and Slovenia) or implemented by agreements between producers and take-back systems as in Italy or Czech Republic (Cenelac, 2017). Despite the fact, there are no further legal requirements to ensure proper treatment in Romania some treatment facilities obtain additional quality standards such as WEEELABEX certification. In 2015, Remat Holding and GreenWEEE International were the first companies to obtain such standards in Romania (Ecotic, 2015).

GreenWEEE is a major player in the recycling sector of Romania which aims to recover all materials in E-wastes and finding solutions to their introduction into new production flows (http://greenweee.ro/). The WEELABEX excellence standard covers all E-waste handling, sorting, treatment, and recycling operations, including auditing all organizational and management processes. In February 2009, this company inaugurated the only recycling line in Romania designed to treat refrigeration appliances in line with international standards BATRRT (Best Available Techniques of Recovery, Recycling, and Treatment) as well as recycling lines for IT equipment and small IT appliances (GreenWEEE, 2019). In 10 years of activity, the company claims recycle over 8 million items of E-waste (refrigerators, TVs, LCD, and mobile phones) within two recycling plants (Buzau and Campia Turzii since 2017) which have the total treatment capacity of 100,000 E-waste per year with 400 employees and a business of over 20 million Euros in 2018 (GreenWEEE, 2019). This company is a member of the EERA (Electrical Equipment Representatives Association) and part of Green Group Romania.

Green Group Romania is the biggest integrated recycling park in South-Eastern Europe (https://www.green-group.ro/en/, integrating the operations of six companies specialized in the collection and recycling of waste while two of them are dedicated to E-waste fractions such as GreenWEEE and GreenLamp Reciclare for recycling of used lighting equipment.

Green Lamp Reciclare SA claims to be the only recycler in Romania which is using an in-house distillation process in order to separate fluorescent tubes components and other discharge lamps such as high-intensity discharge lamps (HID). GreenLamp Reciclare can recover the mercury residuals form the phosphor powder by using the Superior Distiller, this facility has a WEELABEX certification (Greenlamp, 2019).

Remat Holding is authorized to collect and treat all 10 categories of E-waste and has several special treatment plants focusing on metal wastes. Shredder Plant is dedicated for end of life vehicles (ELVs) and large E-waste appliances with a capacity of 30−50 tons/hour. Eden plant process aluminum and copper electric caldrons of all sizes of E-wastes (capacity 2−4 tons/hour) with a crushing capacity up to 4 mm, separation of ferrous, nonferrous, and nonmetallic fractions by shredding, magnetic separation and pneumatic transport (Remat Holding, 2019).

This company has a treatment and dismantling plant for monitors and TVs (ranging 8−40 inch) with a capacity of 30 pieces per hour and the materials resulted from dismantling activities of E-wastes are further recycled or disposed of (http://rematholding.ro/colectare-si-valorificare-deseuri-reciclabile/#DEEE3). This company has a widespread recycling activity including E-wastes, scrap metals (ferrous and nonferrous), nonmetallic wastes, batteries, and accumulators and hazardous wastes.

22.5.7 Innovative approach for recycling and reuse of E-waste

Reconnect is a project made by "Asociatia Ateliere Fara Frontiere (AFF)" which aims to collect the E-waste and to turn into reconditioned IT equipment. These are further donated to the schools through the EDUCLICK computer donation platform. This association claims to collect 1010 tons of E-waste of which 30% were prepared for reuse and 70% were processed for the material recycling purpose (AFF, 2019).

The innovative approach of this project is social inclusion through recycling and treatment E-waste activities of vulnerable and marginalized individuals (18 employed persons) combined with social and psychological support gaining the necessary competencies to make an easier transition toward labor market. This project shows social, economic, and environmental benefits to the community building a success story toward sustainability. Poverty and marginalized communities are significant social issues in Romania which lead to an increasing rate of school dropout among the young. Throughout this project, 13,891 IT equipment has been refurbished and donated to over 2000 schools and associations all over the country, serving 415,000 beneficiaries from disadvantaged communities in Romania. Also, this project helped to recycle 603 tons of E-waste (AFF, 2019). This initiative points out the key role of environmental and social NGOs in promoting integrated and sustainable E-waste management activities with a positive impact on the community. Besides retailers, municipalities, and recycling companies, such NGOs could further support recycling activities related to E-waste stream. Such projects could act as a catalyst to the improvement of current E-waste collection schemes in Romania neglected so far by municipalities and to increase the responsibility level of E-waste holders.

22.6 Conclusions

The chapter points out the current challenges associated with disposal activities of E-waste stream (illegal dumping, open burning, and landfill of E-waste) and collection schemes which need to be further developed across urban and rural areas.

E-waste diversion from municipal bins and urban landfills toward recycling companies and treatment facilities should be a priority for central and local authorities besides EEE producers and importers. E-waste collection targets are difficult to achieve without a proper formal E-waste collection infrastructure with wide geographical coverage. There is a large informal sector in Romania; therefore the real magnitude of E-waste flows in Romania is difficult to assess. The chapter points out several pathways for sustainable practices starting from better statistical data, better law enforcement, and monitoring activities; expansion of E-waste collection schemes via "producer responsibility organizations" (PROs), retailers, and municipal E-waste collection centers; developing of E-waste collection campaigns in smaller urban areas and rural communities; certified treatment facilities; and actions for stimulating environmental awareness among citizens and innovative projects among stakeholders. This chapter reveals the best practices in E-waste management sector from Romania and the role of nonprofit organizations in such endeavors. Their efforts provide the necessary steps toward a circular economy approach of E-waste management activities.

References

Ateliere Fara Frontiere (AFF) Association. Reconnect Project. Socio-Professional Insertion Workshop of the Association. <https://www.reconect.ro/>.

Cenelac, 2017. European Standards for Waste Electrical and Electronic Equipment (WEEE). Meeting of the Experts group on Waste on the implementation of Directive 2012/19/EU on WEEE (Brussels, February 13). <http://www.weeeforum.org/sites/default/files/documents/european_weee_standards_cenelec_presentation_2017_02_13.pdf>.

Ciocoiu, C.N., Colesca, S.E., Rudăreanu, C., Popescu, M.L., 2016. Management of waste electrical and electronic equipment in Romania: a mini-review. Waste Manag. Res. 34 (2), 96−106.

Ciocoiu C.N., Hîncu, D.L., Dobrea R.C., Colesca S.E., 2011. Performance of WEEE management system in Romania. Recent Researches in Urban Sustainability and Green Development, 178−182. <http://www.wseas.org/multimedia/books/2011/Prague/USCUDAR.pdf>.

Colesca, S.E., Ciocoiu, C.N., Popescu, M.L., 2014. Determinants of WEEE recycling behavior in Romania: a fuzzy approach. Int. J. Environ. Res 8 (2), 353−366.

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE).

Ecotic, 2009. Annual Activity Report in 2009 <https://www.ecotic.ro/wpcontent/uploads/2015/07/451934b7e24c6cae7f6f72459fe2cde22993aeda.pdf> (accessed 05.09.19).

Ecotic, 2010. Annual Activity Report in 2010. <https://www.ecotic.ro/wpcontent/uploads/2015/07/a165f724459ddaaf14759d31b92eb75dfe6638a9.pdf> (accessed 05.08.19).

Ecotic, 2015. Annual Activity Report in 2015. <https://issuu.com/ecotic/docs/retrospectiva_2015_b-min.compressed> (accessed 05.08.19).

Ecotic, 2018. Annual Activity Report in 2018. https://issuu.com/ecotic/docs/retrospectiva_2018 (accessed 05.06.19).

Environ, 2011. Ecorampa Project. <https://environ.ro/images/presa/Comunicat%20de%20presa%20Asociatia%20Environ%20inaugureaza%20EcoRampa%20luni%2014%20februarie%202011%20v03.pdf> (accessed 05.09.19).

Environ 2017. Activity Report in 10 years. <https://environ.ro/brosura/> (accessed 05.06.19).

Greenlamp, 2019. <http://www.greenlamp.ro/index.php/en/> (accessed 05.09.19).

GreenWEEE,2019. Activity Report in 10 Years. <https://greenweee.ro/10-ani-de-activitate-greenweee/>(accessed 05.08.19).

Huisman, J., Botezatu, I., Herreras, L., Liddane, M., Hintsa, J., Luda di Cortemiglia, V., et al., 2015. Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap, August 30, 2015, Lyon, France.

Kling M., Zotz F., Huranova, D., 2017. WEEE compliance promotion exercise. Final Report for EC. Bipro and Deloitte (07.0201/2016/737282/ETI/ENV B.3).

Lates, D., Moica, S., 2015. Comparative analysis of WEEE recovery strategies and the WEEE treatment status in China and Romania. Proc. Technol 22, 840−847.

Magalini F., 2017. All WEEE Flows: Study in the Netherlands, Italy and Romania. <http://ec.europa.eu/environment/waste/weee/pdf/WEEE%20workshol%20february%202017/All%20WEEE%20flows_F_Magalini.pdf> (accessed 03.11.19).

Mihai, F.C., Gnoni, M.G., Meidiana, C., Ezeah, C., Elia, V., 2019. Waste electrical and electronic equipment (WEEE): flows, quantities, and management, a global scenario. In: Prasad, M.N.V., Vithanage, M. (Eds.), Electronic Waste Management and Treatment Technology. Elsevier Science & Technology Books, pp. 1−34. Available from: http://doi.org/10.1016/B978-0-12-816190-6.00001-7.

Mihai, F.C., 2018. Waste collection in rural communities: challenges under EU regulations. A case study of Neamt County, Romania. J. Mater. Cycles Waste Manag. 20, 1337−1347.

Mihai, F.C., Gnoni, M.G., 2016. E-waste management as a global challenge (Introductory chapter). In: Mihai, F.C. (Ed.), E-Waste in Transition: From Pollution to Resource. Intech, Rijeka, Croatia, pp. 1−8.

National Environmental Protection Agency, 2017. WEEE Management Status in Romania. <http://www.anpm.ro/documents/12220/2023847/Informatii + privind + gestionarea + DEEE_10.01.17.pdf/26d81c92-8250-4ccc-8020-94fe30b02594> (accessed 05.06.19).

National Waste Management Plan (version 5). Available from: <http://mmediu.ro/app/webroot/uploads/files/PNGD_vers5.pdf> (accessed 01.14.18) (In Romanian).

Orlescu, C.M., Costescu, I.A., 2013. Solid waste management in Romania: current and future issues. Environ. Eng. Manag. J. 12 (5), 891−899.

Păceşilă, M., Ciocoiu, C.N., Colesca, S.E., Burcea, Ş.G., 2016. Current trends in weee management in Romania.. Theor. Empir. Res. Urban Manag. 11 (4), 47−59.

Pop, I.N., Baciu, C., Bican-Brişan, N., 2015. Survey on household waste composition generated in Cluj-Napoca, Romania during the summer season. Environ. Eng. Manag. J. 14 (11), 2643−2651.

Popescu, M.L., 2015. Waste electrical and electronic equipment management in Romania. Harmonizing national environmental law with the UE legislation. Proc: Soc. Behav. Sci. 188, 264−269.

Recolamp, 2017. Annual Report in 2017. <https://recolamp.ro/wp-content/uploads/2018/01/RaportAnualRecolamp2017.pdf> (accessed 03.11.19).

Regions for recycling, WEEE Recycling in Ilfov County. August 2014. <http://www.regions4recycling.eu/upload/public/Good-Practices/GP_Ilfov_WEEE.pdf> (accessed 03.11.19).

Remat Holding. Technologies and Equipment. <http://rematholding.ro/tehnologii-si-echipamente/>(accessed 03.11.19).

Tartiu, V., 2011. Selective collection of municipal waste in Romania: characteristics and challenges. Manag. Res. Pract. 3 (3), 53–62.

Toretta, V., Ragazzi, M., Istrate, I.A., Rada, E.C., 2013. Management of waste electrical and electronic equipment in two countries: a comparison. Waste Manag. 33, 117–122.

United Nations University –Institute for Advanced Study of Sustainability (UNU-IAS), 2015. Quantifying waste of electric and electronic equipment in Romania. Available from: <https://www.ecotic.ro/wp-content/uploads/2015/11/WEEE-Generated-study-2015.pdf> (accessed 01.07.19).

