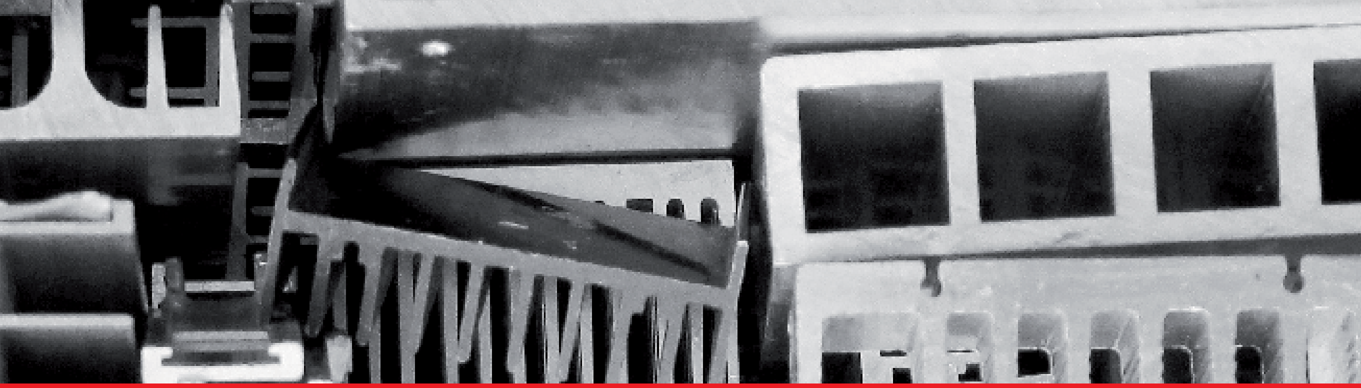

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E-Waste in Transition

From Pollution to Resource

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E-WASTE IN TRANSITION - FROM POLLUTION TO RESOURCE

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http://dx.doi.org/10.5772/60487
Edited by Florin-Constantin Mihai

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First published in Croatia, 2016 by INTECH d.o.o.
eBook (PDF) Published by IN TECH d.o.o.
Place and year of publication of eBook (PDF): Rijeka, 2019.
IntechOpen is the global imprint of IN TECH d.o.o.
Printed in Croatia

Legal deposit, Croatia: National and University Library in Zagreb

Additional hard and PDF copies can be obtained from orders@intechopen.com

E-Waste in Transition - From Pollution to Resource
Edited by Florin-Constantin Mihai

p. cm.

Print ISBN 978-953-51-2499-3

Online ISBN 978-953-51-2500-6

eBook (PDF) ISBN 978-953-51-6660-3

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Meet the editor

Dr. Florin-Constantin Mihai holds a PhD degree in Geography from the Department of Geography, " Alexandru Ioan Cuza" University of Iași (Romania), and BSc and MSc degrees in Environmental Science. He published 40 peer-reviewed articles and conference proceedings on various topics regarding the environmental and waste management issues at local, regional, national, and EU levels. He promotes the geography of waste as a new complementary approach in the environmental and social sciences. His research aims to develop new methods and waste indicators in order to assess the key waste management issues across various geographical scales, particularly in transition and developing countries.

Contents

Preface

Countries, regions, and cities are facing real challenges in handling the increasing amounts of e-waste due to the consumer society and globalization process. This waste stream needs special attention due to the toxic potential of electrical components. Separate collection schemes must be implemented in the majority of countries in order to avoid the landfill of e-waste. Frequently, such wastes are mixed-collected with municipal fraction further sent to dumps or landfills without any prior recovery or recycling process. On the other hand, the e-wastes are a source of valuable elements for industry or recycling materials (e.g., plastics) which can be further processed. This book reveals the both sides of e-waste fraction as pollution source due to the lack or improper waste management practices, particularly in transition and developing countries, and as a resource for the industrial sector under the circular economy paradigm. The book covers the key issues concerning e-waste management, such as the legal framework, pollution and public health, e-waste flows, exports and imports, rudimentary dismantling process, recovery and recycling options, bad and best practices in the field, and global interactions.

The book has an *introductory chapter and six full chapters* with a wide geographical coverage, such as EU, China, India, and Mexico. Global interconnections are obvious, reflecting complex geographies in e-waste traders.

The introductory chapter reveals a critical overview of e-waste management issues which point out the transition stage at the global scale. The chapter highlights the specific challenges in developing and developed countries with significant impacts on the environment and the gaps, interactions, and routes toward a recycling society.

The table of contents is organized taking into consideration the transition stage of e-waste from pollution to resource as the book title suggests.

The first chapter presents an overview of toxic elements found in WEEE stream. These are classified as follows: primary contaminants as constituents are used in the manufacture of EEE products, secondary contaminants as products or residues generated after the processing of e-waste during the recovery of valuable materials, and tertiary contaminants as reagents used during the processing of e-waste. The impact of processing e-waste is further examined on several environmental factors (soil and vegetation, air, water) and human health.

The second chapter examines public health and environmental pollution issues in a major e-waste dismantling region in China. The effects of persistent organic pollutants (POPs) are further analyzed with detailed data, revealing the critical contamination of soil, crops, fish, and livestock with inherent impacts on the human body (fat, blood, breast milk) of children, women, and occupational population.

The third chapter analyzes the e-waste management issues in a global context based on the literature review across various stages such as generation, collection, treatment, and disposal. A comparative analysis of developed countries (e.g., EU, USA, Japan,) and emerging economies (e.g., Brazil, China, India) is performed. Furthermore, the best waste management practices are highlighted across several countries, and the global illegal e-waste trade is examined.

The fourth chapter points out the current challenges of a Latin America country in e-waste management sector. The chapter provides a depth analysis concerning the e-waste regulation framework in an international context and the actors involved in the field. The gaps and the first steps toward a sustainable e-waste management in Mexico are further analyzed.

The fifth chapter focuses on the recovery side of e-waste in emerging economies such as India. The global context of e-waste management and recycling potential are discussed. The chapter describes the e-waste recycling technologies available, and it highlights the current practices in India. The chapter provides a depth analysis of metal recovery issues from e-waste.

The sixth chapter focuses on the reuse side of secondary raw materials such as plastics. The chapter examines the EU legal framework and several policy instruments which may improve the recycling and reuse of plastics with a focus on a Germany case. A new strategy is proposed based on a holistic approach.

The book covers the theoretical and empirical backgrounds of e-waste management sector in a global perspective. Current major issues are examined, and future opportunities are revealed in this field. The book has a wide coverage interests among academics, professionals, international and regional organizations, authorities, and members of civil society.

Hopefully, the transitions toward a sustainable e-waste management practice will emerge in the following decade at the global scale.

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Chapter 1

E-waste Management as a Global Challenge (Introductory Chapter)

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/64596

1. E-Waste Management in transition and developing countries

Waste Electrical and Electronic Equipment management (E-waste or WEEE) is a crucial issue in the solid waste management sector with global interconnections between well-developed, transitional and developing countries. Consumption society and addiction to technology dictate the daily life in high and middle-income countries where population consumes large amounts of EEE products (electrical and electronic equipment) which sooner become e-waste. This fraction is a fast-growing waste stream which needs special treatment and management due to the toxic potential of public health and environment. On the other hand, the e-waste contains valuable materials which may be recovered (precious metals, Cu) reused and recycled (metals, plastics) by various industries mitigating the consumption of natural resources.

The new challenge of e-waste management system is to shift the paradigm from a toxic pollution source to a viable resource in the context of sustainable development. Waste hierarchy concept focuses on waste prevention and 3R policy (reduce, reuse, recycle) and give less attention to landfills. The "end of waste" criteria under Waste Framework Directive (Directive 2008/98/EC on waste) specify when certain waste ceases to be a waste and it obtains a status of a product (or a secondary raw material). EU policy promotes the circular economy where wastes are regarded as resources and set up the directions toward a recycling society. E-waste is a special waste stream with proper legislation.

Furthermore, a new WEEE Directive 2012/19/EU became effective on 14 February 2014 due to the importance of this waste flow across the EU. The Member States are required to collect 45 % of the EEE put on the market (in the three preceding years in that Member State) by 2016. This is a more suitable approach considering the flat collection rate for private households until 31 December 2015 (4 kg.inhab.yr^{-1}) of the previous Directive which did not take into consideration the socioeconomic disparities across EU-27. In this context, new EU members

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like Romania cannot yet comply such collection rate despite recent improvements in this sector due to a lower purchasing power and a greater lifespan of EEE products, particularly in rural areas.

Developed countries tend not to recycle e-waste due to the lack of facilities, high labor costs, and tough environmental regulations and this waste stream is disposed in landfills or exported to developing countries [1]. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal prohibits the export of toxic and hazardous waste to poor countries and the national waste regulations of developed countries restrict the landfill of waste in order to promote the recycling and recovery options.

Take-back systems, special collection points for e-waste stream, ad-hoc e-waste collection campaigns, recycling centers, industrial technology may divert the e-waste disposal from landfills in developed and transitional countries and the e-waste collection performed by informal sector in case of developing countries. The EU promotes the Extended producer responsibility (EPR) which moves the responsibility of local authorities to EEE producers and importers regarding e-waste management and the achieving targets on collection,recycling, and recovery. The implementation of this policy has different results across the Europe [2]. However, large quantities of e-waste are legally or illegally exported from high-income countries to emerging economies and low-income countries, creating serious health and environmental threats in the latter case.

National regulations which permit, ban or ignore the electronic and e-waste export/imports practices vary from one country to another, except EU which has a more homogeneous legislation in the field. Several developing countries banned the imports of e-waste (Nigeria, Cambodia, China, Vietnam, Malaysia, Pakistan) others have not ratified this issue (Benin, Cote D'Ivoire, Kenya, Liberia, Senegal, Uganda, South Africa, India) and some of them permitted such imports (Ghana) with special approvals (Thailand, Philipines) according to Jinhui et al. [3]. Transboundary shipment of obsolete EEE and e-waste is a complex issue at regional and global scale and it is difficult to monitor the illegal activities. India, China, Philippines, Hong Kong, Indonesia, Sri Lanka, Pakistan, Bangladesh, Malaysia,Vietnam, and Nigeria are among the favorite destinations for e-waste and significant amounts of e-waste containing hazardous materials can be seen dumped in open lands and waterways [4]. However, e-waste flows have more complicated patterns than the notorious route Global North to Global South where intra-regional trades (e.g. Canada - USA -Mexico, China- Bangladesh) may play a more significant role in present due to the Basel Convention [5]. Secondly, there is no clear distinction between e-waste and second-hand EEE flows in electronic trades between countries.

Major concerns are that many shipments of e-waste are disguised as second hand goods or safe disposal of waste imported in developing countries is either dumped or unsafely recycled in reality [6]. Other key issues are to know the share of e-waste source (domestically vs imported) across formal and informal recycling sites, data about regional and local e-waste collection schemes, the role of the informal sector in this matter.

Dismantling areas of e-waste from Asian or African countries are heavily polluted with persistent organic pollutants (POPs) listed by *Stockholm Convention* such as: polychlorinated dibenzodioxins and furans (PCDD/Fs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) or other toxic substances as follows: polychlorinated and polybrominated dioxins and furans (PXDD/Fs), polycyclic aromatic hydrocarbons (PAHs), heavy metals (cadmium, mercury, lead, chromium). E-wastes contain toxic components such as batteries, brominated flame retardants (BFRs), asbestos waste and components which contain asbestos, and obsolete EEE (e.g. refrigerators) may contain gasses that are ozone depleting such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs).

Such toxic components are required to be removed prior to any treatment or disposal under EU Directive. Specific regulations addressed to e-waste management issues must be further developed and enforced by big players of e-waste market such as USA, EU, China, India, Japan,South Korea, Australia. The lack of legislation, the weak administration, corruption, smuggling practices, lack of a formal waste management system, poor living standards expose the developing countries to primitive recycling activities and to e-waste dumping and burning pollution. China is a major e-waste dismantling area with a developed informal sector involved in rudimentary recycling activities such burning, melting and acid bath in order to recover valuable metals and materials for industry and to assure a regular income despite serious health risks. A comprehensive review focusing on heavy metals reveals the scale of this environmental pollution in air, dust, soil, sediments, plants, particularly in the largest e-waste recycling sites such as Taizhou, Guiyu, and Longtang with severe implications on public health [7]. India is facing similar issues due to low-tech of e-waste recycling activities provided by the informal sector [8].

Recycling companies and informal sector exploit the poor labor force in dismantling areas of developing countries which perform their work in poor conditions, manually, frequently without any protection measures. Such activities are also performed by individuals at the household level as the sole income source.