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E-waste management practices in Australia

23

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23.1 Introduction

According to Solving the E-waste problem (Step), the term "E-waste" is an abbreviation of "electronic and electrical waste." A key part of the definition is the word "waste" and what it logically implies—that the item has no further use and is rejected as useless or excess to the owner in its current condition (STEP, 2019b). E-waste became a global environmental problem due to shorter product lifespan and posing serious challenges to policymakers managing such waste in environmentally, socially, and economically sustainable manner (Islam et al., 2016). Global E-waste generation reached 44.7 million tons (Mt) in the year 2016 and expected to reach 52.2 Mt by the year 2021 with an annual growth of 3%−4% (Balde et al., 2017). E-waste is generally categorized into six major product categories, as shown in Table 23.1. EU WEEE Directive is considered as the most comprehensive regulatory initiative based on extended producer responsibility (EPR) principle. Organization for Economic Co-operation and Development (OECD) defined "(EPR) as a policy approach under which producers are given a significant responsibility—financial and physical—for the treatment or disposal of post-consumer products." Metal fraction (ferrous and nonferrous), plastics, glass, and several rare-earth elements (REEs) are the major components that can be recovered from E-waste. On the other hand, if not properly managed, metals such as lead, cadmium, and mercury can seriously damage to the natural environment and human health. Recast of the Directives introduced 5% increase of collection (recovery) and reuse and recycling of several E-waste categories, for example, large household and small equipment from the previous mandate. Circular economy and urban mining are some of the critical policy implications that are now being implemented in several European countries, for instance, Belgium, Germany, and Denmark. Switzerland is one of the countries in Europe which implemented E-waste-related regulation far earlier (in 1998) than the inception of the Directive. Both in terms of harmful chemical components present and valuable secondary material recovery potential, E-waste possesses significant challenges to stakeholders in both developed and developing countries. Until recently, many of the developed countries disposed of their E-waste either to landfill or export to the developing countries, such as China and India where E-waste is recovered by following the crude process without considering human-health and degradation of the environment.

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00015-2

Table 23.1 E-waste categories and recovery and/reuse/recycling percentage according to EU WEEE Directive 2012/19/EU.

Category	Product category	Example of product	Recovered (%)	Prepared for reuse or recycled (%)
1	Temperature exchange equipment	Temperature exchange equipment, more commonly referred to as cooling and freezing equipment: refrigerators, freezers, air conditioners, and heat pumps	85	80
2	Screens and monitors	Televisions, monitors, laptops, notebooks, and tablets	80	70
3	Lamps	fluorescent lamps, high-intensity discharge lamps, and LED lamps	-	80
4	Large equipment	Washing machines, clothes dryers, dish-washing machines, electric stoves, large printing machines, copying equipment, and photovoltaic panels	85	80
5	Small equipment	Vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring, and control instruments	75	55
6	Small IT and telecommunication equipment	Mobile phones, global positioning systems (GPS), pocket calculators, routers, personal computers, printers, telephones	75	55

Source: Adapted from Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment (WEEE)/E-waste: a comprehensive literature review. Resour. Conserv. Recycl. 137, 48–75. Available from: https://doi.org/10.1016/j.resconrec.2018.05.026; and STEP, 2019b. What is E-waste? Available from: http://www.step-initiative.org/E-waste-challenge.html (accessed 15.03.19.).

In this chapter, the current management system for E-waste in Australia (as one of the OECD developed countries) will be explored to have an overview of the system architecture, management strategies, and current barriers. Outlook will also be examined to make the system more sustainable, in terms of resource efficiency by proposing an innovative approach by which actors in the E-waste management system can achieve valuable insights in redesigning collection and recovery network.

23.2 EEE import, E-waste source, and generation

Australia is a large country (total area of 7,692,024 Km^2) with a relatively small population (24.6 million as of 2017) where the population is mainly concentrated in the major metropolitan areas and urban city centers which makes it as one of the most urbanized countries in the world (Australia, 2019). Australia is a net importer of electrical and electronic equipment (EEE). From 1988 to 2014, per capital, EEE increased from 10 kg to 35 kg that is growing dramatically between 2001 and 2004 (Fig. 23.1). Similar quantities of EEE consumption was experienced in the USA (23.5 kg/capita) and the UK (24.4 kg/capita) in the year 2012 (STEP, 2015). Australia shares a similar pattern in customer purchasing power parity (PPP) like as other European Union (EU) countries (Golev and Corder, 2017). Fig. 23.2 shows the EEE import in various categories, which is mostly dominated by the small IT, small equipment, and large equipment (mainly temperature exchange equipment) and screen and monitors. Products such as the laptop, tablet under the screen, and monitors dominate the most in the category. All these products represent almost 88% of the total EEE import. Screen and monitor category showed a relatively declining trend in the recent import, whereas small equipment (see Table 23.1) predominately possesses the largest share of EEE import. Overall, the import of EEE in Australia increased 10-fold from the year 1988 to 2014, and in the last decade, the import was doubled (Golev et al., 2016).

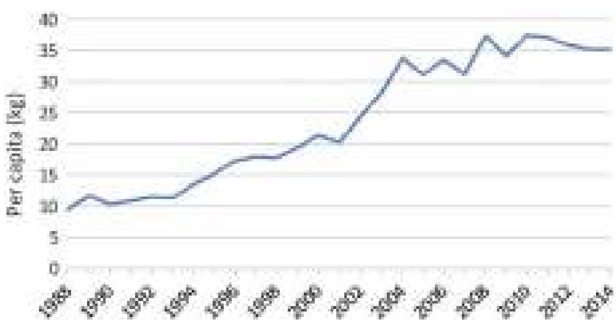

Figure 23.1 Estimation of EEE imports to Australia per capita.
Source: Adapted from Golev, A., Schmeda-Lopez, D.R., Smart, S.K., Corder, G.D., McFarland, E.W., 2016. Where next on E-waste in Australia? Waste Manag. 58, 348−358. Available from: https://doi.org/10.1016/j.wasman.2016.09.025.

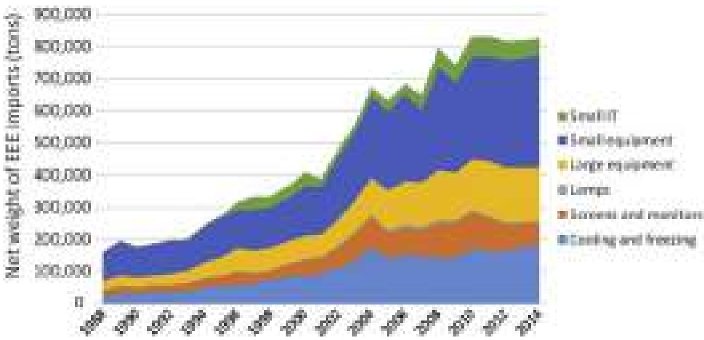

Figure 23.2 EEE imports to Australia (in net weight).
Source: Adapted from Golev, A., Schmeda-Lopez, D.R., Smart, S.K., Corder, G.D., McFarland, E.W., 2016. Where next on E-waste in Australia? Waste Manag. 58, 348−358. Available from: https://doi.org/10.1016/j.wasman.2016.09.025; UNComtrade, 2015. United Nations Commodity Trade Statistics Database.

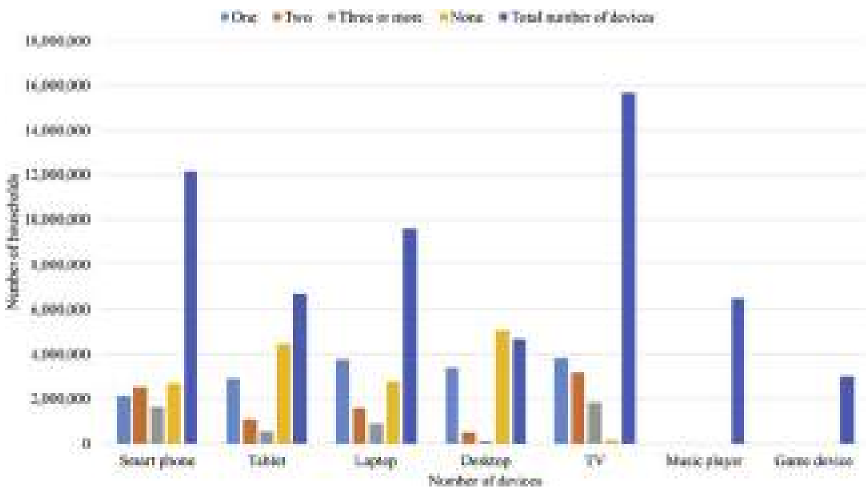

Figure 23.3 Number of households having electronic devices.
Source: Adapted from Zhu, X., Lane, R., Werner, T.T., 2017. Modelling in-use stocks and spatial distributions of household electronic devices and their contained metals based on household survey data. Resour. Conserv. Recycl. 120, 27−37. Available from: https://doi.org/10.1016/j.resconrec.2017.01.002.

A research study by Zhu et al. (2017) showed that within the product category of screen and monitor and small IT equipment, Australian households possess a significant number of equipment per households. Fig. 23.3 shows that TV sets stood the first in terms of possession (approximately 4 million households have at least one TV set) by the households, followed by smartphones (estimated 2 million households have two smartphones) and laptop (over 3 million households have at least one laptop). According to the latest study by Australian Communications and Media Authority (ACMA), approximately 18.7 million working TV sets are available in the Australian households with an average number per households 2.2 (based on research conducted in the year 2011). This research also identified that the number of TV sets present in a household depends on the number of people (considering both adults and children) resides in a household. Sales of liquid crystalline display (LCD) and plasma TV sets increased from 1,348,000 to 3,036,000 units from the year 2007 to 2010 (ACMA, 2012). On the other hand, over 6 million households and close to 4 million households have a music player and gaming devices in their households. Several households that have tablet are higher compared to the mobile phone (for one item) (Zhu et al., 2017).

The state-wise distribution of various EEE components across Australia is shown in Fig. 23.4 indicating the highest number of the selected EEE (in all category) are in the state of New South Wales (NSW) followed by Victoria and Queensland. Most of these items fall under the category of small IT and screen and monitor. Mobile phones represent one of the key EEE items that are in use in all the states. By the end of 2014, in-use stocks of mobile in Australia reached approximately 46 million units, which are around two phones per person. Besides, in-use stock, there is an increasing amount of waste (obsolete) mobile are currently residing at the Australian home, which reached about 22.5 million units (Read, 2015). Laptop and Flat screen TV are the other items that also represent high in-use stock across the states in Australia. In the year 2017, around 800,000 units of laptop/notebook computers were shipped to Australia, which is higher than the Desktop and other workstations which were shipped roughly about 300,000 units (Spencer, 2018). This research has been carried out by International Data Corporation (IDC) which also

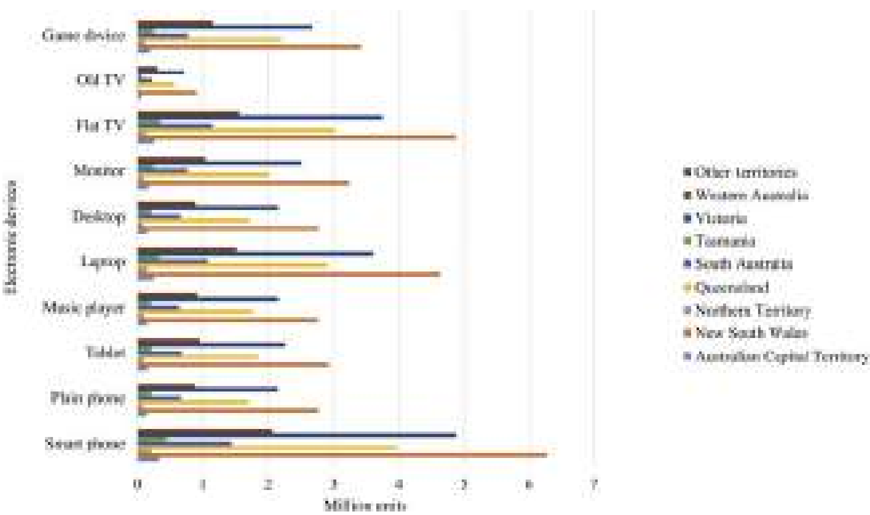

Figure 23.4 Number of electronic devices in Australian households across states (Zhu et al., 2017).

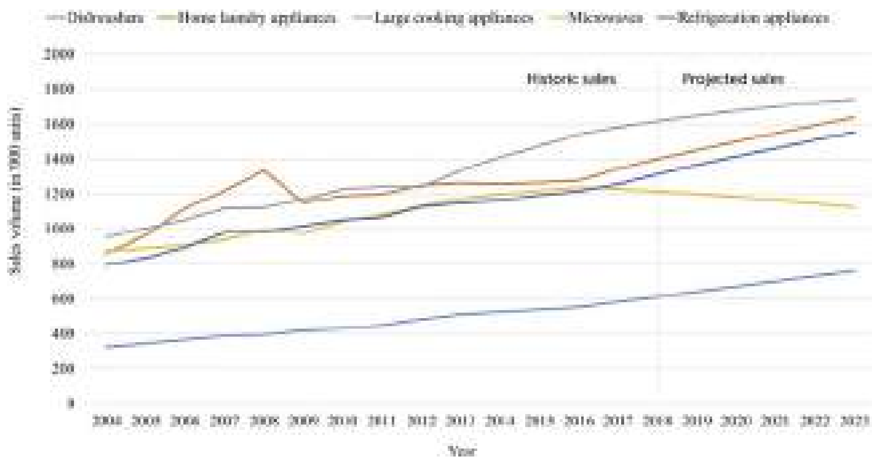

Figure 23.5 Sales volume of major consumer household appliances in Australia.
Source: Data from Passport, Euromonitor International (Euromonitor, 2019. Major consumer appliances in Australia. Available from: http://www.portal.euromonitor.com/ (accessed 22.03.19.)).

show that at the end of 2017, household customers (around 0.5 million customers) were the major buyer of traditional personal computer devices (IDC, 2018). These products fall under the product category of small IT equipment, which is higher in the concentration of precious and REEs.