E-waste dump sites are "hot spots" of heavily environmental pollution usually located in the proximity of residential or agricultural lands. Such sites discharge the leachates and toxic liquids into rivers,ponds, groundwater and soil pollution contaminates the crops, livestock and finally its consumers. Open burning sites of e-waste are severely air pollution sources with heavy metals, dioxins, furans, particulate matter, hydrocarbons ashes including PAH's in the surroundings.

Informal sector plays a crucial role in the waste collection and recycling activities across developing countries. The key issue is to improve the dismantling activities in terms of decent safety, health and environmental standards, to develop the formal sector which hires poor population susceptible to such rudimentary practices supported by proper regulations as shown in figure 1. An integrated approach at global scale may consider a combination of best manual pre-processing activities performed at local scale in developing countries with high-tech end-processing activities of developed countries [9]. Separate collection of e-waste must be improved in transition countries where mixed municipal waste (which contain e-waste) are disposed in landfills with significant losses in terms of recovery and recycling and to increase a rigorous control EEEE and waste exports.

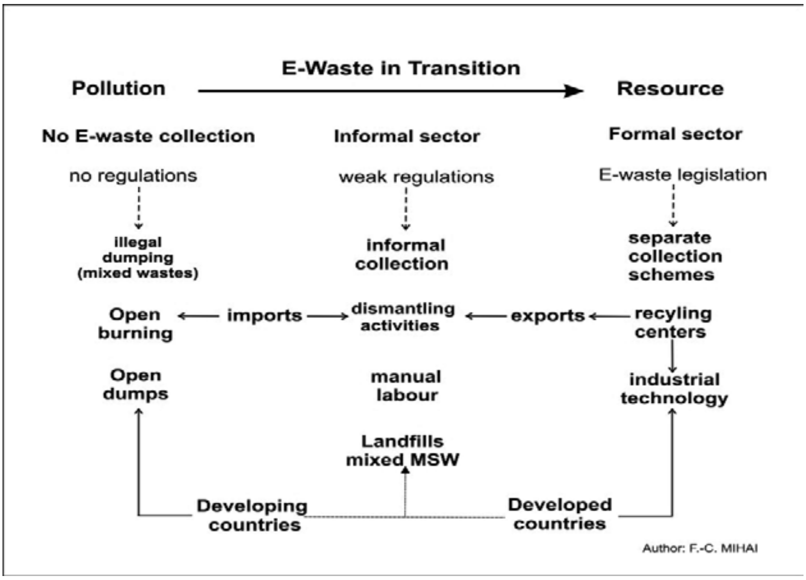

Figure 1. E-waste management interactions in a transitional stage

2. E-waste management in developed countries

WEEE management is carried out worldwide through different approaches. The most holistic national regulation system is the EU directive as it affects the whole life cycle starting from the design phase of an EEE to its end of life management. The recent last update (2012) has posed new targets for recycling as well as for take-back collection schemes: see for example the insertion of "one-to-zero" – distributors have to take back a used product without a purchase of a new one- option for collecting small WEEE. Japan has developed a legislative system similar to the EU [10]; these two systems are quite similar in several common points [11]. A different legislative approach is applied in the US, where there is a lack of a common federal legislation about e-waste management: each state has defined its own system with specific targets and organizations [12-13]. One attempt towards a unified approach has been introduced in 2011 with the so-called 'National Strategy on Electronics Stewardship' [14]: it aims to point out federal actions to improve the design of electronic products and enhance management of used or discarded electronics [15]. Although a common legislative standard could not be outlined worldwide, WEEE management systems applied have common features as well as differences based on the specific legislative approach. One common basic concept is the EPR principle [16]: the EU legislation is heavily based on this approach as collective and individual take back systems shall be applied by producers in managing all phases in the product's life cycle, including also the post-consumer stage [17-19]. The EPR principle is also well established in Japan: manufacturers and importers must organize the take-back system for EEE. Recently, the EPR principle has been also applied in Canada to define new legislation about WEEE [20].

The adoption proposed in the US focuses mainly on the design phase: several incentives and specific programs are developed for supporting manufacturers in designing greener electronic products: the aim is to prevent and reduce these waste flows. Prevention usually represents the most efficient policy to reduce environmental and social impacts arising from wastes: the two options, mostly adopted for WEEE are eco-design strategies and increasing product lifespan [15]. One example belonging to the first category is the Electronic Product Environmental Assessment Tool (EPEAT), defining performance criteria for designing greener electronic products. It is also used as a procurement tool created to help institutional purchasers in the public and private sectors evaluate, compare, and select desktop computers, notebooks, and monitors based on their environmental attributes [21]. The adoption of the EPR principle influences also the cost allocation model for financing the take-back collection system and, also the recycling and disposal processes [22-23]. In Japan, home consumers pay a fee to cover a portion of the recycling and transportation costs; this option could be also applied under the EU directive. By analyzing the second category of intervention – i.e. increasing the life span of an EEE – one possible option is its re-use: positive (mainly due to resource conservation in the production phase) as well as negative (mainly due to increased energy consumption during the use phase) impacts of re-using EEE [24]. The global efficiency of two options – i.e. product re-use versus lease - in Japan was examined by Tasaki et al. [25]. An innovative organizational model for supporting EEE second- hand markets in the U.S was proposed by was proposed by Kahhat et al., [12].

Differences start from the waste flows included in the WEEE legislation: the EU directive is the widest legislation on WEEE as it includes electronic products (e.g. PC, monitors, Tv, etc.), but also household appliances, e.g. brown and white goods. A similar legislative approach has been developed by Japan, which also includes large and small household appliance in its national e-waste legislation. Differently, only electronic products are currently included in e-waste initiatives in the US and in Canada. There is also a restricted use of hazardous substances in EEE products according to Restriction on Hazardous Substances Directive or RoHS recast Directive 2011/65/EU which promotes the alternative environmentally friendly materials in the production and design of EEE products across the EU. Another point of differentiation between national systems is the adoption the Basel Convention (UNEP, 1992) on the control of transboundary movements of hazardous wastes (such as e-waste and used electronics): it affects the interconnections between single national systems to international waste transhipments [26-27]. The adoption of this convention forces stricter rules about international transshipment of these waste flows. National systems where the Basel convention is active are "interconnected" as this convention defines strict rules for international waste transhipments. This topic is a critical issue in WEEE management as it involves environmental, economic but also social impacts.

3. Conclusions

The e-waste management sector is in a full transitional stage at global scale. Despite the major disparities between high-income, transition and developing countries the e-waste management is a global environmental concern. Governments and local authorities across the globe face serious challenges in order to collect, treat, recycle and dispose this fast growing waste stream in a safety manner for the environment and human health. The global interconnections between developed and developing countries, national and regional analyses are further revealed in the book.

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Chapter 2

Environmental Impact of Processing Electronic Waste – Key Issues and Challenges

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V. Sahajwalla

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/64139

Abstract

Extensive utilization of electric and electronic equipment in a wide range of applications has resulted in the generation of huge volumes of electronic waste (e-waste) globally. Highly complex e-waste can contain metals, polymers and ceramics along with several hazardous and toxic constituents. There are presently no standard approaches for handling, dismantling, and the processing of e-waste to recover valuable resources. Inappropriate and unsafe practices produce additional hazardous compounds and highly toxic emissions as well. This chapter presents an overview of the environmental impact of processing e-waste with specific focus on toxic elements present initially in a variety of e-waste as well as hazardous compounds generated during e-waste processing. Hazardous constituents/ and contaminants were classified in three categories: primary contaminants, secondary contaminants, and tertiary contaminants. Primary contaminants represent hazardous substances present initially within various types of e-waste; these include heavy metals such as lead, mercury, nickel and cadmium, flame retardants presents in polymers etc. Secondary contaminants such as spent acids, volatile/toxic compounds, PAHs are the by-products or waste residues produced after inappropriate processing of e-waste and the tertiary contaminants include leftover reagents or compounds used during processing. A detailed report is presented on the environmental impact of processing e-waste and the detrimental impact on soil contamination, vegetation degradation, water and air quality along with implications for human health. Challenges and opportunities associated with appropriate e-waste management are also discussed.

Keywords: E-waste, contaminants, hazards, environmental issues, recycling

1. Introduction

Extensive use of electric and electronic equipment (EEE) for everyday needs in a wide range of applications has led to the generation of huge volumes of electronic waste (e-waste) all

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around the world. Some of the key factors responsible for the global generation of e-waste are the programmed obsolescence of EEE, rapid advances in technology and the insatiable desire for smaller/faster/up to date devices. While the electronic waste has been accumulating over several decades, keen awareness regarding their environmental impact and issues associated with e-waste management has become highlighted in recent years. Currently, only a small fraction of e-waste is being treated or recycled appropriately; most of it is either dumped or disposed of in landfills.

A wide range of substances are present in waste printed circuit boards (PCBs), the central processing unit of electronic devices. These are present as a highly complex mixture of ceramics, metals and polymers; some obsolete electronic equipment can contain more than 1000 different compounds [1]. This heterogeneous composition can include valuable constituents as well as hazardous and toxic elements or compounds. Due to inherent complexity of these devices, there is presently no standard, well-established process to treat a wide variety of e-waste. Current processing approaches are focused mainly on the recovery of copper and precious metals; the recovery of these materials is economically attractive due to their significant quantities present in e-waste as compared to corresponding concentrations in respective ores [2]. Some of the methods used to achieve these goals include open burning, manual dismantling/disassembly, mechanical processing, pyro-metallurgy, hydrometallurgy etc. Wherever the operation of these processes is inadequate or unsafe, it can lead to the generation of additional hazardous compounds, and may also release highly toxic emissions.

A significant proportion of e-waste is currently recycled using either hydrometallurgy or pyrometallurgy. Dismantling/disassembly or mechanical sorting is generally carried out prior to the metallurgical processes to improve the recovery of materials. Mechanical processing can also be used by itself to recover materials from obsolete EEE. Some of the techniques used to separate metals and non-metals include crushing, grinding, electrostatics, gravity, shape, density-based and magnetic separation [3]. Hydrometallurgical recycling processes generally consist of leaching/dissolution of the material, a purification/concentration process and electrowinning, chemical reduction or crystallization processes for the recovery of metals. In the concentration step, methods such as precipitation, cementation, solvent extraction, adsorption, ion exchange and activated carbon have been employed [4].

The pyro-metallurgical approach to recover metals from e-waste consists of melting the material along with other substances or by itself to enhance slag formation and to concentrate and purify target metals. The steps used include smelting, converting, refining and electro refining [5]. One of the latest techniques being used to recycle e-waste is bio-metallurgy that consists of the utilization of micro-organisms to improve the leaching of metals. However, this approach has only been used on a research scale to date.

This chapter presents a brief overview of the environmental impact of processing e-waste. It focuses on toxic elements present initially in a range of e-waste as well as on the characterization of hazardous compounds generated during their processing. A detailed investigation on the composition of different types of e-waste such as large & small household appliances, IT and telecommunications equipment, light equipment, among others, is presented with an aim to provide a characterization of hazardous materials present in electronic equipment.

We also report on the in-situ generation of hazardous and toxic compounds from the reaction of base constituents present in several types of e-waste upon exposure to a range of operating conditions in various processing techniques. A comprehensive understanding of their behavior is essential to create recycling technologies that can recover valuable materials in an environmentally sustainable manner. It is also important to prevent the use of unsafe processing approaches and techniques that may create pollution and damage the environment in several different ways.

Hazardous compounds present in waste electronics can get released when these end-of-life equipment are dumped, disposed of or processed inappropriately. Such constituents have been classified in three groups based on the nature of the pollutant: primary contaminants, secondary contaminants and tertiary contaminants. A detailed report on various contaminants is presented in this section.

2. Primary contaminants

Primary contaminants are constituents present initially in e-waste that may have hazardous and/or a toxic nature. These constituents are used in the manufacture of electric and electronic equipment for their special intrinsic characteristics. Some of these hazardous constituents are listed below:

2.1. Metallic constituents

A wide variety of metals are present in electronic waste. Some of these can be hazardous when disposed of inappropriately. Key metallic constituents present in e-waste have been summarized below:

Lead

Lead metal is soft, ductile, malleable and flexible; it has high electrical conductivity and thermal expansion. As it also has a low melting point, hardness and strength, it is commonly used in a range of alloys. Some of the most common alloying elements with lead are tin, arsenic, antimony and calcium [6]. In electronic equipment, Lead is present in cathode ray tubes (CRTs), fluorescent tubes, found as solder in printed circuit boards, as well as in liquid crystal displays LCDs and batteries [7].