Besides the small IT equipment category, huge sales volume is observed in other categories of EEE items, for example, large and small equipment. Fig. 23.5 shows the sales volume of major appliances in Australia from 2004 to 2018, where projected sales volume is estimated from the year 2019 to 2023. Small equipment, such as microwave ovens experienced a sales growth by 28% from the year 2004 to 2018, which will be stabilized in the future years as per projection. Refrigeration appliances, mostly temperature exchange equipment, such as freezers/fridges sales, were 873,000 units, which then increased to 1,313,000 units in the year 2018. It is obvious that with the increasing population (in other terms as a number of households), the major consumer equipment category will tend to increase as these are an indispensable part of modern households.

After the useful life or service life, the EEE items became obsolete and being disposed of in several channels. As mentioned earlier, Australia is one of the highest per capita E-waste generating nation with an average E-waste generation close to 25 kg/capita in 2014 as per research conducted by Golev et al. (2016) which will increase to 30 kg/person in the year 2024 (see Fig. 23.6). This figure is similar to some of the advanced nation in the European Union, for example Switzerland, wherein 2014, the per capita E-waste generation was 26.3 kg (STEP, 2019a) but slightly above in the context of other large countries, such as Germany (E-waste generation was 21.7 kg/capita in the year 2014) (STEP, 2019a). A wide variety of E-waste (depending upon the product types starting from small equipment to large

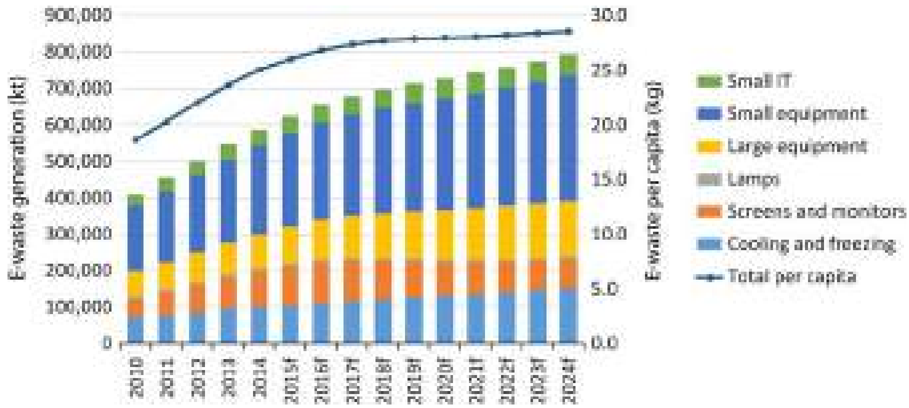

Figure 23.6 Estimated E-waste generation in Australia.
Source: Adapted from Golev, A., Schmeda-Lopez, D.R., Smart, S.K., Corder, G.D., McFarland, E.W., 2016. Where next on E-waste in Australia? Waste Manag. 58, 348−358. Available from: https://doi.org/10.1016/j.wasman.2016.09.025.

Table 23.2 The average lifespan of different EEE.

Sl. no.	EEE product	Average lifespan (in years)
1	Desktop computers	3−8.4
2	Flat-panel display (FPD) televisions, excluding CRT television sets	3.5−13
3	Laptop	2−9.1
4	Printer	3.4−8
5	Monitors (excluding CRT monitors)	1.8−10

industrial electrical and professional appliances) is generally generated from multiple sources, for example, households, businesses, and organizations. From Fig. 23.6, it is also evident that small equipment category consists of the highest proportion in the Australian E-waste generation scenario.

After the import to EEE products, customers use the products for several years (depending upon the lifespan of the product/service life of the components) then eventually reaches end-of-life phase or E-waste. Table 23.2 shows the average lifespan of different IT equipment and TV sets based on extensive data mining on the lifespan-related literature published in the international peer-reviewed journals.

At present, in Australia, households and small businesses can dispose of IT (mainly computer desktop and laptops), printers, and other IT peripheries and TV sets through National Television and Computer Recycling Scheme (NTCRS). The scheme is an industry-funded recycling program organized by the federal government, local government, and State and territory authorities via coregulatory

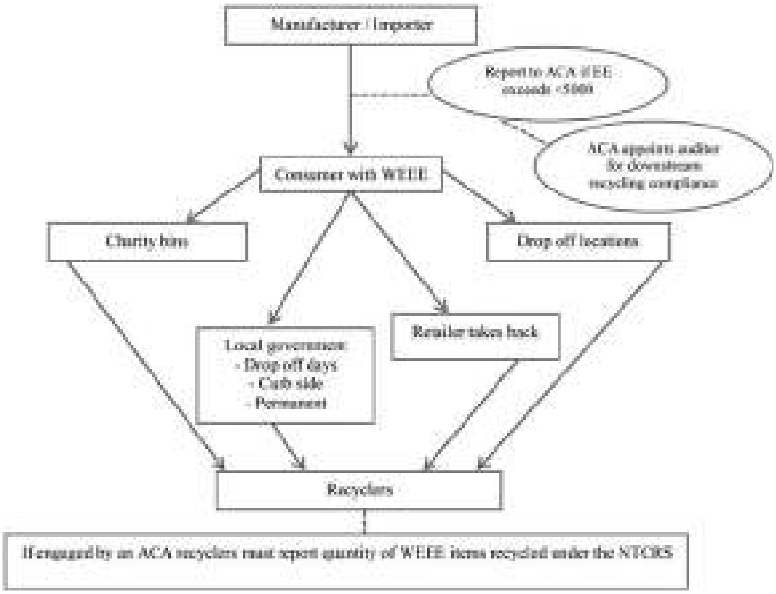

Figure 23.7 Flowchart of Australia's system for WEEE auditing, compliance, and reporting under the NTCRS.
Source: Adapted from Morris, A., Metternicht, G., 2016. Assessing effectiveness of WEEE management policy in Australia. J. Environ. Manage. 181, 218–230. Available from: https://doi.org/10.1016/j.jenvman.2016.06.013. ACA refers to approved co-regulatory arrangements.

agreements (detailed description will be given in Section 23.3). Customers from the households can drop-off their waste TV sets and computers and IT peripherals (later these are called as NTCRS products) at different locations such as local council collection points, event collections or via mobile community recycling centers (see Fig. 23.7). The latter is recently being introduced in some councils in greater Sydney metropolitan areas organized by the local councils and funded by Environmental protection agency (EPA) of the New South Wales (NSW) government. The collected waste TV sets and IT equipment then transferred to storage facilities to coregulatory arrangements (CRAs) which later then taken to approved licensed recyclers assigned by the coregulatory agreements. The CRAs work on behalf of the government to audit and report the amount of E-waste collection and material recovery. Details of the roles and responsibilities and structure of the NTCRS scheme and the CRAs activities are described in Section 23.3.

It is to be noted that customers from the households can only dispose of their NTCRS products under the current scheme and other types of E-waste (small and large equipment), as well as batteries, are not covered by the NTCRS. Majority of the products under small and large categories are either collected via scrap metal recyclers and disposed of in the council clean up a collection that eventually goes to landfill as customers have no other options available for the categories. Mobile phone and battery are currently collected and recycled under a voluntary scheme

Table 23.3 E-waste-related regulatory scheme and industry-funded collection programs.

Type of E-waste	E-waste category according to EU WEEE Directive	Name of the regulatory scheme	Type of scheme, year of inception	Collection results (latest reported)
TVs, monitors, laptops, tablets, desktops, printers, computer parts, and peripherals	Screens and monitors, small IT	National Television and Computer Recycling Scheme	Co-regulation, 2011	41,630 tons (2014/15)
Mobile phones (including batteries and accessories)	Small IT	Mobile Muster	Voluntary, 1998	76 tons (including 423,000 handsets) (2015/16)
Household batteries	—	Australian Battery Recycling Initiative (ABRI)	Voluntary, 2008	403 tons (10 million batteries) (2012/13)
Printer cartridges	—	Cartridges 4 Planet Ark	Voluntary, 2003	1500 tons (4 million cartridges) (2015/16)

Source: Adopted from Golev, A., Corder, G.D., 2017. Quantifying metal values in E-waste in Australia: the value chain perspective. Miner. Eng. 107, 81–87. Available from: https://doi.org/10.1016/j.mineng.2016.10.021.

named as MobileMuster and Australian Battery Recycling Initiative (ABRI), respectively. Large companies and institutions are generally used third-party leasing companies to take back the used IT equipment which is later sent to overseas for reuse. Table 23.3 represents the collection activities of different schemes in the existing E-waste management system in Australia.

The waste arising or the E-waste generation (under the NTCRS) is being calculated by the Australian government using the following Eq. (23.1):

$$\text{Waste arising or } E-\text{waste generation} = \frac{\text{Total weight of imports over past three years}}{3} \times \text{Scaling factor} \quad (23.1)$$

Here scaling factor depends upon the product type which was 0.8 for computers and 0.88 for printers at the beginning of the scheme (Government, 2018b) and now changed to 0.72 and 0.71 for computers and printers, respectively as per recent change in the regulation in the year 2018 (Government, 2018a). According to ANZRP (2017), use of scaling factor and subsequent calculation regarding E-waste generation is a good proxy of E-waste generation estimation, which considers the fact that all imported products will replace the existing e-products (that eventually disposed of as E-waste) that are currently in use. The scaling factor is related to

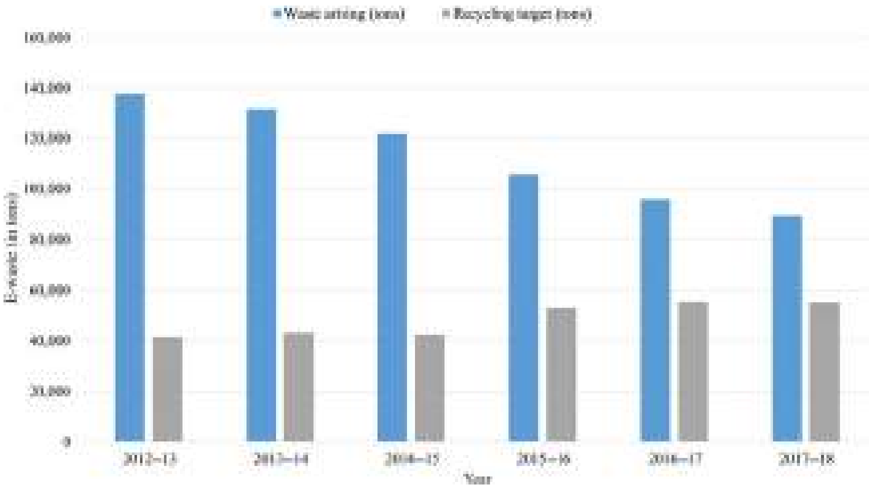

Figure 23.8 E-waste arising and recycling target over the years under NTCRS.
Source: Government, A., 2018b. Review of the Product Stewardship Act 2011 including the National Television and Computer Recycling Scheme. Available from: http://www.environment.gov.au/protection/waste-resource-recovery/product-stewardship/consultation-review-ps-act-incl-ntcrs (accessed 25.03.19.).

replacement level factor which was set previously 90% (or 0.9), meaning that in the same year, 90% of the products that are imported will result in the amount (in percentage) of as E-waste in that year. In terms of methodological approach results in overestimation and the total amount of E-waste generation (ANZRP, 2017). Fig. 23.8 shows the E-waste arising and recycling target using the formula shown in Eq. (23.1). It is seen that during the start of the scheme, the waste arising was higher compared to recent year (i.e., 2017–2018). This is because recently the scaling factor was adjusted and for computers and printers because presently it is considered that not all imported products replace existing products, and also some of the products do not become waste in Australia but instead of exported to other countries (Government, 2018a). Recycling target was achieved close to 60,000 tons in the year 2017–2018. However, there is still a considerable gap between the waste arising and recycling target. In the year 2015–2016, out of 105,699 tons of E-waste, only 43% of the E-waste was recycled (Government, 2018a).

23.3 E-waste-related regulation and program and management structure

The federal government of Australia enacted the National Waste Policy 2009 (Australia, 2009) in the year 2009 to update and integrate the existing waste management-related policy envisioning for the next ten years plan. Later on, in 2011, under the policy statement, Product Stewardship Act 2011 (Government, 2011b) was established based on the EPR and product stewardship principles, "to effectively manage the environmental, health and safety impacts of products, and in particular those impacts associated with the disposal of products and their associated waste". The Act included three different types of product stewardship—voluntary, coregulatory, and mandatory. From Table 23.2 (illustrated before) showed that at present, there is no mandatory product stewardship scheme found active in Australia for E-waste management. NTCRS falls under the category of coregulatory product stewardship (PS) scheme. After the inception of the scheme in 2012, in the year 2012−2013, a total of 40,813 tons of E-waste (mainly TV and IT equipment) were recycled which increased to 46,206 tons in the year 2015−2016 (Australia, 2018). Up to today, the scheme has successfully recycled approximately 230,000 tons of electronic waste (Australia, 2018).

Initially, five CRAs were introduced in the scheme to conduct the operational activities (collection, auditing and reporting to the federal government) which is now become four as of the year 2018. Manufacturers, users, distributors and importers (later on called as "liable parties") of EEE who imports more than 5000 products or 15,000 peripherals need to subscribe with one of the CRAs with an obligation to collect and recycle a percentage of the items they import or manufacture in a year (Morris and Metternicht, 2016). One of the main outcomes of the act was to initiate the NTCRS providing the framework managing waste generated from computer, TV, and their peripherals. At present, there are four major CRAs working under the scheme named as Australian and New Zealand Recycling Platform (ANZRP), E-cycle solutions, EPSA, and MRI PSO. A total of 105 liable parties are currently involved with the CRAs under the scheme who are mainly importing EEE products to Australia. The parties fund the CRAs for the smooth running of the system, which also facilitates the "free" of charge drop-off services to the customers (i.e., households and small businesses).

The main duties of the CRAs as enterprises are achieving NTCRS outcomes (i.e., fulfilling collection and material recovery targets set by the Department of the Environment) and communicating with the public regarding the information on collection and recycling. The other important stakeholder in the NTCRS is the electronic waste recyclers who are contracted by the CRAs as per regulation of the NTCRS and follows the Australian Standard (AS5377) (Australia, 2013). Australian Government (the Department works on behalf of the government) is the supreme authority that computes the amount of NTCRS product's waste generation based on import data as well ensure compliances of the liable parties and CRAs meeting the scheme outcomes. Besides, these main actors, local government and state and territory government plays an important role in collecting the E-waste from the customers. However, their obligation is not mandatory, and they are authorized to execute any external measures for managing E-waste under their jurisdictions. Customers are not obliged to return their waste e-products under the scheme (Government, 2011a). As there is no substantial responsibility being placed on the households/general consumers, there is a presence of "free rider" effect on the system. For example, customer can dispose of their waste TV, computers, and printers with the other bulky household wastes at the local government council's clean-up collection. Fig. 23.9 shows the roles and responsibilities of different actors under the NTCRS scheme. The whole scheme is funded by the industries (by liable parties) and the Australian government regulates it.

In terms of collection of the E-waste, as mentioned earlier, for NTCRS products, customers and small businesses can dispose of their waste TV and IT equipment to designated collection points provided by the CRAs. As per 2015−2016, there are just over 1200 collection points are made available for the customers to drop-off their E-waste, "free of charge" under the scheme, which collected approximately 50,000 tons of E-waste. Fig. 23.10 shows the collection amounts and the number of collection points available under the NTCRS over the years. From the figure, it is seen that the collection amount does not correlate with the collection points. One of the main mandates of the NTCRS scheme is that to provide reasonable access to collection points all over Australia, regardless of the characteristics of the area—metropolitan, inner regional, out regional, and remote locations. The collection points are generally organized by the local government councils. CRAs are being funded by the liable parties and collects E-waste from the permanent collection centers placed in the local government council areas. CRAs work towards achieving scheme target set by the Australian Government, and if they over-collect, they are not generally being paid off by the liable parties or any other source. It is to be mentioned that logistics services are being contracted by the CRAs to collect E-waste from the collection points to the storage areas and finally to the recycling facilities. The over-collection leads to removal of collection points from the certain council, which is often criticized by the residents of the council (ANZRP, 2017). This creates another problem for the councils that leads to landfill the E-waste, which is considered as the cheapest solution for them. On the other hand, even though reasonable access is required by the scheme, collection center locations are not optimized, especially for the rural and remote areas (DOEE, 2017). Another important choice of E-waste collection by the local councils is arranging an event drop-off event across Australia by which a considerable amount of E-waste is being collected. E-waste is also collected by the recyclers directly from the customers, but in some cases, they have to pay a nominal fee for the refurbishment of the product. However, this practice is not widely implemented by recyclers.

After the collection of the E-waste from the collection drop-off points, event drop-off, they are transferred to the recycling facilities for initial separation, segregation, and disassembly/dismantling. As per the regulation of the NTCRS, these recyclers are called first stage recyclers those are located in Australia. After initial processes, almost 90% of the materials (sorted) goes to overseas for further processing, and this process is called downstream recycling where sophisticated material recovery process is performed, such as pyrometallurgy, hydrometallurgy, and electrowinning. Schematic diagram of the entire supply chain (both forward and reverse flow) is shown in Fig. 23.11. In Section 23.4, the E-waste recycling process and technology used to conduct preprocessing is described.

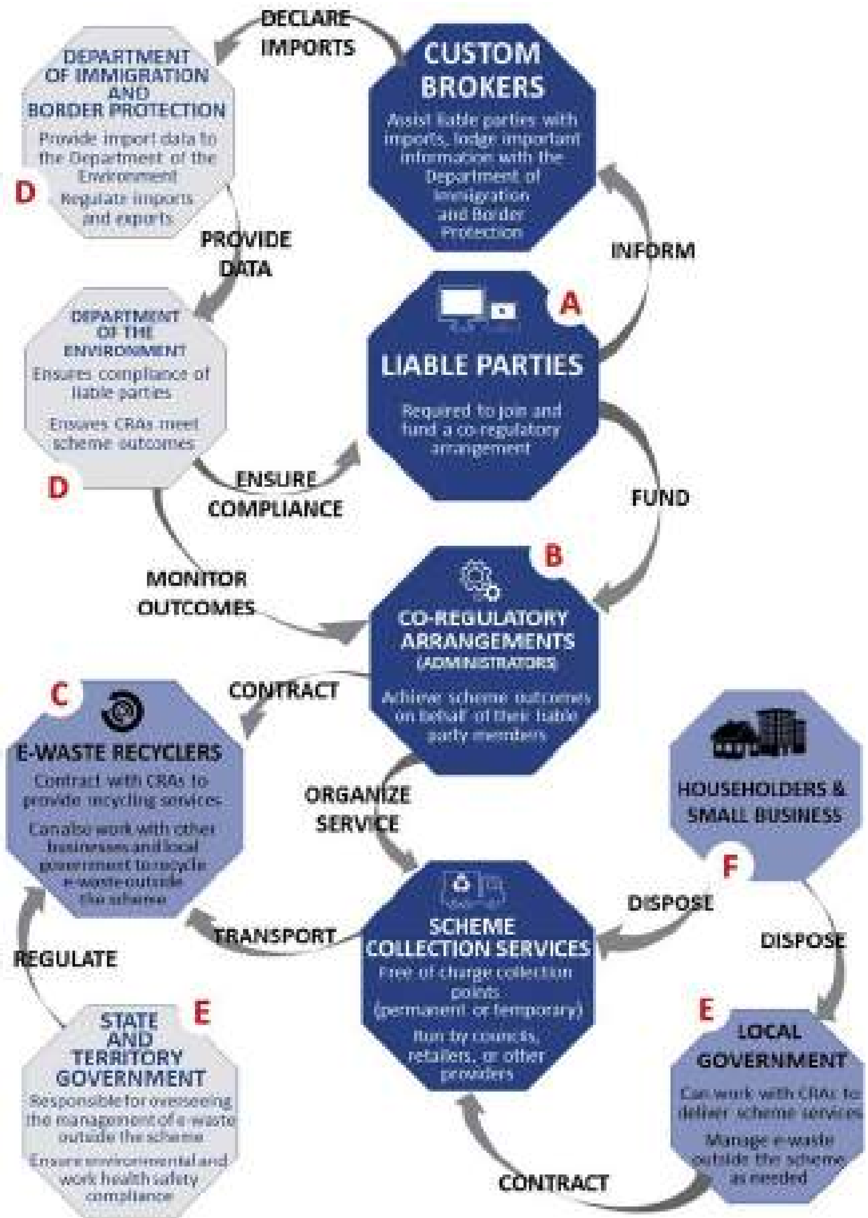

Figure 23.9 Roles and responsibilities under the NCTRS scheme.
Source: Adapted from Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750−764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

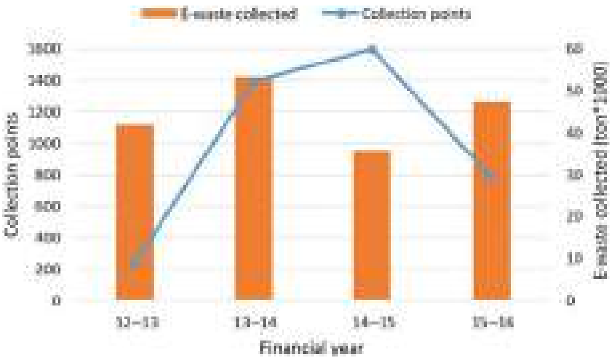

Figure 23.10 Permanent drop-off collection centers in Australia and collected amount of E-waste under NTCRS.
Source: Adapted from Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750–764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

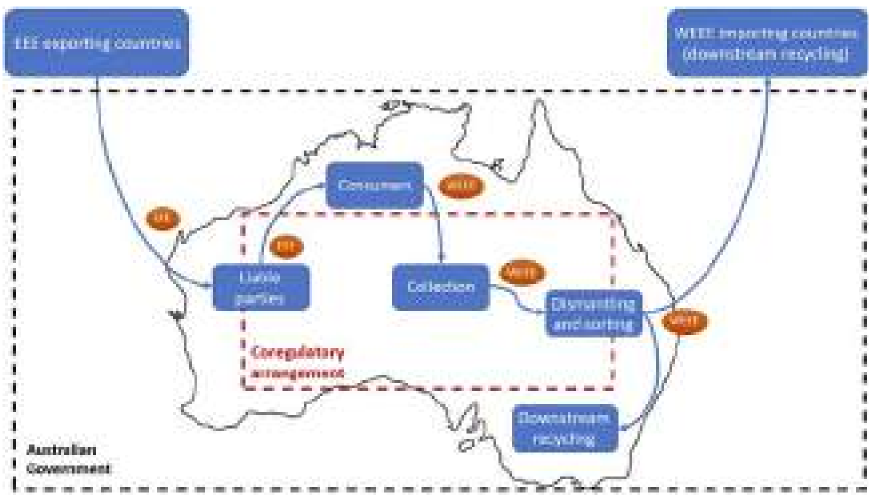

Figure 23.11 The current structure, WEEE flow and responsibility boundaries of the NTCRS.
Source: Adapted from Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750–764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

23.4 E-waste recycling system and treatment processes

The E-waste collected from different sources, customers, and businesses transferred to recycling facilities. Dias et al. (2018) identified that there are currently 31

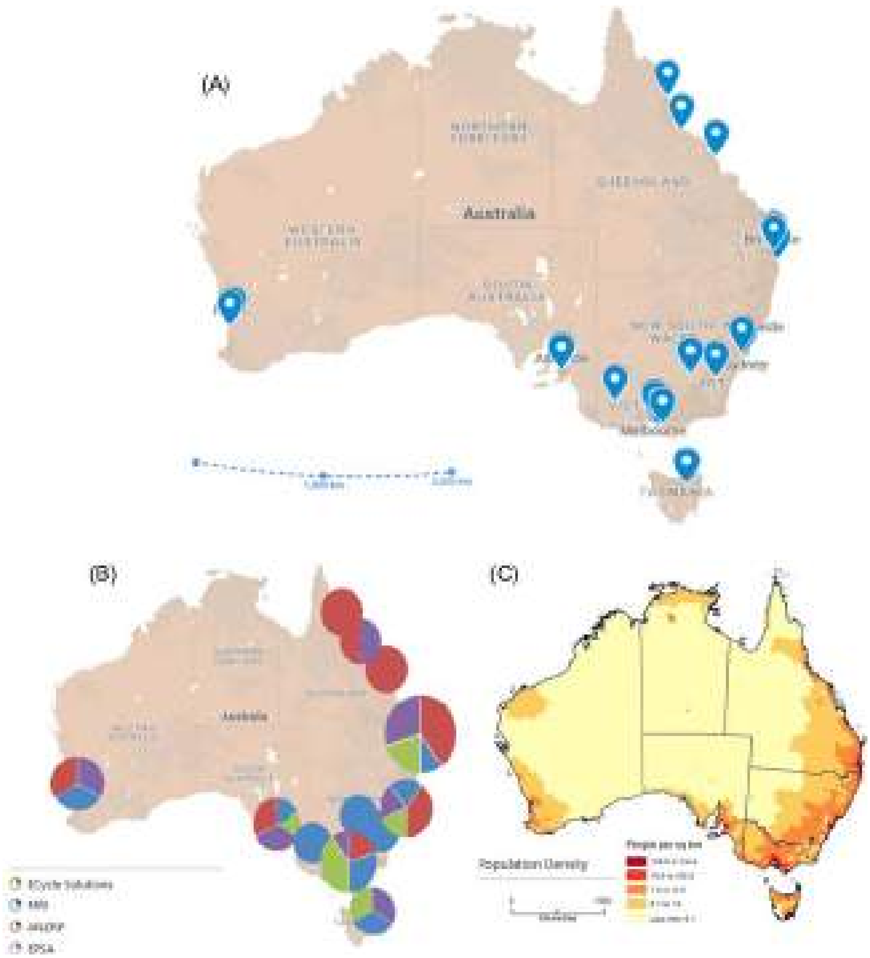

Figure 23.12 (A) Distribution of WEEE recyclers under the NTCRS in Australia; (B) influence of CRAs per facility per location; and (C) the population density in Australia in 2016.
Source: Adapted from Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750−764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

recycling facilities (run by 18 different E-waste recycling companies) in Australia under the NTCRS, which are responsible for initial processing according to the standard for the collection, storage, transport and treatment (AS5377). Locations of the recyclers across the states, the influence of CRAs on recyclers and population density of Australia are shown in Fig. 23.12. However, it is found that in some cases, recycling facilities are not optimized according to the population, especially in the state of New South Wales (NSW) and Western Australia (WA). For example, one facility for every 500,000 people (Dias et al., 2018). Among the CRAs, ANZRP has the highest number of contracts with the recyclers (around 31.8%), followed by MRI (27.3%), EPSA (20.5%), and E-cycle (20.5%). There are some other recycling facilities that works outside the scheme for NTCRS product recycling which are categorized by independent recyclers (works on behalf of the liable parties), recycling facilities run by the liable parties itself and international and local downstream recyclers (who conducts further material recovery activities after receiving materials from the 31 affiliated facilities). Recycling facilities are often shared by the CRAs (who contract the recyclers and the recycling facilities) to enhanced amount of collection, minimize the reverse logistics fuel-consumption and cost (Dias et al., 2018).