One of the main uses of lead in EEE is in cathode ray tubes in TVs and computers monitors. The purpose of lead in CRTs is to protect from UV and X-rays generated in the operation of CRTs. CRTs are composed of a front panel or screen, a funnel or rear part of CRTs, and the neck. The front panel contains up to 3% Pb, while the funnel contains up to ~25 wt% PbO. The neck is also made of PbO [8]. In recent years, CRTs have been replaced by LCDs, plasma or LED displays.

However, old CRTs are still being used in developing and third-world countries, and these still form a part of the old electronic waste. Waste CRTs are a major concern due to their high lead concentrations and its toxic nature. The presence of strontium, cadmium and barium, among other metals make their recycling highly challenging and hazardous. On the other hand, printed circuit boards are one of the main constituents of EEE and most of old devices contain Pb-Sn solder. Solder is used to connect various electronic components on the surface of the printed circuit board. In recent years, the use of lead-free solders has become quite prevalent. However, most of the obsolete printed circuit boards contain hazardous lead and pose a challenge.

Tin

Tin improves the hardness and strength when used as an alloying element. This metal is generally present in EEE as a tin-lead alloy. These alloys are employed for their good melting, wetting and bonding properties with metals such as copper and steel. As lead has poor wettability with these metals, the addition of Tin gives the alloy fluidity, reduces brittleness and gives a finer structure [6]. Tin is present in EEE in printed circuit boards solders and in LCDs.

Antimony

Generally present in tin-lead alloys, the addition of Antimony is used to give additional hardness and strength in these alloys. It also makes these alloys more resistant to compressive impact and minimizes contraction upon cooling. About 2 to 5% Sb is usually used in Pb-Sn-Sb alloys [6]. Antimony, found predominantly in printed circuit boards, is known to be toxic and highly volatile [9].

Mercury

Mercury is in a molten state at room temperature, and has a tendency to volatilize due to its high vapor pressure. It can form several compounds, and is known to be highly toxic [10]. Mercury is present mainly in mercury lamps and also found in batteries, LCDs, switches, thermostats and sensors. The function of mercury in lightning equipment is to transform electrical energy into radiant energy in the UV range. Phosphor compounds then convert radiant energy into the visible spectrum [11]. Mercury lamps include fluorescent tubes, compact fluorescent lamps (CFLs), mercury vapor, sodium vapor, metal multi-vapors and mixed lamps.

The concentration of mercury in various lamps depends on the type, manufacturer and the year of manufacturing [12]. With increasingly strict regulations, the mercury content in lighting equipment has decreased considerably over time. Fluorescent tubes have been increasingly replaced by CFLs; these contain much lower levels of Hg as low as ~2.7 mg Hg per lamp [13]. However, a typical discarded fluorescent lamp can contain around 20 mg Hg on average [11].

With some manufacturers still using obsolete technologies and during the disposal of old fluorescent tubes, or mercury can get released during recycling. These lamps are likely to break when disposed of or handled inappropriately. The release of mercury depends on the quantity contained within the lamp and the temperature. The form of mercury released also depends on several factors, such as the type and age of the lamp, and whether the lamp was operated continuously or intermittently. However, the exposure to mercury in any form is known to be toxic to humans [11].

Nickel

Nickel easily forms alloys with several metals such as copper, chromium and cadmium [6]. Nickel is predominantly found in Ni-Cd batteries as a hydroxide. This metal is also present in printed circuit boards in small amounts [14]. Ni-Cd batteries generally come in two forms: sealed or open (vented). Vented Ni-Cd batteries are generally used for industrial applications, such as for power sources in commercial applications as well as in aircraft and communications applications [6].

Sealed batteries are manufactured in button, rectangular and cylindrical forms, and are used in small household appliances, cordless tools, radios, calculators, video cameras and especially in mobile phones [15, 16]. These batteries have increasingly been replaced by nickel-metal hydride, lithium-ion and lithium-polymer batteries [17]. However, Ni-Cd batteries were used extensively over the last few decades; therefore a significant amount of spent Ni-Cd batteries are still present in e-waste worldwide.

Cadmium

Cadmium is a silvery-white, malleable and soft metal. It is used extensively in the electronics industry: ~45% of Cd is used in batteries, while 20% is used in pigments and 14% in stabilizers [6]. It is generally found as a compound in batteries, toners and cartridges [7]. This metal is also present in engineering plastics, printed circuit board solder, chip resistors, infrared detectors and semiconductors, and in the fluorescent powder coatings used in color CRTs [18]. It is present in Ni-Cd batteries as cadmium oxide. As a stabilizer in engineering plastics, it is found in the form of cadmium sulfides and cadmium salts. Various plastics can contain up to 100 mg/kg cadmium [19]. The main source of cadmium found in municipal solid waste is from NiCd batteries [20]. Due to the toxic nature of cadmium, toxic/hazardous fumes and dusts can form during waste processing and management, with serious detrimental influence on population health in surrounding areas.

Chromium

Chromium is usually used as an alloying element. One of its common applications is to prevent corrosion in steel, as it has excellent corrosion resistance properties [21]. Chromium is present in printed circuit boards, data tapes, floppy disks, pigments and polymers in the form of Cr_2O_3 pigment [7, 22]. It has a highly toxic nature, however the level of toxicity depends strongly on the valence of Chromium: Cr (0), Cr (III) and Cr (VI). Cr (VI) is considered to be 1000 times more toxic than Cr (III). However, exposure to high levels of Cr(III) can also affect the health of people living around recycling areas [23].

Copper

Copper is one of the most widely used metals in electric and electronic equipment due to its excellent conductive properties. It is the main metal present in printed circuit boards, cables, heat exchangers, among many other uses. Copper is commonly found linked with polymers.

In the informal sector, this metal is recovered through open burning and acid leaching. When combusted at low temperatures, it increases the risk of dioxin formation as well as of emissions of copper as particulate matter [24]. High exposure of copper can lead to the accumulation of excess metal into the body. This in turn can cause oxidative damage, and is known to be associated with metabolism issues and neurodegenerative changes [25].

Other metals

A number of other metals are also present in a variety of e-waste. A brief summary of these metals and potential hazards has been provided below:

Arsenic can be found in light equipment in small quantities. However As is known to be highly toxic, and exposure may lead to chronic diseases.

Barium is mainly present in CRTs. The panel of a glass CRT can contain up to 12% barium oxide and around 12% strontium oxide [18]. Ba is unstable in pure form, but can form toxic oxides when in contact with air. Even a short exposure to Ba can lead to serious health issues.

Zinc is used in the manufacture of printed circuit boards, LCDs, among others. Metals such as zinc and copper are persistent in the environment and have a tendency to accumulate in organs of the body. While these metals are essential for general health and wellbeing, excessive exposure during e-waste processing can lead to their accumulation in high levels in the human body and animals, leading to toxic and detrimental health effects [26].

Rare earth metals are mainly employed in the manufacture of CRTs, printed circuit boards, and also to improve thermal properties and toughness of alloys in batteries [27]. An exposure to rare earth metals has been to increase the risk of respiratory and lung related diseases, such as pneumoconiosis [28].

Other metals present on e-waste include americium, gallium, selenium and beryllium etc. These are generally present in ppm range. These elements are mainly found in smoke detectors, data tapes, semiconductors and rectifiers respectively. **Beryllium** is classified as a carcinogen as it can cause lung cancer, and can be inhaled as a dust, fume and/or mist. Short exposure may lead to several diseases. Exposure to **Selenium** is also hazardous as it may cause selenosis.

2.2. Organic pollutants

A range of organic pollutants are either present in-situ in e-waste or may get produced during its processing or handling. Key pollutants are described below:

Polychlorinated biphenyls (PCBs)

These belong to the family of poly-halogenated aromatic hydrocarbons (PHAHs) [29]. These organic compounds are classified as persistent organic pollutants (POPs) along with other 11 groups of chemicals, included in the Stockholm Convention. POPs are toxic, highly stable, resistant to degradation, lipophilic and bio-accumulative in organisms. These compounds can be transported through air, water as well as through migratory species. These not only can accumulate in human bodies, but also in fauna, terrestrial and aquatic ecosystems [30].

Polychlorinated biphenyls are present in transformers and capacitors as coolants, lubricants and dielectrics fluids due to their chemical inertness and high temperature stability. These can also be found as hydraulic and heat exchange fluids, such as in condensers [31-33]. Being soluble in fat, these can accumulate in humans and fauna, provoking intoxication [34]. These compounds can either be emitted or produced during the processing or handling of e-waste [35]. Being highly toxic, the use of these POPs was banned in the 1980s. However, these may still be present in old accumulated e-waste or could get formed during their processing. Therefore there still is a risk of exposure to these compounds during the recycling of obsolete e-waste.

Flame retardants

Flame retardants are compounds present in plastics due to their ability to resist temperatures high enough for a device and/or appliance to work. These are used to reduce the flammability of combustible materials such as plastics. Flame retardants are found in the form of hazardous solids. Most widely used retardants are brominated flame retardants (BFRs), which belong to the family of PHAHs [29]. Some of these have been classified as POPs due to their environmental persistence and toxicity [30]. BFRs have been used extensively due to their effectiveness and low cost.

Further details on four brominated flame retardants, namely polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol-A (TBBPA), polybrominated biphenyls (PBBs), and hexabromocyclododecane (HBCD) are provided below.

Polybrominated diphenyl ethers (PBDEs): Large amounts of PBDEs are used in the electronics industry. These have physicochemical properties similar to polychlorinated biphenyls [31]. These have low reactivity, high hydrophobicity, and as other POPs, are persistent in the environment, toxic and bio-accumulative. As these are not chemically bonded to the polymer (reactive component), there is a strong possibility for them to get released through leaching or volatilization. Even though these are a more recent development in the field, these are still highly toxic and harmful to humans. Studies have shown that PBDEs are distributed in the atmosphere, sediments as well as found in human milk [36].

Tetrabromobisphenol-A (TBBPA) is one of the most commonly used BFRs. It is used as a reactive component in epoxy resins as a flame retardant in printed circuit boards, and also in several types of polymers, such as HIPS, ABS and PET. However, this compound can get released to the environment when it is present as a reactive component or an additive component (not chemically bonded to the polymer). While TBBPA can get released into the air, soil and sediment, due to poor solubility in water, it is generally not found in water samples [37].

Polybrominated biphenyls (PBBs) are chemicals used as flame retardants in a wide variety of plastic products, such as monitors and TVs. Used as an additive component in polymers these can easily get released to the environment. Similar to other POPs, PBBs have low vapor pressure, low water solubility, and are stable and persistent in the environment and bio-accumulative due to their lipophilic properties [38]. PBBs particles mainly persist in the atmosphere, and can also be absorbed in the soil and sediments. These can be released during combustion processes. Consequences of exposure to PBBs have been detailed in later sections.

Hexabromocyclododecane (HBCD) is generally used as an additive flame retardant in thermoplastics. As these are not chemically bonded to the polymer, HBCDs are able to volatilize and leach easily. As a POP, these are highly lipophilic and can bio-accumulate. These also have low water solubility [37].

Refrigerant gases

Refrigerant gases are mainly present in fridges, air conditioners and freezers. Three types of compounds generally used for refrigeration are: chlorofluorocarbons (CFCs), hydro-chloro-fluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). Also known as fluorinated refrigerants, these are hazardous in nature. As these exist in a gaseous state at room temperature and have low water solubility, these preferentially get released into the atmosphere and have long enough lifetimes to mix well. Emissions reported here only refer to the end of life equipment being disposed of. The most harmful compounds that can be released are CFC-12, HCFC-22 and HFC-134a, which are abundant in the atmosphere. However, they have a deleterious influence on the ozone layer and have been known to contribute to the global greenhouse effect [39].

The compounds containing chlorine have been known to contribute to ozone depletion since 1930s when CFC-12 was first developed as a refrigerant. CFCs are highly stable and easy to release to the atmosphere. The use of HCFC-22 started in 1960s, resulting in increasing emissions to the atmosphere. HCFCs are less stable than CFCs, and are called transitional substances. There has been a gradual replacement of CFCs and HCFCs with HFCs as these do not contain chlorine. HFCs are called substitution substances [39, 40]. However these also get released to the atmosphere.

3. Secondary contaminants

Secondary contaminants are the byproducts or residues generated after the processing of e-waste during the recovery of valuable materials. These are generally produced during the treatment of e-waste via pyro-metallurgical or hydrometallurgical techniques. Usually a pre-processing step is carried out to reduce particle sizes of various waste materials. Shredding is one of the most commonly used techniques to achieve this. A brief overview of secondary waste products produced during these activities is presented in this section.

3.1. Pre-processing byproducts

Two types of contaminants are likely to be produced during preprocessing steps such as shredding and crushing.

Dusts: Handling, manual dismantling or shredding of e-waste in processing workshops can generate a significant amount of dusts [41]. Even loading and/or unloading equipment can produce fine dust particulates [42]. Manual dismantling taking place inside close environments can produce a significant amount of indoor dust as well [43]. Dusts consist of fine particulates in a range of sizes (typically in the μm range), and these can contain plastics, ceramics, and possibly heavy metals. There has been evidence regarding the release of high levels of Cd, Cr, Cu, Pb, Ni, Hg and Zn during dismantling and shredding activities. These metals are released not only during pre-processing activities, but also during inappropriate high temperature processing methods such open burning, de-soldering or metal melting as well.

A number of researchers have investigated the levels of heavy metals present in suspended air particulates, surface dust and floor dust collected from several areas within and near e-waste workshops. High levels of these metals were found in the surface and floor dusts of an e-waste workshop dismantling area [41]. These particles have also been found to travel long distances through migrating species, winds and/or waters. Exposure to heavy metals can take place through ingestion, dermal contact and inhalation. Even when a small amount of these metals are essential for the body to function, excessive amounts of these metals in the human body can lead to high levels of toxicity.

Other particulates that may be released during preprocessing of e-waste are PBDEs, TBBPA, HBCD (described above in the Primary Contaminants section), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs). The formation of dioxins and furans is generally related to the presence of brominated and chlorinated flame retardants. The presence of chlorine can lead to the generation of chlorinated dioxins and furans PCDD/Fs, while the presence of bromine is known to form brominated dioxins and furans PBDD/Fs. Moreover, both together could lead to the formation of mixed dioxins and furans PXDD/Fs. It is however important to note that dioxins and furans are primarily formed during combustion processes.

3.2. Pyro-metallurgical byproducts

During the pyro-metallurgical processing of e-waste and recovery of valuable metals and products, several secondary and undesirable waste products are also produced. Their details are presented in this section.

Incineration of flame retardants:

When plastics containing flame retardants are incinerated, several pollutants such as PCDD/Fs, PBDD/Fs are likely to be generated. Both these products belong to the group of poly-halogenated aromatic hydrocarbons (PHAHs), and polycyclic aromatic hydrocarbons (PAHs).

Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs*):* PCDD/Fs are also classified as persistent organic pollutants (POPs), as these compounds are highly stable in the environment, can travel long distances and accumulate in the fatty tissue of living species [44]. Unlike POPs such as PCBs or PBDEs mentioned in primary contaminants, PCDD/Fs are produced as a byproduct of manufacturing and combustion processes.

A major source of PCDD/Fs is the uncontrolled burning of solid waste. Open burning of e-waste and de-soldering of printed circuit boards in coal grills releases large amounts of these compounds during the processing of e-waste [36]. When PCDD/Fs are released into the atmosphere, these are not only transported over long distances, these pollutants can also get deposited in other environments. These compounds are present in the atmosphere in the gas as well as the particulate phase [44]. Human exposure to these pollutants is extremely likely near e-waste processing workshops. There has been evidence of elevated levels of PCDD/Fs in environmental and health analysis near recycling facilities. Exposure to chlorinated dioxins and furans is known to cause neurologic toxicity, dermal, hepatic and gastrointestinal issues in humans, and reproductive and immunologic toxicity in animals.

Polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs): These compounds have physicochemical characteristics and environmental behavior similar to the corresponding chlorinated compounds. These dioxins and furans have been found to be present as complex mixtures as PXDD/Fs in living organisms. These PHAHs are highly toxic and accumulate in the fatty tissues and food chains, leading to a wide range of adverse health and environmental effects [29]. The half-life of dioxins in humans has been estimated to be around 7 to 11 years. While the major source of dioxins is due to uncontrolled/incomplete burning activities, these are also known to be produced during natural processes such as fires and volcanic eruptions. Investigations on the effects of PBDD/Fs have shown that these may cause severe issues, such as reproductive issues, immune-toxicity and lethality. Dioxin exposure can affect breast milk, placenta and hair, and may cause cancer and other health issues [45].

Polycyclic aromatic hydrocarbons (PAHs): PAHs may be produced from natural sources as well as from human activity. Similar to other compounds mentioned above, these can be generated during combustion or incineration. PAHs can spread around in the atmosphere, and can also get disseminated in soils, water and vegetation [46]. Low weight or lighter PAHs exist predominantly in the gas phase, are volatile and are generally considered to be less toxic than heavier PAHs. However, these can react with other compounds, such as sulfur dioxide, nitrogen dioxide and ozone, and form sulfuric acid, nitro- and dinitro-PAHs and diones respectively, increasing the toxicity [47]. Heavier PAHs exist as particulate matter in the atmosphere as they have low vapor pressure [48]. PAHs can cause lung, skin and bladder diseases and may cause cancer over extended exposure [49].

Slags: Slags are a byproduct of the smelting process, and is mainly composed of oxides and heavy metals targeted to be separated from the metal to be recovered in the pyro-metallurgical process. Slags produced during the smelting of e-waste generally retain heavy metals and other hazardous elements, such as Pb, Cd, Cr, As, Sb, Bi, among others.

Gaseous emissions: A gaseous fraction is also generated during the smelting process. These are generally composed of greenhouse gases, as well as other gases. Some of the emissions are carbon monoxide, carbon dioxide and methane among others.

Particulate matter and dusts: There is a release of heavy metals as a particulate matter as well as carbonaceous particles. These are generally carried out in the generated gaseous fraction.

For example, open burning of copper wires may produce ~100 times more dioxins than burning domestic waste [50].

3.3. Hydrometallurgical byproducts

A number of secondary residues are generated during the hydrometallurgical processing of e-waste. Main byproducts are summarized below:

Spent acids: In hydrometallurgical processes, acids are the main chemicals used to treat e-waste. After leaching, concentration and electro-winning processes, spent acids are generated as a secondary waste. These are generally produced in significant quantities and can contain heavy metals, PBDEs, PCBs, and polycyclic aromatic hydrocarbons (PAHs).

Sludges: Sludges are the semi-liquid mixture that gets separated from a leaching solution. These are commonly generated after leaching e-waste and contain concentrated heavy metals removed from the solution.

Solid residues: Solid residues left after leaching processes are typically composed of plastics and other metals.

Spent activated carbon: Activated carbon is used in concentration processes to adsorb metals, and becomes a waste residue when its effectiveness becomes significantly reduced.

Volatile compounds: Hydrometallurgical processes generally use hydrochloric and/or nitric acids for metal recovery purposes. Their use can potentially emit volatile compounds of chlorine and nitrogen.

4. Tertiary contaminants

Tertiary contaminants are reagents used during the processing of e-waste either to capture target metals or to enhance the separation of various compounds. These substances have the potential to become hazardous when managed inappropriately. In this section, reagents used in the hydrometallurgical as well as in the pyro-metallurgical processes have been summarized.

4.1. Reagents used in hydrometallurgical processes

Leaching agents: Various types of solutions are used during the leaching of e-waste. These include a range of acids (sulphuric, hydrochloric, nitric, aqua regia), cyanides, halides (fluorine, chlorine, bromine, iodine and astatine), thiourea or thiosulphate etc.

Concentration substances: Dense organic liquids are usually used in the solvent-extraction processes. These include organic solvents comprising of extractants and diluents that together form an organic solution. Acid solutions are also used, where in the solvent-extraction step target metals are transferred from one solution to another. Activated carbons have also been employed in the concentration processes.

Electrowinning solutions: A range of acids are used in electrowinning for the recovery of metals. Large quantities of sulphuric acid and its solutions are generally used in this process.

4.2. Substances used in pyro-metallurgical processes

Fluxes and salts: Some approaches mix these substances with e-waste in the smelting process to either capture valuable metals or to separate and concentrate materials.

Gas injection: In smelting, oxygen bearing gases such as air are injected to the bath to oxidize metals.

Electro-refining: In the electro-refining process, electrolyte solutions composed of acids are used to capture the target metal in a highly pure form.

5. Environmental impact of processing e-waste

Most of the contaminants and hazardous materials detailed above are associated with severe environmental and health consequences. Some pollutants can be dispersed through the air, ground water and soil as well as found in the surrounding air in zones neighboring the processing areas. In other cases, by-products get dumped directly into the soil or waterways, where the subsequent leaching of pollutants could contaminate the environment and influence food chain supplies as well. Direct human exposure to these contaminants can also have irreversible short and long term health effects. These contaminants can have severe consequences for the exposed flora and fauna. A comprehensive overview on the environmental impact of e-waste is presented in this section.

5.1. Soil and vegetation

Several types of contaminants have been observed in soils and vegetation near e-waste processing areas. Various investigations have confirmed such contamination in a range of samples.

High levels of polychlorinated biphenyls (PCBs) were found in the soil and the plant samples of an e-waste recycling village in northern Guangdong province, China. Chrysanthemum coronarium L. from vegetable fields and Bidens pilosa L. (wild plant) from the e-waste open burning site were found to have higher concentrations of PCBs than other plants. Analysis of soil specimens from the burning site presented much higher concentrations than nearby zones; vegetable soils were found to have higher levels of PCBs than paddy soils [35]. PBDEs were also found present in soils and vegetation near e-waste processing areas as well as in the neighboring environment. Paddy and vegetable soils, and Brassica alboglabra L were contaminated with PBDEs. However, the levels of the pollutant were seen to decrease with increasing distances from the recycling sites. PBDEs entered the food chain through some vegetables [51].

17 types of PCDD/Fs, 36 types of PCBs and 16 types of PAHs were analyzed from agricultural soils near an e-waste processing site in Taizhou, China. All of these contaminants were found

to be present in the soils, and their source was determined to be the dismantling and open burning of e-waste [52]. Concentrations of ten congeners of PBDEs and nine of PBBs in soils were analyzed in three e-waste disposal sites: Removal of printed circuit board components in coal grills, acid baths, and dumping sites. High levels of both types of pollutants were found in all three soils, with the highest concentration of total PBDEs and PBBs observed in dumps (990.87 ng/g and 1943.86 ng/g, dry weight, respectively), followed by the components removal site and then the acid baths [53].

PCBs and PBDEs were also analyzed in soil samples as well as in apple snails (snails of the Ampullariidae family) within a 70 km radius from an e-waste dismantling site in southeast China. A total of 25 PCB congeners and 14 PBDE congeners were measured. Total PCB levels in apple snails ranged from 3.78 to 1812 ng/g, dry weight, which was found to be much higher than total concentration determined in soils (0.48–90.1 ng/g dry weight). PBDE content in apple snails ranged from 0.09 to 27.7 ng/g dry weight; a similar concentration was observed in soils (0.06 to 31.2 ng/g dry weight). With increasing distance from the dismantling site, concentrations of both groups of pollutants were found to decrease and were much lower. These results indicate a correlation between the dismantling activities and the release and transport of PCBs and PBDEs to surrounding regions and zones [54].

A total of 12 heavy metals were analyzed from the surface, middle and deep sediment from an acid leaching site. These were determined to be Be, V, Cr, Mn, Co, Ni, Cu, Zn, Cd, Sn, Sb and Pb. Results showed considerably high levels of Cu, Zn, Cd, Sn, Sb and Pb, especially in the middle sediments [55]. Another investigation also found high levels of Cd, Cu, Ni, Pb and Zn in sediments in Guiyu, China [56]. Analysis of the soil of Wenling, an e-waste processing area in Taizhou, China, showed it to be heavily contaminated not only with heavy metals (Cu, Cr, Cd, Pb, Zn, Hg and As), but also with POPs, including PAHs and PCBs [57].

Rice samples and paddy soils from an e-waste processing site in Taizhou, China, were analyzed for 10 heavy metals (As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Ni and Pb). Results showed that the agricultural soil was highly contaminated with Cd, Cu and Hg, while Pb concentrations in the rice sample were above maximum allowable levels. It was also found that heavy metals contamination occurred mainly through air migration of particulates [58]. Another study on heavy metal contamination had shown high levels of Cd, Cu, Pb and Zn in soils that were used for the open burning of e-waste. Cd and Cu were found in high quantities in soils near paddy and vegetable sites, while Cd and Pb were found in the edible tissues of vegetables [59].