It is to be noted that in general, the recycling facilities have their discretion in determining whether or not E-waste being recycled in Australia or not.

If considered E-waste recycling processes of the NTCRS products majority of the activities fall under the category of initial processing that includes manual sorting, manual dismantling, shredding, magnetic separation, eddy current separation, and so on (see Fig. 23.13A). As mentioned earlier, the recyclers who such processes are called "first stage recyclers." There is only one recycler in Australia that uses Blubox technology (that combines shredding and material separation altogether with high technology separation such as the x-ray separation). After the preprocessing, the material is forwarded to downstream recycler mostly to overseas affiliated recyclers. Exporting E-waste is also widely practiced. However, there is limited information so far identified in which condition and to what extent products are being exported (Fig. 23.13B).

E-waste exporting for processing in overseas countries is continuously increasing, starting from the year 2014−2015. China is the single most important recipient of E-waste from Australia under the scheme, which was over 40% (in all the years) of the total exported E-waste. Indonesia is another importing country that received around 35% of the NTCRS products in the financial year 2016−2017 (Fig. 23.14). India is the recent addition in the importer's group that imported approximately 3% of the E-waste from Australia. The CRAs mention that overseas recycling companies follow the Australian standard (Australia, 2013) for recovering metal from the E-waste items (ANZRP, 2017). However, the issue of monitoring the recycling process of the downstream overseas recyclers is still questionable (DOEE, 2018).

23.5 Challenges and recommendation

Morris and Metternicht (2016) pointed out that even though after the inception of the NTCRS, a significant portion of waste NTCRS products was diverted from landfill, but still there are opportunities for improvements. Some of the key areas such as the expansion of product coverage, refining role, and responsibilities of the E-waste management-related stakeholders, ease to customers and their engagement

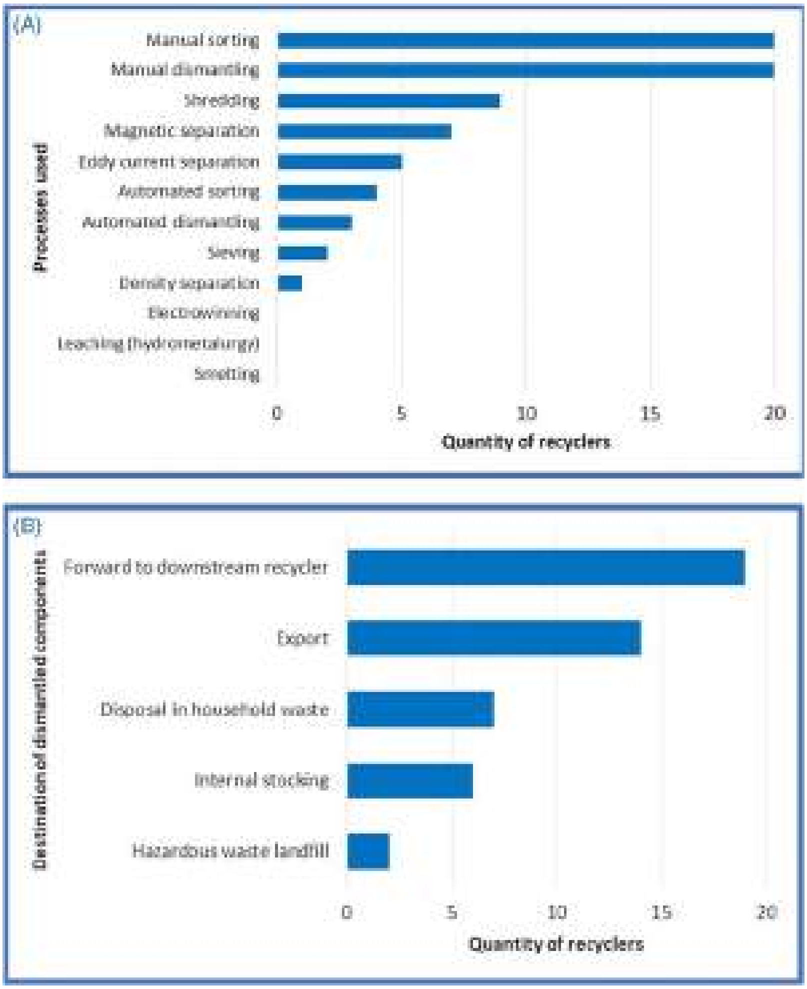

Figure 23.13 (A) Response to which processes are used and (B) response to the destination of the dismantled components.
Source: Adapted from Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750–764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

in the overall management system, setting enhanced and justified recycling, material recovery targets, ensuring audit, and compliance of the material flow of the system need attention. Based on the research identification and with other evidence, there are still several challenges that exist inside the scheme as well as in the whole E-waste management system in Australia, which needs to be overcome. These are described here in brief.

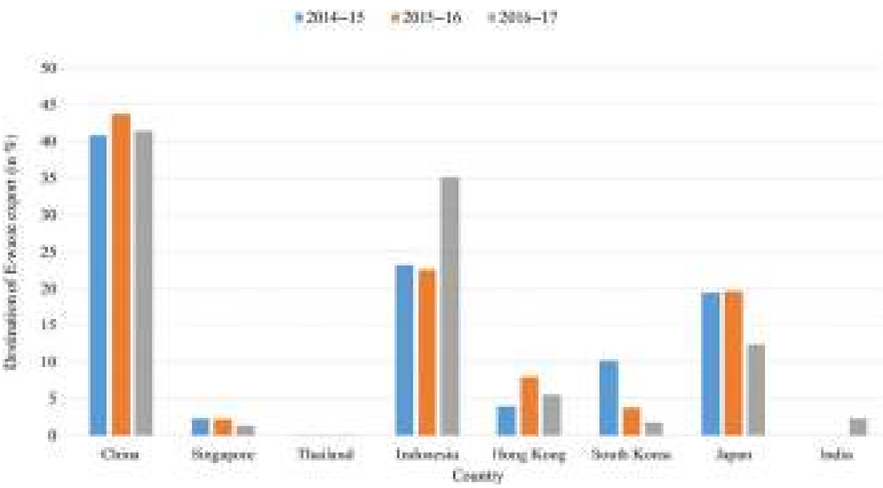

Figure 23.14 E-waste export to various countries from Australia.
Source: Adapted from Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750−764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

23.5.1 Role and responsibilities of stakeholders

Clear and defined stakeholders role in the E-waste management policy in Australia is one of the crucial issues that has been found by Morris and Metternicht (2016). Under the current E-waste management system, state and local governments need to manage E-waste outside of the NTCRS, which is significantly different from the management practice in Japan and Switzerland wherein all level of government need to have an active role in the system. Only the federal government of Australia maintains a consistent and active role in the current system. At present, not all local government councils are not working voluntarily with the CRAs in the NTCRS. However, it is found by the research conducted by Morris and Metternicht (2016) that due to cost effectiveness and service for the households, councils are more likely to engage with the NTCRS actively. Despite local councils are providing one of the most significant facilities to the scheme, which is the permanent collection points, "shared responsibility" from the council's perspective is not clear. Furthermore, local government councils receive the lowest amount of material or financial support, managing E-waste under the current system. Lack of funding as one of the key issues identified by Morris and Metternicht (2016). Increase the level of funding, increased involvement in the collection of E-waste defined the role of the local government council will substantially increase the performance of the E-waste management system in Australia.

23.5.2 Collection and recovery network

Existing collection and recovery network, particularly for remote and regional areas for E-waste at present is found insufficient research conducted by Morris and

Metternicht (2016) and Dias et al. (2018). Under the product stewardship regulation and the subsequent NTCRS, it is mentioned that "reasonable access" must be ensured for all Australian under the scheme. In that case, the definition of the reasonable access is not well defined, and it is found that currently, one service per 100 km for inner regional towns is operationalized which is found insufficient. In Japan and Switzerland, collection points are being placed in public places where consumers generally visit often, such as transport hubs and shopping precincts (Morris and Metternicht, 2016). However, not only placing the collection points at convenient locations but also substantial efforts have been given in the Japanese and Swiss system in educating consumers disposing of their E-waste in the collection points which is not very much evident in the Australian system. Furthermore, as there are no legal obligations among public disposing of their E-waste in designated collection points, there are hardly any complaints found from the consumers regarding reasonable access. Service areas by establishing collection points in the regional and remote areas need to be increased. Inconsistency has been shown in terms of reliability and access to service in Australian E-waste management. CRAs activities should be monitored regarding servicing or removing a collection site without prior notice given to local government councils. Local government plays an important role in placing collection points, and educating the public for them is easier than other stakeholders. This issue needs to be highlighted shortly by all government level along with how collection points can be established in the highest public proximity.

23.5.3 Expansion of product scope in the E-waste management system

Scope of products, particularly consumer electronics and small devices, need to be included in the future E-waste management system in Australia. At present, majority of the E-waste generated under small equipment category [the extensive list can be found in Forti et al. (2018)] does not belong to any specific recycling scheme, and there is hardly any retailer take-back operation present in the Australian EEE market right at this moment. In small device collection and recycling, customers are considered as the main actor in the entire loop, and EIU (2015) mentioned that retailer-based take back could be an appropriate option for this. Furthermore, Morris and Metternicht (2016) also mentioned that country like Australia, where the population density per kilometer is low, retailer based drop-off point for E-waste collection is one of the most suited options. Expansion of E-waste category in the management system will also eliminate the public confusion on what can or cannot be recycled in the council collection points. Insufficient public awareness of WEEE items exists in the current E-waste management system in Australia (Dias et al., 2018). Local and state governments across Australia should focus much on this issue to bridge the gap by providing adequate education and awareness, raising the program to the public. On the other hand, there are various means in including financial responsibility to consumers such as advanced recycling fees collected at the point of purchase (like as practiced in Switzerland and the State of California in the United States) or in Finland; consumers must return their small equipment or EEE items to retailers. Another way making consumer responsible in disposing their E-waste at household-level is the introduction of "pay-as-you-throw," or PAYT system currently operated in the Netherlands. The amount of fees is calculated for a particular household based on the amount of waste they throw, which is comparatively higher compared to households that pay flat tax towards disposing of their waste. In the PAYT system, households are given strong incentives for disposing of their small E-waste in the appropriate channels, not as part of the waste generated as household waste. The major identification of the PAYT system in the Dutch E-waste management system found that consumers and small WEEE are a vital part of the holistic E-waste system. Another important fact that need to be understood at the first place that for large, temperature exchange equipment and small electrical and electronic equipment, there is no scheme or regulation currently exists, which gives opportunity to free raiders in the system, and tend to conduct activities such as illegal export despite being one of the signatories of Basel convention. Furthermore, due to lack of expansion, consumers most often dispose of their small and large equipment at the kerbside for council clean-up collection that eventually goes to landfill.