Leung et al. carried out investigations on the levels of PBDEs and PCDD/Fs in soils and residues of combustion from a Chinese e-waste dismantling and processing site, Guiyu. The levels of PBDEs in combustion residues from a residential area were the highest measured in this study: 33,000 – 97,400ng/g, dry weight. These concentrations ranged from 2,720 to 4,250 ng/g dry weight in samples from an acid leaching site. An analysis of soil samples from the acid leaching site showed the highest levels of PCDD/Fs (12,500- 89,800 pg/g). The concentrations of PCDD/Fs in the combusted residue were found to range from 13,500 to 25,300 pg/g. These results further confirm that these two informal e-waste processing activities released very high levels of PBDEs and PCDD/Fs in the surrounding areas [36].

As more strict regulations have come into force in China, the extent of these pollutants is starting to show a downward trend in their concentration over time. The PCB contents in soils of Taizhou have decreased from 2005 to 2011, while PCDD/Fs have remained fairly constant. PBDEs have shown a slight decrease as well [60]. These pollutants have also been analyzed in rice hulls over a period of time; an overall reduction was observed [61].

The situation in Bangladesh is quite similar to the ones described above. Illegal exports and informal sectors processing e-waste inappropriately have kept on increasing every year. Leaching of toxic compounds as well as pollutant emissions was seen to occur in ship yards as well as in processing areas. Investigations on pollutants released from e-waste were carried out in a ship yard in Chittagong, Bangladesh. Soil samples showed high levels of lead, cadmium, chromium, mercury, selenium, antimony trioxide, arsenic, cobalt and brominated dioxins [62].

An analysis of eleven metals (Ag, As, Cd, Co, Cu, Fe, In, Mn, Ni, Pb, and Zn) in surface and soil samples from both formal and informal processing sites in Manila, Philippines was carried out. Results showed that levels of these metals in informal processing sites were similar to those measured under similar conditions around other Asian countries. High levels of metals were recorded in both formal and informal dust analysis [63]. Another study on heavy metal levels in the soil surface of an informal e-waste processing site in Manila showed the place to be contaminated with copper, zinc and lead [64].

An analysis of heavy metals in an informal e-waste processing site in Mandoli, Delhi, India also showed their high concentration in surface soils. Concentration of lead was the highest measured, reaching 2,645.31 mg/kg, followed by zinc (776.84 mg/kg), copper (115.50 mg/kg), arsenic (17.08 mg/kg), selenium (12.67 mg/kg) and cadmium (1.29 mg/kg). Heavy metal content was also high in the local groundwater as well as in native plants [65].

5.2. Air quality

A number of studies have been carried out on the air pollution caused by the informal and inappropriate e-waste processing activities. A brief description of these is presented in this section.

An analysis of PCDD/Fs, PCBs and PBDEs were carried out in ambient air samples of Taizhou, an e-waste dismantling area. The concentrations of total PCDD/Fs, PCBs and PBDEs were found to range from 2.91 to 50.6 pg/m^3, from 4.23 to 11.35 ng/m^3 and from 92 to 3086 pg/m^3 respectively. The levels of these three pollutants were found to be directly associated with the dismantling activities. The chlorinated dioxins and furans were mainly observed in the particulate phase, while PCBs were found only in the gas fraction [44]. Levels of PCBs and PBDEs were also measured in air of houses in an e-waste processing area in Vietnam. The concentrations of these two pollutants were observed to be much higher (1000–1800 and 620–720 pg/m^3, respectively) than in the control areas [66].

Chlorinated and brominated dioxins and furans were analyzed in Longtang, China, and two other villages in the vicinity. The levels of PCDD/Fs were observed to be ~17 times higher than those observed in the distant neighborhood. However, high measured levels in these two vicinity sites were mainly attributed to dismantling activities in Longtang; as these particulates are known to be persistent and can be transported over long distances through air [67]. Chlorinated and brominated dioxins and furans contamination in air was analyzed in the e-waste dismantling area of Guiyu, China. Levels of PCDD/Fs were found to be among the highest in the world ranging from 64.9 to 2365 pg/m^3. PBDD/Fs concentrations in air were also determined to be very high [68].

Total suspended particles (TSP) and particulate matter 2.5μm were analyzed from the air of Guiyu. PAHs related to TSP and PM2.5 was found to range from 40.0 to 347 and 22.7 to 263 ng m^{-3} respectively. The levels of Cr, Cu and Zn in PM2.5 were observed to be between 4 and 33 times of values typically measured in other countries of Asia. Such an exposure was inevitable for the people living in the dismantling area [69]. Another study in Guiyu showed that all congeners of PBDEs analyzed in air were ~58–691 times higher than in other cities and were more than 100 times higher than recorded in previous studies [70].

Air samples from the Agbogbloshie market located in Accra, Ghana, were analyzed to assess levels of metals and corresponding exposure of workers and people moving around in different areas of the market. The site is known to be a dismantling and trading place for end of life electronic items, as well as an informal processing and dumping site. Both air and soil in these and surrounding regions were found to be heavily polluted. Air samples had high levels of aluminium, iron, zinc, copper and lead [71].

5.3. Water quality

Water tables have also been found to be contaminated by the crude e-waste processing activities. Some of the studies on water pollution are described as follows.

An analysis of heavy metals contamination in ponds and well waters was carried out in the vicinity of a former e-waste processing site in Longtang, China. Results showed acidification and contamination with Cd and Cu of the pond water used for the irrigation of paddy soils. Well water was less contaminated with heavy metals, however it was observed that the surface soil showed high concentrations of these metals which were transported to other areas such as pond water [72]. Concentration of lead in the groundwater of an e-waste processing site was found to be elevated. Such a contamination has a high potential for producing cancer [26]

Rivers Lianjiang and Nanyang in Guiyu, China, were both found to be highly contaminated with a range of metals. Lianjiang river showed high levels of As, Cr, Li, Mo, Sb and Se, while Nanyang river had high contents of Ag, Be, Cd, Co, Cu, Ni, Pb and Zn. Sediments of these rivers had concentrated levels of Cd, Cu, Ni, Pb and Zn [56, 73].

PCBs levels in fish from two ponds near a solid waste site in Kolkata, India, were analysed. Results showed levels of 33,000 pg/g lipid weight in fish from a pond located 2 km away from the site. 4,400 pg/g lipid weight was found in fish from the pond located 3 km away. These levels are extremely higher compared with a reference sample taken, which was 1,900 pg/g lipid weight [74].

5.4. Human health

A number of investigations have been carried out to show the impact of inappropriate processing of e-waste on human health and associated consequences. A brief overview of these studies is presented in this section.

Human breast milk was analyzed for PCBs and PBDEs in three e-waste processing sites of Vietnam. PBDEs concentration was significantly higher in two of the processing sites (20–250 ng/g lipid weight) than in the reference city, Hanoi. PCBs levels were much lower than PBDEs (28–59 ng/g lipid weight). Exposure to these pollutants was believed to have occurred through inhalation and the ingestion of dust [33]. Both PCBs and PBDEs levels were analyzed in two e-waste processing villages in China. While recycling facilities in Luqiao process PCB containing e-waste, PBDEs containing e-waste is processed in Wenling. Dual exposure and associated burdens were found to be significantly high at both processing sites [75].

Samples of human milk were taken from women living nearby a solid waste dump in Kolkata, India. Average levels of PCBs reached 1700 ng/g lipid weight, while in the reference site the concentration was as low as 60 ng/g lipid weight [76]. PCDDs levels obtained were 610 ± 280 pg/g, while PCDFs reached 44 ± 20 pg/g in mothers giving birth for the first time [74]. Hair samples were also analyzed for PBDEs as well as for PCDD/Fs in Taizhou, China. PBDEs levels ranged from 22.8–1020 ng/g dry weight, which was three times higher than the reference samples. PCDD/Fs levels were found to be 126–5820 pg/g dw, which was 18 times higher than reference samples. This study has shown evidence of the high level of exposure to persistent organic pollutants from e-waste [77]. PCB concentrations as well as PBBs and PBDEs were also analyzed in people diagnosed with cancer living in an e-waste disassembly site in Zheijiang, China.

Levels of these three pollutants were found to be high enough to relate with high incidences of cancer in this e-waste processing site [78]. The concentrations of PCBs, PBDEs and dioxins and their correlation with thyroid stimulating hormone in children from Luqiao were assessed. The levels of all pollutants were much higher in children from Luqiao than in the control area, while levels of TSH were found to be lower in children from the e-waste processing site, as well as the distribution of TSH in their bodies was affected [34].

PCBS, PBDEs and HBCDs were analyzed in human milk samples in Ghana. Even when the levels of these were lower than measurements in Chinese e-waste processing sites PBDEs (0.86–18 ng/g lipid weight) and PCBs (15–160 ng/g lipid weight), Ghana is much less industrialized. The source of these pollutants is believed to have come from the informal handling and disposal of e-waste [31]. PAH metabolites were analyzed in the urine of the workers from an e-waste processing site in Agbogbloshie, Ghana. These were found to be significantly higher than a control group. Two thirds of the workers had cough, while one quarter had chest pain [79].

Serum of workers of an e-waste processing site in India was analyzed to study the presence and levels of PBDEs. Results showed an average of 340 pg/g wet weight, higher than a control site [80].

In regions where the exposure to POPs was high, there was also an evidence of correlations between the accumulation of POPs and DNA lesions and dysregulation of DNA damage repair mechanisms [81]. Exposure to metals released from informal e-waste processing has been also analyzed. High concentrations of Fe, Sb, Pb, As in urine were found for workers of an e-waste processing site in Ghana [82]. Trace and heavy metals were also analyzed from the scalp hair samples from people living near an e-waste processing site. Lead and copper were found to be the highest compared to control areas [83].

Various studies on the exposure of children to metals have been reported in the literature. Analysis of chromium, nickel and manganese and their relation to lung function was assessed in children living in an e-waste processing site in China. Levels of Mn and Ni were found to be comparatively higher than for children from the control areas. These two metals can be responsible for lower pulmonary function as well as oxidative damage [84]. Levels of lead and cadmium were analyzed in children of Guiyu, China. Both metals had much higher concentrations in children from Guiyu than from Chendian (control area). These enhanced levels were associated with significantly lower height of Guiyu children [85].

Lead exposure and their correlation with physical growth, bone and calcium metabolism in children from Guiyu, China were investigated. The exposure to lead was found to affect growth and increased bone resorption that may lead to osteoporosis. [86]. Lead levels in blood of children of Guiyu, China, were also analyzed and correlated to temperament alterations. Authors found evidence of significant differences in activity levels, approach withdrawal, adaptability and mood of Guiyu children and a control area (Chendian, China). The main risk factor was the absence of hand washing prior food consumption [87]. Lead concentrations were measured in children from Luqiao, China. 6.97 μg/dL of lead were found in children from Luqiao, compared to 2.78 μg/dL of a reference area. Some consequences of lead levels were lower calcium, and a negative relationship between lead levels and intelligence quotient [88].

Levels of lead in cord blood were measured in Guiyu, China. Analysis showed that Pb concentrations in Guiyu children were much higher than in the control area, Xiamen 10.78 μg/dL vs 2.25 μg/dL. These levels were related to adverse birth outcomes, such as stillbirth (four times higher risk than in Xiamen), lower birth weight and lower Apgar scores (test related to the tolerance of birth and the requirement of medical attention) [89].

Ha et al. analyzed the levels of zinc, copper, lead and manganese contained in the hair of workers of an e-waste processing site in Bangalore, India. Zn content was 141 μg/g dry wt., while Cu, Pb and Mn reached 22.8, 9.07 and 1.16 μg/g dry wt, respectively [90]. A similar situation was observed in Pakistan. Activities to extract metals generally comprise dismantling, open burning or acid leaching. Informal sector receives end of life equipment from illegal imports. Typical age of workers ranges between 6 and ~50 years, with children doing the same work as adults. Exposure to toxic compounds present and released from the informal processing directly affects their health with severe consequences. Breathing problems, cuts, burns, fever and body aches were reported from workers in this sector [91, 92].

Open burning is used in Lima, Peru, for the removal of polymer from copper wires. The scale of these operations is far smaller than the ones reported in Asia and Africa, but carried out under similar conditions. There is generally little processing of e-waste in Peru, only collection and dismantling, a common practice in Latin America. Printed circuit boards and valuable parts are exported to China and Europe for final recovery processing. However, if gold content is high, local workers recover the metal by using hydrometallurgical methods, such as acid or cyanide leaching, or amalgamation with mercury. Residues such as cathode ray tubes glass or secondary leftovers are generally dumped, leading to severe environmental and health issues [93]. An analysis of the health of workers of an informal e-waste processing site located in Santo André, Brazil, has shown the workers to suffer from pain in the back, shoulders, arms and legs, and respiratory diseases such as flu and bronchitis [94].

6. Challenges and opportunities

As described in this chapter, there are a range of hazardous and toxic compounds that may be present in significant quantities or can be formed during the processing of e-waste. All these different types of contaminants are associated with severe environmental and health consequences. Some pollutants can be dispersed through the air, water and soil. In other cases, by-products are dumped directly into the soil or waterways, where the subsequent leaching of pollutants could contaminate the environment and influence food chain supplies as well. Direct human exposure to these contaminants can also have irreversible health effects. There is evidence of dermal, gastrointestinal, hepatic, neurologic toxicity and breath issues in humans, immunologic toxicity and reproductive issues in animals, high levels of lead, copper and chromium, especially in children, changes in milk, placenta, hair and thyroid hormone levels, and even lung cancer and leukemia cases.

The identification of various hazardous substances present in a range of e-waste, toxic compounds generated during processing, as well as the public awareness regarding the severe consequences to health and environment caused by improper handling and processing of e-waste is crucially important. This knowhow will lay the foundations of sustainable processing of e-waste, and prevent the release of toxic pollutants during the recovery of valuable resources. This chapter has presented an overview on the nature and associated impact of a number of harmful compounds that could be produced by a range of recycling approaches.

Better practices in collection, handling and processing of e-waste are needed, especially in the developing countries where e-waste is mostly processed informally and inappropriately, with huge consequences on environment and health. While stricter regulations have improved and reduced the toxic emissions to the environment, however, there has been an accumulation of hazardous compounds over time. There is an urgent need to improve current approaches towards developing environmentally friendly waste recycling and material recovery.

Acknowledgements

The financial support for this research was provided by the Australia India Strategic Research Fund Round 6, Department of Innovation Industry, Science and Research, Australia.

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Chapter 3

Regional Distribution and Human Health Effects of Persistent Organic Pollutants (POPs) in Zhejiang Province

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/62407

Abstract

Zhejiang (ZJ) is a developed province located in the southeast coast of China. In recent years, growing concern has been aroused over the persistent organic pollutants (POPs) pollution associated with electronic and electric waste (e-waste) in this province. This chapter has provided numerous and integrated information concerning POPs pollution level and human health effects in ZJ. The residue levels of major POPs, including DDT, PCDD/Fs, PCBs and PCP/PCP-Na, in the environmental media, local food and human body were relatively higher in polluted areas of intensive e-waste dismantling industry compared with control areas. POPs pollution levels and cancer incidence in both polluted areas and control areas were comparable with the national data. In vitro test and population survey provided evidence that PCBs exposure altered the expression of genes involved in nervous system- and immune system-related diseases, and the CCL22 gene could serve as an effective biomarker for PCBs exposure. Additionally, e-waste management in ZJ province was discussed. Taken together, these data suggest that POPs pollution in ZJ may be correlated to local e-waste recycling activities. In the future, more efforts should be devoted to improve the techniques for e-waste recycling and establish a sound e-waste management framework.

Keywords: e-waste, POPs pollution, health effects, POPs, PCDD/Fs, PCBs

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1. Introduction

Electronic and electric waste (e-waste), referring to obsolete or end-of-life electronic devices such as printers, computers, transformers, television sets, and mobile phones, has become a global concern due to the release of toxic contaminants during the disposal and recycling processing. In recent years, with the rapid economic and technologic development, the amount of e-waste is steadily increasing. It has been estimated that more than 50 million tons of e-waste are generated each year worldwide, and in the United States, over 500 million computers become obsolete between 1997 and 2007 [1, 2]. According to statistics, 50–80% of the e-waste from developed countries is legally or illegally exported to developing countries in Asia, 90% of which is transported to China [3]. A recent study reported that 75% of the e-waste from the United States has been transported to southern regions in China, such as Guangdong and Zhejiang (ZJ) provinces [4]. Nevertheless, in the developing countries, rude and uncontrolled e-waste disposal leads to release of considerable amounts of hazardous contaminants into the environment, creating an emerging environmental problem.

Pollutants released during e-waste recycling processing include various heavy metals and persistent organic pollutants (POPs). In recent decades, POPs pollution and the relevant environmental effects associated with e-waste disposal and recycling activities have received growing public attention. These pollutants enter the environment through atmospheric precipitation or surface runoff. Documented studies reported high residue levels of polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), polycyclic aromatic hydrocarbons (PAHs), and polybrominated diphenyl ethers (PBDEs) were detected in the soil and water column around e-waste dismantling and recycling sites [5, 6]. POPs in the environment enter biological system through food chain, posing great risk to the health of wildlife and human. Knowledge of sources and prevalence of POPs in environment and biota are essential to reduce POPs discharge and to diminish environmental burden and human health risk. Recently, a number of researches have been devoted to chemical analysis of POPs in the environment media and biota, and assessment of their toxicity and the mechanistic basis. However, systematic research concerning the sources, prevalence, and health effects of POPs on a large regional scale is limited.

ZJ province, located in the southeast coast of China (**Figure 1**), is well developed in agriculture and industry. In the littoral zone of this province, a cluster of small towns and villages have become intensive e-waste disassembly and recycling centers. Recent studies provided evidence of serious POPs pollution in these coastal areas of this province, voicing public concern over the environmental health effects of e-waste recycling activities [7–9]. However, to the best of our knowledge, there was no systematic investigation about the regional distributions and human health effects of POPs on the whole province scale, 105.5 thousand km^2. Moreover, the correlation between the prevalence of major POPs and the incidences of cancers in ZJ province remains unknown.

In the present study, systematic analysis was carried out to identify the burden of major POPs, including DDT, PCBs, PCDD/Fs, PCP/PCP-Na in the environment media, local foods, and human body in ZJ province. As well, the potential link between POPs prevalence and cancer incidence was determined using epidemiological surveys and laboratorial experiments. Furthermore, e-waste disposal and management in ZJ province were discussed.

Figure 1. Sampling locations in Zhejiang province.

2. Distribution of POPs in the environment

2.1. Major POPs levels in environmental media (air, soil, etc.)

2.1.1. PCBs levels in atmospheric particulate matter (PM10)

In the period from August to December in 2009, PM10 samples were collected in ZH, LQ, and LY areas. The sampling sites in ZH and LQ were about 1 km downwind of a dismantling area. LY was selected as the control area. The concentrations of total PCB congeners in PM10 were 348 ng/g dw (5.16 pg/m^3), 499 ng/g dw (92.4 pg/m^3), and 1139 ng/g dw (127 pg/m^3) in LY, LQ, and ZH, respectively. The data of ZH and LQ areas were significantly higher than other areas reported in China, but comparable to those of developed countries.

2.1.2. PCDD/Fs and PCBs levels in soil

Based on documented data about the schistosomiasis history of ZJ province, soil samples (500 g) in 10 areas, that is, CS, JX, JH, YJ, TZ, YH, TT, LY, ZH, and DY, were collected and stored at −20°C for analyzing PCDD/Fs. Concomitantly, sediments in ponds or lakes surrounding the sampling sites were also collected. Both soil and sediment samples were dried at room temperature, freeze-dried, and grinded to pass a 200-mesh sieve for further analysis.

Regions	PCDD/Fs concentration	PCBs concentration
CS	5099	5498
JX	1331	1367
JH	2675	2347
YJ	581	54,632
TZ	182	72,156
YH	98	1100
DY	509	1730
TT	504	1950
LY	290	1840
ZH	*1.1.1.* 780	*1.1.2.* 2912

Note: These data were determined by the authors.

Table 1. Total concentrations of 17 kinds of PCDD/Fs and 18 kinds of PCBs (pg/g dw) in soil of ten regions.

A total of 50 soil samples were collected (a mixture sample of five individual samples in each area), and the residue levels of 17 kinds of PCDD/Fs were analyzed (**Table 1**). The detected PCDD/Fs concentrations were in the range of 98–5099 pg/g dw, with the mean to be 1205 pg/g dw. The highest concentration of PCDD/Fs was in CS, which was about 2- to 50-fold higher than those of other areas. OCDD was the predominant congener, accounting for 66.9–95.8% of the total concentration, which suggested the identical source of PCDD/Fs in all sampling areas. Relatively lower levels (4.5 pg/g dw) were found in the soil in Beijing [10].

According to the results in our study, PCDD/Fs contamination in CS and JD district of JH was worse than that in other areas, which may arise from historic contamination. More specifically, CS and JH were the two areas of high schistosomiasis incidence in the past. Sodium pentachlorophenate (PCP-Na) has been widely used in these two areas for controlling oncomelania in the last decades, unintentionally resulting in the formation of the main by-product of PCDD/Fs.

Additionally, levels of 18 kinds of PCBs in the soil samples were determined (**Table 1**). PCBs concentrations ranged from 1100 to 72,156 pg/g dw, with the mean of 14,553 pg/g dw. LQ showed the highest PCBs concentration, which was about 2- to 70-fold of the concentrations in other areas. Comparatively, PCBs levels in these areas were lower than those in heavily polluted regions reported by Chu et al. (430–788 ng/g) [11], but higher than those detected in the soil of Beijing (0.39–13 ng/g, mean of 3.1 ng/g) [12], Qingdao (3.06–14.88 ng/g, mean of 8.04 ng/g) [13], and Yangtze River Delta (mean of 1636.8 ng/kg in rice field, 919.2 ng/kg in vegetable field, and 553.5 ng/kg in historical vegetable field) [14].

The data revealed PCBs contamination was most severe in YJ and LQ. This may be explained by the fact that LQ was an area of intensive e-waste dismantling plants, and rough management, open burning, and random discharge of industrial waste resulted in heavy environmental pollution of PCBs.

2.1.3. PCP/PCP-Na and DDT levels in soil

As presented in **Table 2**, PCP/PCP-Na contamination in the five sampling areas was relatively mild at concentrations of 0.4–1.9 ng/g dw, which were far lower than the standard value of the former Soviet Union (0.5 μg/g). The residue levels in different areas were in an ascending order as YJ, JH, YH, CS, and LQ. Higher level detected in LQ was speculated to be implicated with the local e-waste dismantling industry. Additionally, with the exception of AX, PCP/PCP-Na concentrations in other seven sites in YH area were in the same order of magnitude (**Table 3**).

Regions	N	PCP/PCP-Na	p, p′ –DDE	p, p′ –DDD	o, p′ –DDT	p, p′ –DDT	Total DDT
YH	24	0.70 ± 0.71	5.12 ± 3.52	1.82 ± 1.43	0.32 ± 0.89	2.84 ± 4.07	10.11 ± 7.58
CS	4	1.01 ± 0.78	22.02 ± 22.94	1.34 ± 0.96	12.60 ± 22.76	4.96 ± 4.96	40.92 ± 49.79
YJ	2	0.34 ± 0.12	3.86 ± 3.58	1.12 ± 0.88	1.99 ± 1.92	4.76 ± 1.20	11.74 ± 7.57
JH	3	0.38 ± 0.14	6.83 ± 7.80	1.02 ± 1.32	0.51 ± 0.49	1.03 ± 1.08	9.40 ± 8.09
LQ	1	1.86	14.75	4.52	3.59	61.5	84.36

Note: These data were determined by the authors. n, number of soil samples.

Table 2. Concentrations of PCP/PCP-Na and DDT (ng/g dw) in soil of five regions.

Regions	N	PCP/PCP-Na	p, p′ –DDE	p, p′ –DDD	o, p′ –DDT	p, p′ –DDT	Total DDT
DH	5	0.51 ± 0.48	2.21 ± 0.35	0.98 ± 0.25	–	3.61 ± 3.87	6.80 ± 4.39
DT	4	0.87 ± 0.74	7.16 ± 1.03	3.95 ± 0.83	1.94 ± 1.39	8.41 ± 6.78	21.47 ± 9.39
WH	5	0.52 ± 0.16	6.45 ± 5.99	0.97 ± 0.84	–	1.65 ± 1.24	9.10 ± 6.63
GZ	3	0.22 ± 0.03	8.41 ± 1.30	3.45 ± 1.06	–	1.10 ± 0.44	12.96 ± 1.93
YH	5	0.80 ± 0.51	2.75 ± 0.60	0.73 ± 0.22	–	0.57 ± 0.56	4.05 ± 0.68
LZ	1	0.29	7.04	2.44	–	1.53	11.01
AX	1	3.28	4.78	1.72	–	0.61	7.11

Note: These data were determined by the authors. n, number of soil samples.

Table 3. Concentrations of PCP/PCP-Na and DDT (ng/g dw) in soil of several YH areas in HZ.