23.5.4 Effectiveness of compliance and audit on material recovery and recycling targets

As mentioned earlier, Australia's current NTCRS has been developed from the experience of Japan, Switzerland, and the European Union's WEEE Directive (Islam et al., 2018). In terms of material and recycling target, the NTCRS follows the example of Japan, and in June 2015, the target was set to 50% for the 2015 − 16 financial year which is envisioned to increase by 80% to 2026−27 (DOEE, 2018). The increase of recycling target resulted from several facts such as WEEE stockpiling, job losses across among the stakeholders, and termination of contracts and services. However, achieving set recycling target under the current management system is well debated (Morris and Metternicht, 2016). With increased recycling target the scheme needs to recycle a total of the 53,000 tons additional waste computer, TV, and IT peripheral, which is again, represents less than 10% of the overall E-waste generation in Australia. Furthermore, without a clear roles and responsibilities of local government councils, achieving such target will eventually a burden on the other stakeholders and without necessary enforcement and compliance measures, it is often hard to achieve such target (Morris and Metternicht, 2016). Also, due to inadequate compliance and auditing measures, it is also found that industry and public, in general, have a lack of confidence in the current E-waste management system. The E-waste management system is currently considered a standard called Australian/New Zealand Standard AS/NZS 5377:2013 for collection, storage, transport, and treatment. However, without the actual auditing at all the stages mentioned in the standard is not in place right at this moment. On the other hand, as the recycling and labor cost is high in Australia, Morris and Metternicht (2016) mentioned that large volume of E-waste is being shipped to overseas illegally on the top of that lack of compliance and audit measure. The material flow analysis (MFA) is used in the Swiss E-waste management from the starting point of product recovery to the final material recycling providing a transparent outlook of the whole system and producer responsibility organizations in Switzerland are bound to generate such report each year to Swiss Federal Agency for Environment, Forests and Landscape (Wath et al., 2010). After the inception of the NTCRS, the downstream recycling process has not monitored by the CRAs. However, this is not the case for Australia, and a large-scale gap exists in Australian E-waste system for which illegal export of E-waste to developing countries is questionable, and responsibilities as a signatory under the Basel Convention often difficult to measure under the current system. Transparency by conducting an audit is one of the significant tasks that need to be undertaken by the stakeholders.

23.6 Conclusion

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams all over the world. As a developed OCED country, E-waste generation in Australia showed an exponential growth in the past decades. Electrical and electronic equipment (EEE) of all variety starting from large and temperature exchange equipment to small IT and small equipment, the Australian market is fully saturated confirmed by the various market research organization. Before 2012, almost all waste generated from EEE, go to the landfill, which is loss of valuable metal sources and threat to the environment for possible environmental contamination. However, in 2012, under the product stewardship Act, National Television and Computer Recycling Scheme (NTCRS) has been initiated that diverted large amount of waste television sets, computer, and IT peripherals from landfill. However, the products covered by the scheme only covers less than 10% of the overall E-waste generation in the country. Besides, NTCRS currently MobileMuster is another voluntary, not-for-profit scheme accredited by the Australian government that collects and recycle waste mobile phones. Although NTCRS recovered a significant amount of E-waste from household and small businesses, there are still challenges that exist in the system. For example, allocating collection points in the regional and remote areas in the country, clear definition and shared roles and responsibilities of all stakeholders, especially the local government councils and state government. Lack of consumer awareness is found as one of the significant inhibitors in the current E-waste management system. Retailer-based collection and recovery network is one of the promising ways of recovering small IT and small equipment of the E-waste categories. Expanding the scope of E-waste in the management system is one of the potent ways in achieving economies of scale and avoiding consumer confusion on what can and what cannot be recycled in the system. Developing a detailed material flow analysis (MFA) model starting from the import of EEE to the material recovery at the overseas under enhanced compliance and auditing is one of the most important and crucial tasks need to be carried out by the stakeholders in the system in the coming future. These all will ensure the sustainability of the E-waste management system in Australia.

References

ACMA, 2012. TV sets in Australian households. Available from: https://www.acma.gov.au/theACMA/Library/researchacma/Snapshots-and-presentations/tv-sets-in-australian-households-research-library-landing-page (accessed 18.03.18.).

ANZRP, 2017. Review of the product Stewardship Act and National Television and Computer Recycling Scheme. Available from: https://www.anzrp.com.au/wp/wp-content/uploads/ANZRP-NTCRS-and-PS-Act-Review-White-Paper-FINAL-Aug-secured.pdf (accessed 25.03.19.).

Australia, C.o., 2009. National waste policy: less waste, more resources. Available from: http://www.nepc.gov.au/node/849/ (accessed 25.03.19.).

Australia, C.o., 2018. Review of the Product Stewardship Act 2011, including the National Television and Computer Recycling Scheme. Available from: https://www.environment.gov.au/system/files/consultations/79a39335-ee07-4f94-ab7f-cd8323641af0/files/ps-act-review-consultation-paper.pdf (accessed 22.03.19.).

Australia, P., 2019. Australia population 2019. Available from: http://www.population.net.au/ (accessed 22.03.19.).

Australia, S., 2013. AS/NZS 5377-2013. Available from: https://www.standards.org.au/standards-catalogue/sa-snz/publicsafety/ev-019/as-slash-nzs--5377-2013. (accessed 25.03.19.).

Balde, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-Waste Monitor 2017: Quantities, Flows and Resources. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Vienna.

Dias, P., Bernardes, A.M., Huda, N., 2018. Waste electrical and electronic equipment (WEEE) management: an analysis on the australian E-waste recycling scheme. J. Clean. Prod. 197, 750−764. Available from: https://doi.org/10.1016/j.jclepro.2018.06.161.

DOEE, 2017. Evaluation of the National Television and Computer Recycling Scheme (NTCRS). Available from: http://www.environment.gov.au/system/files/resources/407f8a95-080b-4daa-8189-747c000d5fa3/files/ntcrs-evaluation-report.pdf (accessed 25.03.19.).

DOEE, 2018. Review of the Product Stewardship Act 2011, including the National Television and Computer Recycling Scheme. Available from: http://www.environment.gov.au/system/files/consultations/79a39335-ee07-4f94-ab7f-cd8323641af0/files/ps-act-review-consultation-paper.pdf (accessed 22.04.19.).

EIU, 2015. Global E-waste systems: insights for Australia from other developed countries: a report for ANZRP by the Economist Intelligence Unit. Available from: https://www.anzrp.com.au/wp/wp-content/uploads/Global-E-waste-systems-A-Report-for-ANZRP-by-EIU-FINAL-WEB.pdf (accessed 19.04.19.).

Euromonitor, 2019. Major consumer appliances in Australia. Available from: http://www.portal.euromonitor.com/ (accessed 22.03.19.).

Forti, V., Baldé, K., Kuehr, R., 2018. E-waste statistics: guidelines on classifications, reporting and indicators. Available from: http://collections.unu.edu/eserv/UNU:6477/RZ_EWaste_Guidelines_LoRes.pdf. (accessed 26.10.2018).

Golev, A., Corder, G.D., 2017. Quantifying metal values in E-waste in Australia: the value chain perspective. Miner. Eng. 107, 81−87. Available from: https://doi.org/10.1016/j.mineng.2016.10.021.

Golev, A., Schmeda-Lopez, D.R., Smart, S.K., Corder, G.D., McFarland, E.W., 2016. Where next on E-waste in Australia? Waste Manag. 58, 348−358. Available from: https://doi.org/10.1016/j.wasman.2016.09.025.

Government, A., 2011a. Product Stewardship (Televisions and Computers) Regulations 2011 - National Waste Policy.

Government, A., 2011b. Product Stewardship Act 2011. Available from: https://www.legislation.gov.au/Details/C2011A00076 (accessed 25.03.19.).

Government, A., 2018a. NTCRS regulatory changes and improvements for 2018. Available from: https://www.environment.gov.au/news/2018/06/28/ntcrs-regulatory-changes-and-improvements-2018 (accessed 25.03.19.).

Government, A., 2018b. Review of the Product Stewardship Act 2011 including the National Television and Computer Recycling Scheme. Available from: http://www.environment.gov.au/protection/waste-resource-recovery/product-stewardship/consultation-review-ps-act-incl-ntcrs (accessed 25.03.19.).

IDC, 2018. Australia's PC market posts growth in 2017Q4, driven by strong demand in the education segment, according to IDC. Available from: https://www.idc.com/getdoc.jsp?containerId = prAP43645718 (accessed 22.03.18.).

Islam, M.T., Huda, N., 2018. Reverse logistics and closed-loop supply chain of waste electrical and electronic equipment (WEEE)/E-waste: a comprehensive literature review. Resour. Conserv. Recycl. 137, 48−75. Available from: https://doi.org/10.1016/j.resconrec.2018.05.026.

Islam, M.T., Abdullah, A., Shahir, S., Kalam, M., Masjuki, H.H., Shumon, R., et al., 2016. A public survey on knowledge, awareness, attitude and willingness to pay for WEEE management: case study in Bangladesh. J. Clean. Prod. 137, 728−740.

Islam, M.T., Pablo, D., Huda, N., 2018. Comparison of E-waste management in Switzerland and in Australia: a qualitative content analysis. Int. J. Environ. Ecol. Eng. 12 (10), 610−616.

Morris, A., Metternicht, G., 2016. Assessing effectiveness of WEEE management policy in Australia. J. Environ. Manage. 181, 218−230. Available from: https://doi.org/10.1016/j.jenvman.2016.06.013.

Read, R., 2015. 10 years of consumer insights into mobile use and recycling: 2005−2015. Available from: http://www.globalpsc.net/wp-content/uploads/2015/10/MM_australia_s_mobile_decade_1015.pdf (accessed 22.03.19.).

Spencer, L., 2018. Australia continues to buck global PC trend. Available from: https://www.arnnet.com.au/article/635132/australia-continues-buck-global-pc-trend/ (accessed 22.03.19.).

STEP, 2015. Step E-waste world map. Available from: http://step-info.org/step-E-waste-world-map.html (accessed 18.03.18.).

STEP, 2019a. Step global E-waste map. Available from: http://www.step-info.org/Overview_Switzerland.html (accessed 22.03.19.).

STEP, 2019b. What is E-waste? Available from: http://www.step-initiative.org/E-waste-challenge.html (accessed 15.03.19.).

UNComtrade, 2015. United Nations Commodity Trade Statistics Database.

Wath, S.B., Vaidya, A.N., Dutt, P.S., Chakrabarti, T., 2010. A roadmap for development of sustainable E-waste management system in India. Sci. Total Environ. 409 (1), 19–32. Available from: https://doi.org/10.1016/j.scitotenv.2010.09.030.

Zhu, X., Lane, R., Werner, T.T., 2017. Modelling in-use stocks and spatial distributions of household electronic devices and their contained metals based on household survey data. Resour. Conserv. Recycl. 120, 27–37. Available from: https://doi.org/10.1016/j.resconrec.2017.01.002.

E-waste policies in the United States: minimalistic federal action and fragmented subnational activities

24

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24.1 Introduction

Contrary to other countries and the European Union (EU), the United States (US) does not have a uniform nation-wide waste electrical and electronic equipment (E-waste) law. Instead, 25 US states have adopted their own E-waste policies while the other half of the states has not done so. This has resulted in a fragmented patchwork of diverse requirements and levels of stringency across the country. National legislation only imposes a binding landfill ban on an extremely narrow scope of electronic devices and is complemented by some voluntary national programs and standards. Out of the 25, 23 state-level E-waste laws embrace the concept of extended producer responsibility (EPR) with the exception of California and Utah. This chapter provides an overview of US E-waste policies, compare the different subnational initiatives, and trace their evolution over time.

The near-absence of national E-waste legislation does not mean that there were no any attempts pushing for nation-wide legislation. Policy-makers, company representatives, and NGOs launched a number of initiatives over the course of the 1990s and early 2000s. They recognized and highlighted the various environmental and health problems that accompanied the rapidly growing E-waste stream. Activities in the United States occurred around the same time as E-waste policy developments started in Europe. Yet, while the European Union pioneered in adopting a supranational E-waste law that was transposed into national law of all of its Member States, US activities remained less successful. Federal stalemate created a void that partially was filled by state-level legislation.

Fast technological innovation and growing numbers of electronic devices per person created an ever-growing E-waste stream. In 2007, when a wave of subnational E-waste laws started washing over the United States, only about 20% of US E-waste was collected for recycling. Most other E-waste was landfilled where hazardous substances could leach into the environment or was exported to low-income countries where they mainly were recycled by workers of the informal sector, using methods that harmed their health and the environment (US Government

Handbook of Electronic Waste Management. DOI: https://doi.org/10.1016/B978-0-12-817030-4.00018-8

Accountability Office, 2008; US Environmental Protection Agency, 2008a; US Environmental Protection Agency, 2008b). Confronted with the challenge to keep hazardous E-waste away from landfills and ensuring appropriate recycling, US municipalities, policy-makers and other stakeholders started developing policy solutions that were tailored to local circumstances and politics as well as inspired by developments elsewhere, in most particular Europe (Biedenkopf, 2013).

Section 24.2 describes the minimalistic approach that was taken by the federal US government, in spite of the multiple—yet unsuccessful—initiatives undertaken by policy-makers, company representatives, and NGOs. Federal near-inaction opened a window of opportunity for state governments to adopt their own E-waste policies with California leading the pack. Section 24.3 identifies the factors that shaped California's pioneering efforts. An overview of the wave of subnational E-waste policies that were adopted between 2006 and 2011 is provided in Section 24.4, followed by a description of the fragmentation of the US E-waste policy landscape in Section 24.5 and the identification of various clusters of resembling E-waste laws in Section 24.6. This chapter is based on the analysis of various types of policy documents and the individual E-waste laws. Expert interviews that were conducted in 2010 (Biedenkopf, 2011) informed the tracing of policy developments in California and at the federal level. The concluding section provides some reflections on the implications of the fragmented US E-waste policy structure.