As for DDT, notable difference was observed in the residue levels in these areas, with concentrations of different areas in an ascending order of JH, YH, YJ, CS, and LQ (**Table 2**). LQ was found to have the highest level of p, p′ –DDT. o, p′ –DDT was not detected in YH district in HZ except DT (**Table 3**).

2.2. Major POPs levels in food and fish

It has been well recognized that more than 90% of human exposure to POP is attributed to food consumption. Estimation of POPs levels in food is the most important for risk assessment of POPs to human health. During 2009, residues of major POPs were monitored in late rice, wild crucian, and eggs in ten areas in this province (**Table 4**). PCBs concentrations were also determined in seafood, breast milk, and dairy products [15, 16].

Regions	**Total PCBs**			**TEQ98**		
	Late rice	**Egg**	**Crucian**	**Late rice**	**Egg**	**Crucian**
ZH	208	3123	10,275	0.02	0.81	1.28
XJ	46.5	3648	2300	0.003	1.04	4.01
TT	36.9	10,274	5553	0.003	0.51	1.13
SM	36.5	9349	11,538	0.003	2.30	1.05
LH	31.4	14,971	8329	0.003	3.74	0.84
CX	311	3372	36,945	0.03	2.98	1.96
HY	176	7285	57,959	0.02	1.94	5.51
JJ	234	8881	39,853	0.02	4.99	4.08
WL	333	13,903	45,247	0.03	8.11	3.71
YH	176	17,320	44,757	0.02	7.92	3.67
1.1.3. LY	*1.1.4.* 98	*1.1.5.* 3643	*1.1.6.* 3399	*1.1.7.* 0.006	*1.1.8.* 0.75	*1.1.9.* 0.95
LQ	807	24,780	700,052	0.09	11.1	40.1
YH	–	–	1502	–	–	0.45
LX	–	–	2100	–	–	0.38
JX	–	–	2700	–	–	0.49
CS	–	–	10,286	–	–	1.56
JH	–	–	2480	–	–	0.73
YJ	–	–	23,761	–	–	2.45

Note: These data were determined by the authors.

Table 4. PCBs concentrations (pg/g dw) and TEQ (pg/kg) in late rice, egg, crucian in different areas (n = 5).

2.2.1. PCBs levels

Due to the low-fat content in rice, PCB concentrations in late rice were shown to be at a low level, ranging from 31 to 807 pg/g dw. Highest concentration was detected in LQ, implying severe environmental pollution in this area. Undoubtedly, eggs and wild crucian in these areas, containing high-fat content, were found to have more PCB accumulation.

The LQ district of TZ, one of the large-scale e-waste dismantling areas in southern China with a 20-year history for dismantling, has been heavily polluted by PCBs. Random discharge of untreated transformer oil containing PCB mixtures, as well as open burning of plastic pipe, might be the important reasons for PCBs pollution in the soil. In recent years, due to improved dismantling technique and integrated management of dismantling industry, the polluted land has been partially restored and the soil ecosystem has been improved. However, due to persistence property, PCBs can highly bioaccumulate in various organisms through food chain. The concentration of total PCBs detected in wild crucian in LQ reached 700 ng/g dw, far above other areas. Moreover, diet survey was conducted to identify PCBs exposure of population via food intake in these areas. The results showed that consumption of fish caused an average exposure of 60.4 pg/WHO-TEQ/kg per person per day, far exceeding the WHO standard value 4 pg/WHO-TEQ/kg, implying that the wild crucian in this area was not fit for consumption. PCBs residue levels in different areas were found in the order of LQ > HY > WL in rice, LQ > YH > LH > WL in eggs, and LQ > HY > WL > YH in crucian.

2.2.2. *PCP/PCP-Na levels*

Residue levels of PCP/PCP-Na in wild crucian of different areas ranged from 0.49 to 0.75 ng/g, in the order of JX > YH > LQ (**Table 5**). No significant difference of PCP/PCP-Na concentrations was observed among the six sampling sites in YH district in HZ (**Table 6**).

Regions	n	PCP/PCP-Na	p, p′ –DDE	p, p′ –DDD	o, p′ –DDT	p, p′ –DDT	Total DDT
YH	13	0.72 ± 0.13	13.03 ± 8.71	8.22 ± 8.13	0.15 ± 0.56	13.82 ± 12.82	35.87 ± 24.81
JX	1	0.75	26.61	20.42	–	–	47.03
LQ	8	0.49 ± 0.15	13.08 ± 5.26	6.22 ± 2.09	0.16 ± 0.46	11.82 ± 9.97	31.28 ± 15.13

Note: These data were determined by the authors. n, number of soil samples.

Table 5. Concentrations of PCP/PCP-Na and DDT (ng/g dw) in crucian in some regions.

Regions	n	PCP/PCP-Na	p, p′ –DDE	p, p′ –DDD	o, p′ –DDT	p, p′ –DDT	Total DDT
DH	5	0.77 ± 0.14	18.23 ± 4.58	15.30 ± 4.98	0.40 ± 0.90	26.72 ± 8.60	60.66 ± 16.58
YH	3	0.62 ± 0.04	4.24 ± 0.79	2.05 ± 0.44	–	14.96 ± 1.88	21.26 ± 2.12
GZ	2	0.71 ± 0.06	9.16 ± 0.68	–	–	–	9.16 ± 0.68
WH	1	0.99	32.0	19.42	–	–	51.42
DT	1	0.60	5.45	3.01	–	4.48	12.94
LZ	1	0.71	9.72	1.83	–	5.04	16.59

Note: These data were determined by the authors. n, number of soil samples.

Table 6. Concentrations of PCP/PCP-Na and DDT (ng/g dw) in crucian in several YH areas in HZ.

2.2.3. DDT levels

The total DDT concentrations in crucian of three areas were in an ascending order as YH, LQ, and JX. Among all DDT congeners, o, p′ –DDT had the lowest residue level and was not detected in fish sampled in JX. Obvious difference of DDT concentrations was found in fish collected in the six sampling sites. In GZ, only p, p' –DDE was detected. O, p' –DDT was not detected in all sites except DH (**Table 6**). DDT levels in fish were shown in the order as DH > WH > YH > LZ > DT > GZ.

2.3. Total toxic equivalents (TEQs) of PCBs and PCDD/Fs

As shown in **Figure 2**, TEQs in various foods of LQ were higher compared with YH, and crucian was shown to have the highest TEQ (10.87 pg/g ww). TEQs detected in other food were 3.77 pg/g ww in duck meat, 2.80 pg/g ww in egg, 2.43 pg/g ww in chicken meat, 0.08 pg/g ww in rice, and 0.22 pg/g ww in vegetable. In YH area, total TEQ was shown to be highest in duck meat (0.74 pg/g ww), and TEQs in other food were 0.69 pg/g ww in egg, 0.55 pg/g ww in crucian, 0.44 pg/g ww in chicken meat, 0.002 pg/g ww in vegetable, and 0.0002 pg/g ww in rice. The results revealed that PCBs TEQ in animal-originated food in LQ and YH shared the same order as crucian > egg > chicken and duck meat. Regarding PCDD/Fs, total TEQ was different in the two areas, with the order of duck > crucian > chicken > rice > vegetable in LQ and duck > egg > chicken > crucian > rice > vegetable in YH.

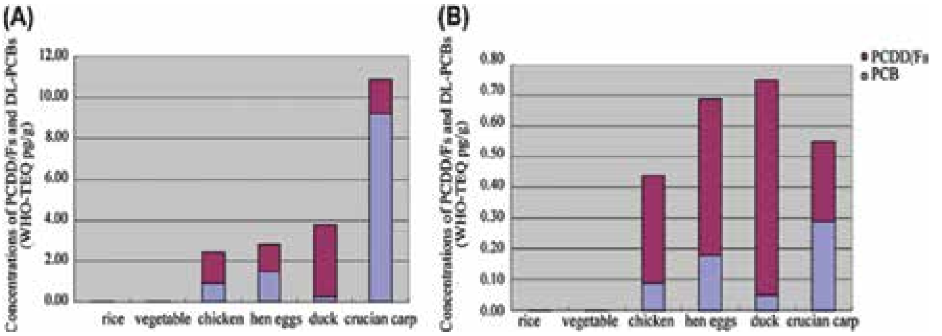

Figure 2. Concentrations of PCDD/Fs and DL-PCBs (pg/g ww) in local food in LQ and YH [15].

The data indicated that, apart from eggs in LQ and crucian in LQ and YH, the other kinds of food made great contribution to the total TEQ value.

3. Human body load of major POPs

Health effects of environmental contaminants on humans and wildlife are usually assessed through external exposure test, and the exposure levels of human population to toxicants are generally estimated by using equations with parameters for exposure routes (oral, dermal, or inhalation), on the basis of the analytical data of toxicant concentrations in ambient environmental media (air, water, or food). Estimates based on external exposure and multiple hypotheses often have big error, since just the approximate doses received by organisms are predicted. The predicted exposure doses generally deviate from the absolute internal exposure level because there are many undefined factors. Assessing toxicity of environmental pollutants by external exposure cannot provide insightful information for environmental conservation, human health protection, and formulation of law and regulation. Study of health effects by monitoring the internal exposure has become a significant and effective mean for risk assessment of environmental pollutants.

Biological monitoring is an effective mean for identifying internal exposure levels by using advanced analytical techniques to measure the concentrations of parent chemicals and metabolite in the whole body or tissues. Due to the advantages of speediness and exactness, biomonitoring has become the important mean for measuring internal exposure doses in biological system. Biomonitoring data provide scientific basis for establishing environment sanitary criterion and medical diagnosis standard and assessing the effectiveness of public health measures.

3.1. Body burden of major POPs in special population

Residue levels and fingerprint of PCDD/Fs and PCBs were determined in fat, breast milk, and blood of general population in this province. The average total concentrations in fat, breast milk, and children's blood samples were 108, 55.0, and 208 pg/g lipid for 17 kinds of PCDD/Fs; 32.8, 8.0, and 9.8 ng/g lipid for all 12 kinds of DL-PCBs; and 154, 15.8, and 28.3 ng/g lipid for all indicator PCBs. The TEQs in these samples were 9.22, 3.09, 11.7 pg/g lipid for PCDD/Fs, and 16.2, 3.56, 11.9 pg/g lipid for PCBs. Similar pattern of PCDD/Fs and PCBs fingerprint was obtained in several kinds of food (fish and eggs) and in human body, implying that food consumption was the main route for human exposure to these POPs. PCDD/Fs concentrations in this study are notably different from those detected in the body fat of westerners, which may be implicated with different eating habits between easterners and westerners.

Body load of PCBs and PCDD/Fs was investigated in occupational population and specific population. Analytical data indicated 90% detection rate of these pollutants in the cerumen of occupational population in dismantling areas and 50% detection rate in non-occupational population. No PCBs but low levels of DL-PCBs were detected in the control subjects. Significant difference of PCBs levels was observed between population in dismantling areas and control group. Data of correlational analysis revealed a positive correlation between PCBs levels in cerumen and service length of workers.

3.2. Concentrations and TEQ of PCDD/Fs and PCBs in body fat

A total of 24 body fat samples were collected, numbered and stored at −20°C for chemical analysis.

3.2.1. PCDD/Fs levels

Concentrations and TEQ of 17 kinds of PCDD/Fs and 18 kinds of PCBs in body fat are shown. PCDD/Fs concentrations were in the range of 33.9–504 pg/g lipid, with mean of 108 pg/g lipid. These data are comparable to those reported in Spain (109 pg/g lipid) [17], higher than Turkey (73.3 pg/g lipid) [18], but lower than Japan (171 pg/g lipid) [19]. Kiviranta et al. [20] reported PCDD/Fs concentrations in human body fat ranged from 171 to 1180 pg/g lipid. As for PCDD/Fs, OCDD was found to be the predominant congener, accounting for 68% of the total concentrations. Other main congeners included 2,3,4,7,8-PeCDF, 1,2,3,6,7,8-HxCDD, 1,2,3,4,6,7,8-HpCDD, and 1,2,3,4,7,8-HxCDF, respectively constituted 6.61, 4.14, 3.62, and 3.23%. The proportional composition of PCDD/Fs is similar to that reported in other countries.

TEQ in fat was calculated using the revised WHO TEQ factor (WHO-PCDD/F TEF 98, 05) [21, 22]. In this study, the average TEQ for WHO-PCDD/F TEF 98 was 9.22 pg/g lipid (1.64–20.3 pg/g lipid), comparable to the data in Turkey (9.2 pg/g lipid) [18], Japan (11.9 pg/g lipid) [19], Korea (12.8 pg/g lipid) [23], and India (14.4 pg/g lipid) [24], but significantly lower than European countries (17.8–48 pg/g lipid) [20]. Numerous studies provide evidence that food consumption is the main route for PCDD/Fs exposure. Due to different dietary habits, consumption of animal-originated food by easterners is far less than westerners, which may be one of the most important reasons for the different PCDD/Fs residues in body fat [25].