24.2 A minimalistic approach: federal E-waste policy

Federal US E-waste policy is a story of many attempts with few results. A uniform national E-waste law is wanting. Instead, policies are fragmented and largely rely on subnational entrepreneurship and decisions. National legislation only imposes a landfill ban on a very narrow set of electronics. Some voluntary programs and standards complement the national approach. The minimalistic reality of federal E-waste measures clashes with the noteworthy number of E-waste-related federal initiatives. Proposals abound during the early 2000s, yet none of the initiatives bared fruits, eventually opening a window of opportunity for impatient state governments. This section outlines the contours of federal E-waste measures.

Binding rules that pertain to E-waste are extremely scarce. Only a very narrow part of E-waste is regulated under the federal Resource Conservation and Recovery Act (RCRA), namely equipment containing a cathode ray tube (CRT), which is banned from landfills since it is considered hazardous waste. CRTs contain not only significant amounts of lead but also cadmium, zinc, and rare earth metals. If lead or other hazardous substances leach from landfills or improper recycling methods, they can harm human health when ending up in drinking water and food (Tsydenova and Bengtsson, 2011). The RCRA ban thus aims at preventing health and environmental harm. Yet, it neglects a large source of E-waste since it only applies to large businesses and public authorities. End-of-life devices discarded by households and small-quantity generators are exempted (Kang and Schoenung, 2005).

While the limitation to large businesses and public authorities already significantly reduces RCRA's impact, the focus on CRTs only further reduces it. When compared to, for example, the scope of EU E-waste law, which includes almost all electrical and electronic devices, CRTs from large commercial and public consumers appears quite restrictive. A second shortcoming of the RCRA provision is that it only institutes a landfill ban but falls short of any other requirements with regard to the collection and recycling of E-waste. E-waste exports to low-income countries are not principally prohibited, as is the case in Europe.

While de facto legislative provisions diverge widely between the United States and the EU, recognition of the E-waste problem and initiatives aiming to address it emerged on both sides of the Atlantic at roughly the same time, yet with different results. In the mid-1990s, some policy initiatives pertaining to E-waste and extended product responsibility were launched at the federal US level (Davis et al., 1997). Whereas extended *producer* responsibility focuses on the waste stage, extended *product* responsibility stresses the responsibility of various actors along a product's life cycle (President's Council on Sustainable Development, 1997). Extended product responsibility is a concept quite specific to the US context in which electronics manufacturers initially rejected the idea of EPR due to the fear of being perceived as the sole bearer of responsibility. The concept more explicitly includes the understanding that also other product-cycle actors should take on parts of the responsibility, including retailers, consumers, and recyclers.

In the early 2000s, federal US initiatives moved from elaborating concepts such as extended product responsibility, which can be applied to a range of product groups, to focusing more concretely on E-waste collection and recycling. A 2000 Product Stewardship Forum, held in Boston, resulted in the creation of the Product Stewardship Institute. The institute's objective is promoting product stewardship as a way to solve waste management problems by encouraging product design changes. The National Electronic Product Stewardship Initiative (NEPSI)—an informal dialogue among industry representatives, governmental actors, retailers, NGOs, and recyclers—was incepted in 2001 with the aim to develop a solution for E-waste management in the United States. Yet, it failed to find consensus and achieve its aim. An unsurmountable conflict arose within industry. Different industry representatives could not agree on who should pay for recycling: Television manufacturers adamantly opposed producer responsibility while computer companies were willing to support it (US Government Accountability Office, 2010). This conflict highlights the importance that was attributed to the philosophical difference between extended producer responsibility and extended product responsibility.

A series of legislative proposals for a federal E-waste collection and recycling system were submitted to US Congress between 2002 and 2008. Yet, none of them was adopted. The first in the series of proposals was the draft Computer Hazardous Waste Infrastructure Program Act (HR 5158), which would have established a fee on the sale of computers, monitors, and some other electronic devices to pay for collection and processing of E-waste. This law would thus have been based on an advance recovery fee rather than an extended product/producer responsibility approach. Other unsuccessful legislative proposals that were submitted to Congress but not adopted addressed aspects as varied as research and innovation incentives, Congress' own E-waste treatment and E-waste exports. A 2008 Concept Paper for a National Electronic Products Stewardship Act aimed at initiating a consultative process and triggering a debate to culminate in a federal extended product responsibility law. A group of eight Members of Congress drafted the paper. However, their entrepreneurship attempt failed and the concept paper never was further developed into a legislative proposal that was officially introduced in the federal US policy-making process.

Not only legislators took initiative, also policy entrepreneurs from a segment of the electronics industry tried their luck. A 2007 industry initiative led by the Electronic Industries Alliance (EIA) developed a framework that reconciled the differences between television and computer manufacturers, which previously brought the NEPSI process to a fall. The proposal was based on a bifurcated approach applying an advance recovery fee to waste televisions and an extended producer responsibility approach to waste computers. The scope of the framework was limited to televisions, computers, and computer monitors. Yet, despite its reconciliatory intentions and similar to the 2008 concept paper, the proposal never garnered sufficient support and no Congress(wo)man ever officially introduced it in the federal legislature.

Although a significant federal E-waste law never materialized, alternative approaches and voluntary programs were developed. In 2003, the Plug-In To eCycling initiative encouraged electronics manufacturers, retailers, and mobile phone service providers to commit to using recyclers and refurbishers who comply with EPA guidelines (US Government Accountability Office, 2010). In 2008, the Responsible Recycling (R2) Practices—a nonbinding certification program for electronics recyclers—were released. In response to the absence of R2 provisions that ban E-waste exports, NGOs launched the competing e-Stewards standard, as a more stringent certification program since it includes the international dimension. The 2006 Electronic Product Environmental Assessment Tool (EPEAT) was launched by the federal Environmental Protection Agency and focuses on institutional buyers such as government bodies. It assists them in comparing products' environmental performances. While EPEAT includes criteria pertaining to the collection and recycling of E-waste, it comprises a much broader set of environmental criteria such as energy efficiency. EPEAT's impact was amplified by a 2007 Executive Order that requires all federal agencies to purchase at least 95% of their total electronic devices EPEAT-certified. More recently, the 2011 National Strategy for Electronics Stewardship sets four overarching goals and provides recommendations for the federal government, companies, and consumers. The goals include enhanced research and technology development, ensure the federal government's leadership, increase effective E-waste management in the United States, and reduce harm from US E-waste exports.

Despite the plethora of federal proposals and initiatives, only voluntary or public procurement measures have been adopted. The RCRA landfill ban is a small exception but given its minuscule scope compared to the E-waste challenge, it cannot be considered a sufficient approach. As in many other areas, the inability to adopt federal US legislation has resulted in some alternative approaches that address parts of the problem. The most notable of these alternative approaches are EPEAT in combination with public procurement requirements, and the R2 and e-Stewards standards. The federal legislative void moreover gave rise to a number of state-level initiatives, which has led to a fragmented patchwork of diverse provisions and requirements. The first to adopt its own subnational E-waste law was California, whose policy-making process is traced in Section 24.3.

24.3 The pioneer: California

California pioneered in adopting subnational US E-waste legislation in 2003. E-waste was perceived as an important policy problem due to a California-specific landfill ban broader than the federal RCRA ban and heightened public pressure. The policy-making process was polarized. Time pressure arising from the California legislative process eventually triggered the governor to push for an advance recovery fee-based E-waste law. This section describes the main factors and developments that culminated in the adoption of the California E-waste Recycling Act.

As of January 1, 2005, California consumers are charged a fee when they purchase a device covered by the law. This fee covers the costs of E-waste collection and recycling. The law is the only of the US subnational E-waste laws based on an advance recovery fee paid by consumers at the time of purchase. The product scope is limited when compared to international E-waste laws such as the European approach. It only covers video display devices. Attempts to expand the product scope to all personal computers instead of only monitors (AB 3001, AB 1535) were introduced in 2006 and 2007 but not adopted. A 2009 legislative proposal to include fluorescent lamps (AB 1173) was vetoed by the governor. Various legislative proposals for product stewardship laws with a broad scope were introduced in 2009 and 2010 but failed. A 2018 legislative proposal to amend the E-waste Recycling Act would expand the scope of the law to mirror the very comprehensive scope of the EU WEEE Directive. Moreover, it would alter the California law's approach to an extended producer responsibility one, making manufacturers financially responsible for E-waste recycling. Yet, at the time of writing this chapter (June 2019), the proposal's fate had not been decided.

The agenda-setting phase of the California E-waste Recycling Act is marked by the recognition of some crucial problems pertaining to E-waste. Those policy problems elevated E-waste on the political agenda and policy-makers perceived them as important enough to dedicate sufficient resources and attention to E-waste policy. In particular California's categorization of E-waste as hazardous waste and growing public pressure fueled by NGO campaigns were two important developments.

The first development that raised the urgency of the E-waste problem relates to a more stringent landfill ban than the national one. Contrary to the federal government, the California Department of Toxic Substances Control classified E-waste as hazardous waste and clearly stated in a 2002 letter in response to local governments' request for clarification that all E-waste was considered hazardous waste. This classification meant that E-waste, including from regular households, could no longer be landfilled. This created tremendous problem pressure on policy-makers to find a solution since local governments were faced with large amounts of E-waste in the absence of adequate collection and treatment infrastructure. Collecting and recycling E-waste is costly and local governments did not have sufficient resources to establish and provide those services. This led to the general recognition of E-waste as an urgent policy problem.

A second development that contributed to E-waste being perceived as policy problem stemmed from E-waste exports to low-income countries. NGOs such as the Basel Action Network, the Silicon Valley Toxics Coalition, and Greenpeace published numerous reports, highlighting the detrimental environmental and health impacts of California-originating E-waste in far-away countries. Monitors with labels that could be traced back to California companies were found in India and China. Newspapers ran this story on their front pages. These activities raised public awareness of the issue and increased public pressure to address the E-waste problem.

In response to the mounting problem pressure, legislators issued a legislative proposal for a collection and recycling system for computer monitors and televisions in February 2002, which however was vetoed by the governor because he did not deem it ambitious enough. Only about one-and-a-half years later, in September 2003, a similar law was adopted.

The debate during the policy-making process that culminated in the adoption of the E-waste Recycling Act was polarized and controversial. There was no industry consensus, which weakened their lobbying efforts while NGOs were relatively united in pushing for E-waste policy. NGOs supported a producer responsibility approach. Television manufacturers advocated an advance recovery fee system, while computer manufacturers did not have a unified position. The American Electronics Association opposed the E-waste legislative proposal outright, while one of its member companies, HP, advocated for a producer responsibility approach. The company already had a system in place to manage its end-of-life products and had established a long-standing partnership with a recycling facility in Roseville, California. It charged consumers a fee when they returned a used monitor. Hence, HP wanted its efforts to be reflected in the Californian E-waste law and level the playing field with other manufacturers who would be required to make similar investments under an E-waste law. Retailers did not favor an advance recovery fee since this approach puts a larger share of the implementation duties in their hands.

Eventually, an advance recovery fee-based law was adopted despite the significant number of advocates for a producer responsibility approach. The reason for this can be found in Governor Davis' eventual support for an advance recovery fee approach. This was the model of the first unsuccessful legislative proposal that had passed both houses of the state legislature but was vetoed by the governor in 2002.

Yet, circumstances had changed: Due to the rules of the California legislative process, an E-waste law had to be adopted fast before the end of the legislative session. Moreover, Governor Davis needed a quick policy success. For those reasons, he pushed for a law of which he knew that there was relatively broad backing. Some pragmatic NGOs shifted to support the governor's position. The California E-waste Recycling Act constitutes a compromise among the different stakeholders and policy-makers. As the pioneer within the US context, the politics and controversy around E-waste legislation at the time seem to have been too high of a hurdle for an ambitious producer responsibility-based approach.

Rising urgency and pressure to adopt E-waste policy in California combined with the federal inability to adopt a nation-wide law in the late 1990s/early 2000s and the anticipation that President George W. Bush's administration would not push for any significant legislative changes provided sufficient impetus for California's pioneering in E-waste policy. As with other environmental policies, California attempted to fill the federal legislative void by adopting avantgarde state-level policy (Biedenkopf, 2017; Carlson, 2008; Vogel, 2018). The coalescence of the different favorable factors resulted in the adoption of the first subnational US E-waste policy in 2003. Yet, the challenging situation of being the first, entering unchartered waters, resulted in the adoption of an advance recovery fee system rather than an extended producer responsibility system. The political circumstances and the governor's position in combination with time pressure made the advance recovery fee the best-possible output at the time.

24.4 2006–11: a subnational wave of E-waste policies

After California pioneered subnational US E-waste policy-making in 2003, Maine followed suit in 2004, and Washington State in 2006. The period between 2007 and 2010 witnessed a wave of E-waste law adoptions in 20 states. Utah and the District of Columbia were the latecomers, adopting laws in 2011 and 2014, respectively. Colorado does not have a full-fledged E-waste law but adopted an E-waste disposal ban in 2012. Fig. 24.1 shows the sequence of US state-level E-waste policy adoptions.

In spring 2004, Maine adopted the second US subnational E-waste law and the first one based on the extended producer responsibility model. Similar to California's law, Maine's E-waste recycling program covers televisions and computer monitors. It makes municipalities responsible for establishing a collection system and gives the responsibility to pay for collection, transportation, and recycling to the manufacturers. Washington State adopted the second extended producer responsibility-based E-waste law in 2006 and heralded the wave of state-level E-waste laws that washed over the country between 2007 and 2011.

The growing recognition of the environmental harm caused by landfilling electronics mounted public pressure to address the problem in most of those states. Many dynamics resemble those that occurred in California with public pressure

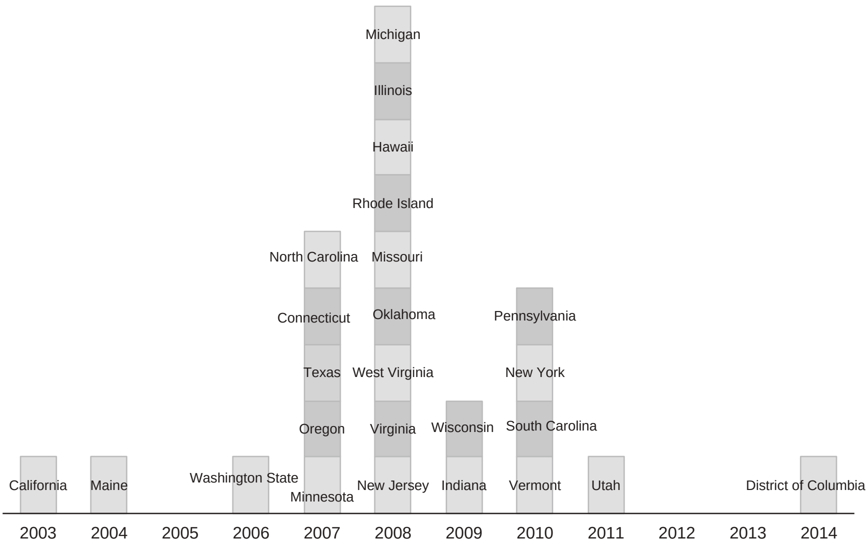

Figure 24.1 Adoption of US subnational E-waste laws.

growing, municipalities not being able to shoulder the burden of appropriate collection and recycling, and different industry segments favoring divergent approaches. In Washington State and Oregon, for example, individual policy entrepreneurs initiated the Northwest Product Stewardship Council, which led to the Western Electronic Product Stewardship Initiative that eventually dissolved in the National Electronic Product Stewardship Initiative. The national initiative however failed to agree on a solution for E-waste management in the entire United States. Anticipating a massive growth of E-waste due to digitalization and the switch from CRT to flat screen-televisions, state legislature, and governors took the matter in their own hands, adopting E-waste policies.

24.5 Fragmentation of E-waste policies

The 25 state-level E-waste policies diverge in provisions related to their scope, labeling, registration, and reporting requirements, reference to recycling standards, the setting of collection targets and whether or not they include a landfill ban. This has led to a patchwork of different variants of E-waste laws, which creates a fragmented approach that poses a challenge for companies that need to comply in multiple or all states. Most laws cover a relatively small product scope that is limited to televisions, computers, and peripherals. This choice was motivated by the intention to start with the highest-volume product categories and those that are most damaging at their disposal stage. A number of states expanded their laws' scope over time. Nonetheless, their laws cover a far narrower scope than the European Union

E-waste law. Although all E-waste laws, apart from those in California and Utah, are based on the extended producer responsibility approach, they fill it in in different manners. Most state-level E-waste laws contain some registration requirements.

All subnational E-waste laws, with the exception of Utah and California, contain the requirement that producers either finance a state-run E-waste collection and recycling program or organize their own collection and recycling program. Producers' responsibility is determined in different ways. In some states it is determined based on their market share while in others it is based on return shares. In market share models, a producer's fee is based on its market share in a given year while, in a return share model, a producer's fee is calculated based on the collected end-of-life devices that carry their brand label. For this reason, labeling requirements are an important element of those E-waste policies that determine a producer's financial responsibility based on its return share. Seven of the states use a market share approach while another seven combine a return share with a market share approach. In the combined approaches, television manufacturers' responsibility is determined based on their market share while computer manufacturers' responsibility is based on their return share. Few states ask manufacturers either to pay an annual fee or to set up their own collection and recycling programs. Six of the states do not specify the ways in which the financial responsibility is determined since manufacturers are required to run their own collection and recycling programs.

A number of the state-level policies are comparatively strict since they prescribe certain ambition levels. They set minimum collection targets, for example, 80% of sold devices in the previous year in Minnesota or a collection target that is calculated based on a specified weight per capita as in the case of Vermont. Another element that makes some of the laws more ambitious than others is the specification of recycling standards. Some of the laws require that recyclers must comply with the R2 standard as, for example, in South Carolina or, more generally, that recyclers must obtain a third-party accredited certification as in the example of Pennsylvania. Fifteen of the subnational E-waste policies contain an explicit landfill ban for products in the respective law's scope. E-waste exports are only covered by a few state-level laws. For example, California requires that E-waste exports be notified and comply with OECD standards, while New Jersey restricts exports for disposal that pose a risk to public health and the environment.

24.6 Clusters of policy designs

Although each of the laws is unique and the overall E-waste policy approach is rather fragmented, different sets of state-level E-waste laws resemble each other more than others. This can be explained by the fact that they stem from the same initiative. Different actors attempted to play the role of policy entrepreneurs by drafting model rules and submitting their ideas to various state legislatures. Those policy entrepreneurs were company actors, independent experts as well as policy-makers.

One set of subnational E-waste laws has commonly been labeled Dell bills. They received this label because they can be traced back to a blueprint for an E-waste law that originally was developed by the computer manufacturer Dell. Some of those laws have partially identical wording, yet they also differ in some aspects. They are based on the same model that requires manufacturers to adopt and implement a recovery plan that is free of charge to consumers. E-waste collection can be conducted through various means, including mail-back programs and collection events, which are relatively low in infrastructure investment costs. Those tend to be the laws that do not include an approach to determining a manufacturer's financial responsibility. The laws do not prescribe performance standards such as collection targets and recycling standards. Overall, the requirements are relatively light. Texas, North Carolina, Virginia, West Virginia, Oklahoma, Missouri, Hawaii, Michigan, and South Carolina adopted a variant of the Dell bill.

Another set of state-level laws that resemble each other can be found in the Northeastern United States. These laws are based on a model E-waste law that was developed in the context of the Northeast Regional Electronics Management Project, an initiative by the Council of State Governments' Eastern Regional Conference and the Northeast Recycling Council. New York, Vermont and New Jersey adopted similar E-waste laws that introduce comparatively strict requirements. Manufacturers must register, pay for collection and recycling of their products, and label products with their brand. The responsible department defines collection and recycling goals, as well as performance standards. Retailers may only sell labeled products of registered manufacturers and provide information to consumers.

In the country's Northwest, Washington State and Oregon worked closely together and adopted similar laws that also have comparatively strict requirements. In both systems manufacturers must register and participate either in a standard recovery plan or in an approved independent recovery plan. They must label their products with their brand name since the producer responsibility in the standard recovery plan is based on return shares. Collection services must be provided in every county and town with 10,000 or more inhabitants. Collectors and recyclers must register and follow guidelines for environmentally sound management that are issued by the responsible department. Retailers must provide information about E-waste recycling to consumers.

In the Midwestern United States another cluster of similar E-waste laws was adopted that can be traced back to the Midwest Regional Electronic Waste Recycling Policy Initiative. Indiana, Illinois, Wisconsin, and Minnesota adopted E-waste laws that are relatively strict. Manufacturers must register, join, or implement a recycling plan that is free of charge for consumers, provide consumer information, and label their products with their brand. The laws set recycling targets and retailers may only sell labeled products by registered manufacturers and inform consumers about E-waste recycling. Collectors and recyclers must register and comply with specified standards.

Regardless of the different clusters of E-waste policies, none of them is an exact copy of another. Some states initially participated in regional initiatives but eventually adopted a different type of E-waste law. One example is Michigan, which initially participated in the Midwest Regional Electronic Waste Recycling Policy Initiative but eventually adopted a variant of the Dell bill. The political dynamics in the policy-making process can explain the shift.

24.7 Conclusions

The overview of US E-waste policy provided in this chapter highlights its complex and fragmented nature. The United States is split in half, with 25 states filling the federal void of near-absent E-waste provisions while the other 25 states have not taken action. In those states voluntary programs may exist but no binding rules that would level the playing field among manufacturers. But also among those states that have adopted E-waste policy divergence can be noted with, for example, the so-called Dell bills imposing much lighter requirements than, for example, some of the Northeastern or Northwestern states. Regardless of their divergences, almost all state-level E-waste laws cover a very limited product scope of televisions and computers. New York stands out with a law that spans the most ambitious scope, including products as diverse as fax machines, music players, digital converter boxes, video game consoles, and small-scale servers in both business-to-consumers and business-to-business transactions.

A subnational E-waste policy wave washed over the United States in 2006−11. Yet, no additional E-waste developments have unfolded since 2011. A number of those states that had E-waste policies already in place altered their laws but no new laws were adopted, with the exception of the 2014 District of Columbia law. The 50−50 division among US states seems to have been cemented, set to prevail for the foreseeable future.

For companies, this means that the difficult-to-navigate patchwork of E-waste provisions will persist. Companies that are active on a national scale are required to monitor the various policy developments and determine their compliance obligations on a state-by-state basis. While these compliance challenges could have softened some manufacturers' stance on and opposition to possible federal E-waste policy, they certainly have not triggered a strong push. Divergences in industry positions persist, weakening any possible legislative initiative, which in any case has been extremely unlikely during the Trump administration. A great degree of issue salience, political prioritization, and leadership would be required to successfully shepherd a legislative proposal through the process.

References

Biedenkopf, K., 2011. Policy Recycling? The External Effects of EU Environmental Legislation on the United States. PhD dissertation defended at the Vrije Universiteit Brussel, Brussels.

Biedenkopf, K., 2013. The multilevel dynamics of EU and U.S. environmental policy: a case study of electronic waste. In: Echinard, Y., et al., (Eds.), L'Union Européenne et Les États-Unis. Processus, Politiques et Projets. Larcier, Brussels, pp. 189−210.

Biedenkopf, K., 2017. Gubernatorial entrepreneurship and U.S. federal-state interaction: the case of subnational regional greenhouse gas emissions trading. Environ. Plan. C: Polit. Space 35 (8), 1378–1400.

Carlson, A.E., 2008. California Motor Vehicle Standards and Federalism: Lessons for the European Union. Institute of Governmental Studies, University of California, Berkeley, Working Paper, 2008/4.

Davis, G.A., et al., 1997. Extended Product Responsibility: A New Principle for Product-Oriented Pollution Prevention. Prepared under Cooperative Agreement with the United States Environmental Protection Agency Office of Solid Waste, Washington, DC.

Kang, H.-Y., Schoenung, J.M., 2005. Electronic waste recycling: a review of U.S. infrastructure and technology options. Resour. Conserv. Recycl. 45 (4), 368–400.

President's Council on Sustainable Development, 1997. Proceedings of the Workshop on Extended Product Responsibility. Washington, DC: Prepared by Eastern Research Group, Inc.

Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31 (1), 45–58.

US Environmental Protection Agency, 2008a. Electronic Waste Management in the United States. Approach 1. EPA 530-R-08-009. Washington, DC.

US Environmental Protection Agency, 2008b. Fact Sheet: Management of Electronic Waste in the United States. Available at: <http://www.epa.gov/waste/conserve/materials/ecycling/manage.htm> (accessed 05.05.11.).

US Government Accountability Office, 2008. Electronic Waste: EPA Needs to Better Control Harmful U.S. Exports Through Stronger Enforcement and More Comprehensive Regulation. GAO-08-1044. Washington, DC.

US Government Accountability Office, 2010. Electronic Waste: Considerations for Promoting Environmentally Sound Reuse and Recycling. GAO-10-626. Washington, DC.

Vogel, D., 2018. California Greenin': How the Golden State Became an Environmental Leader. Princeton University Press, Princeton.

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HANDBOOK OF ELECTRONIC WASTE MANAGEMENT

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- E-waste handling solutions for both urban and rural contexts
- Case studies illustrate the implementation of innovative E-waste treatment technologies

The proliferation of E-waste and its inappropriate treatment and disposal have grown to 44.7 million metric tons annually (according to the United Nations), with the majority ending up in landfills or being incinerated. With the bulk of this E-waste being exported to developing countries, they are now at the forefront of creating innovative best practice for handling, recycling, and disposal. This book explains the latest E-waste treatment technologies and management methods developed in a wide range of countries. Selected case studies are included to illustrate project implementation.

ISBN 978-0-12-817030-4

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An imprint of Elsevier
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