3.2.2. PCBs levels

Both DL-PCBs and indicator PCBs were detected in all fat samples. The average total concentration of PCDD/Fs was 32.8 ng/g lipid (4.11–125 ng/g lipid), comparable to those reported in Japan (29.8 ng/g lipid) [19], higher than the levels in Turkey male fat (14.0 ng/g lipid) [18], but lower than the levels in women from Spain (56.0 ng/g lipid) [26] and those detected in south China (237 ng/g lipid) [27]. PCB118 was found to be the predominant congener of DL-PCBs, followed by PCB156 and PCB105. All the three PCBs made up 77.6% of the total DL-PCBs concentrations. In other studies, consistent results were obtained, showing PCB118, PCB156, and PCB105 are the main congeners of all DL-PCBs [18, 19, 26].

As for indicator PCBs, previous studies indicated PCB153 was the predominant congener, which had been detected in all environmental media. A recent study in Europe reported PCB153 concentration in human body fat was 232 ng/g lipid, and all indicator PCBs levels were 389–855 ng/g lipid with a mean of 606 ng/g lipid [20]. In our study, indicator PCBs concentrations were 8.75–745 ng/g lipid, with mean of 154 ng/g lipid. Consistent with other studies, PCB153 was the predominant congener, but its concentration (52.5 ng/g lipid) was far lower than that detected in Europe.

As regards the PCBs TEQ, PCB126 (83.8 pg/g lipid) made a major contribution (90%) to the total TEQ. The detected PCBs TEQ was in the range of 1.4–61.6 pg/g lipid with mean of 16.2 pg/g lipid, which is higher than that of other countries in Asia, but lower than that of developed countries in Europe (**Figure 3**).

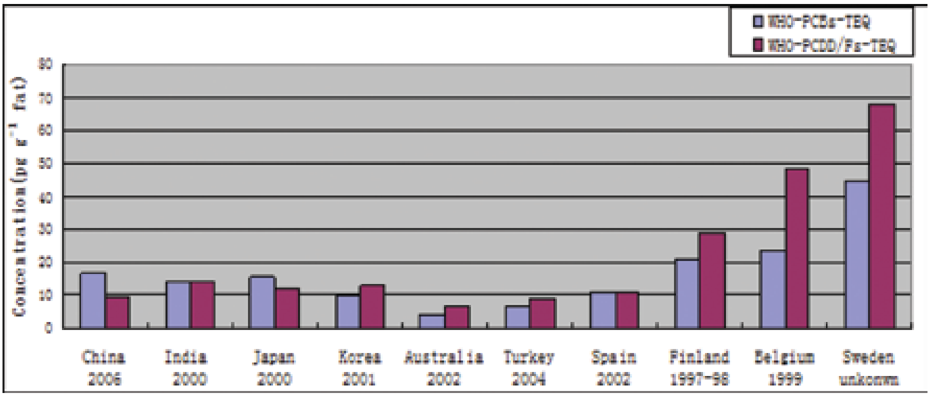

Figure 3. Comparison of PCDD/Fs- and PCBs-TEQ in human body fat from various countries [17–19, 23, 24, 28–30].

3.3. Concentrations and TEQ of PCDD/Fs and PCBs in breast milk

Breast milk contains fatty acid, protein, endogenous hormone, and antibody, which are essential for infant growth and development. WHO recommends exclusive breastfeeding for infants in the first 6 months of life. However, there is a lot of evidence indicating that many POPs, such as PCDD/Fs and PCBs, are transferred from mother to infant via breast milk which is rich in fat. Detection of PCDD/Fs and PCBs levels in breast milk not only reflects the exposure risk of local population to these pollutants, but also indicates the health effects on infant by breastfeeding. The organization of Stockholm Convention has evaluated the impact of implementing emission reductions of POPs, based on the monitoring data of POPs in breast milk worldwide. WHO has successively initiated three programs for monitoring breast milk, whereas, in China, apart from Hong Kong which participated in the third program initiated by WHO, quite limited efforts have been made to monitor POPs in breast milk [31]. POPs levels in breast milk have been reported in e-waste dismantling areas, while systematic study is scarce. In this study, a total of 74 breast milk samples collected in areas of no e-waste dismantling industry have been monitored to identify the PCDD/Fs and PCBs levels in general population [32]. The breast milk samples (25–100 ml each) were numbered and stored at −20°C, then freeze-dried, grinded, and sealed for further pretreatment and analysis.

3.3.1. PCBs levels

The detection limit for PCBs analysis was 0.05 pg/g lipid, and the recovery rate of isotope internal standards was 58–89%. Analysis of the blank control and the standard reference material (WMF-01) conformed to the requirement for quality control. All six kinds of indicator PCBs and 12 kinds of DL-PCBs have been detected in all breast milk samples. The mean of total concentration and total TEQ for PCB congeners were 23,881 ± 9718 pg/g lipid (13,643–45,205 pg/g lipid) and 3.56 ± 1.06 pg/g lipid (2.92–6.31 pg/g lipid), respectively. The top five congeners include PCB138, PCB153, PCB118, PCB180, and PCB105, respectively, accounting for 37.58, 19.07, 11.79, 7.70, and 7.00% of the total concentration. The proportional composition of PCB congeners is shown in **Figure 4**.

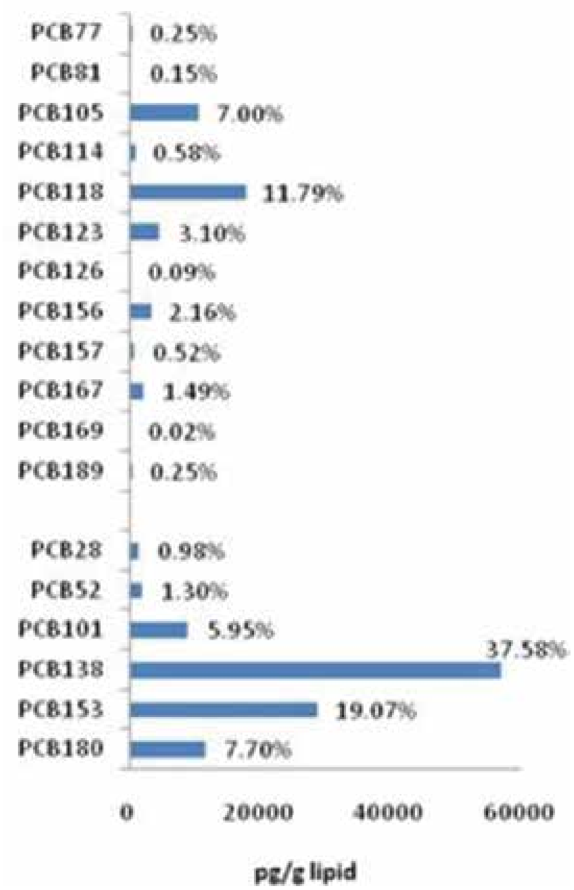

Figure 4. PCBs composition in breast milk [33].

A previous study determined PCBs levels in breast milk of general population in 12 regions of China [31], showing PCBs levels in industrially developed areas were significantly higher than those in underdeveloped areas. The data of our country are relatively lower than those of developed countries (4.9–57.2 pg/g lipid) [31]. The worldwide PCBs levels in breast milk have regional difference. For instance, the data in East Asia (China, Korea, and Japan) are very similar, but much lower than those in US and European countries (10–100 pg/g lipid). Different dietary habit may partially explain this difference. It is well known that 90% of POPs including PCBs in human body is obtained via food consumption, especially animal-originated products which are mostly favored by westerners. Our recent studies also found PCBs fingerprints detected in food and body tissues were accordant [21, 34], providing evidence of the major role of food consumption in human PCBs exposure.

In addition, PCBs levels in breast milk were analyzed in different age groups. However, due to narrow age range (21–30), no positive relevance was observed between PCBs concentrations and age (R2 = 0.220). Further investigation will be conducted in population of wide age range.

3.3.2. PCDD/Fs levels

Levels of PCDD/Fs in breast milk from urban and rural residents were measured to determine whether regional environment had effects on body load of POPs. Generally, our results showed lower PCDD/Fs levels in breast milk in our country compared with developed countries, consistent with the nationwide data [31]. It should be noticed that the data of urban groups (71.4 ± 40.8 pg/lipid, n = 23) were significantly higher than those of rural groups (38.6 ± 38.1 pg/lipid, n = 51). Consistently, previous studies revealed that the data of developing countries were lower than those of developed countries [31, 35–38]. Numerous POPs, such as PCDD/Fs and PCBs, are mostly the by-products of industrial activities, and they enter the ecosystem mainly via atmospheric precipitation and surface runoff, transfer and bioaccumulate via the food chain, and eventually accumulate in human body. Although a limited number of samples have been analyzed in our study, the data absolutely indicate a positive correlation between the body load of POPs and the local industrialized levels.

3.4. Concentrations and TEQ of PCDD/Fs and PCBs in human blood

Occurrence of POPs in the environment may originate from multiple sources. For instance, PCDD/Fs can be formed during natural events such as volcanic eruption, or be created by industrial process such as exhaust emission by steelmaking industry and waste incinerating factory or sewage discharges by paper mill. Statistics show that over one million tons of e-waste are generated annually, 70% of which are introduced in China for dismantling and recycling heavy metals such as copper and gold. LQ and GY are the top two biggest e-waste dismantling areas in China. In LQ, over 60 thousand of people work on e-waste dismantling industry, generating 1.4 billion dollar a year. However, this pillar industry brings about potential hazard to the environment accompanied with enormous economic benefits. Compared with the adults, children have the least chance of occupational exposure to POPs. POPs concentrations in children's blood can exactly reflect the health effects of environmental pollutants. Therefore, our study for the first time analyzed POPs concentrations in children's blood in these areas. Briefly, blood samples of children were collected by the local Centers for Disease Control in LY, LQ, and TT. LQ was considered as the heavily polluted area because of the intensive e-waste dismantling industry, and TT and LY are selected as mildly polluted area and control area, respectively [39].

3.4.1. PCBs levels

The average concentration of PCB mixtures in children's blood sampled in LQ was 40.6 ± 7.01 ng/g lipid, higher than that in LY (20.7 ± 6.90 ng/g lipid) and TT (20.7 ± 8.09 ng/g lipid). This result indicated more PCBs intake of children in LQ through various routs such as food consumption, implying serious pollution in LQ. Improved dismantling techniques, rigorous regulatory process, and scientific guideline in the dismantling industry of LQ are required to alleviate the environmental effects.

Our results are consistent with the data reported previously [40]. DL-PCBs concentrations in LQ, LY, and TT were 16.0 ± 3.32, 7.32 ± 3.53, and 6.68 ± 3.05 ng/g lipid, respectively, far lower than the levels in cord blood reported by Zhao et al. [40] (348 ng/g lipid) but higher than the levels in pregnant women's blood in Japan (5.9–34.3 ng/g lipid) [41, 42]. Due to lipophilic property, PCBs tend to accumulate in tissues of high-fat levels, such as lipid and breast milk. It has been reported that worldwide PCBs levels, including indicator and DL-PCBs, were 30–1800 ng/g lipid in breast milk [43] and 389–4242 ng/g lipid in human fat tissues [20]. The predominant congeners in children's blood included PCB118, PCB105, PCB153, PCB138, and PCB28, which was consistent with the results previously detected in lipid tissues.

3.4.2. PCDD/Fs levels

Different from the results of PCBs, PCDD/Fs levels in children's blood of the heavily polluted area LQ (206 ± 157 pg/g lipid) were shown to be higher than the moderately polluted area TT (160 ± 102 pg/g lipid), but lower than the control area LY (282 ± 261 pg/g lipid). Integrated analysis of the data for the three areas was performed, and the average PCDD/Fs level in children's blood was 208 ± 172 pg/g lipid (54.4–784 pg/g lipid) (**Figure 5**). Our previous study also revealed that PCDD/Fs levels in food (primarily fish and egg) in LY were about 3- to 5-fold of those in LQ. In 1960s, PCB-Na was abundantly produced and extensively applied to control schistosomiasis in LY. But during the production of PCP-Na, a large amount of PCDD/Fs was generated. PCDD/Fs are persistent and can bioaccumulate through food chain, eventually enter human body [44]. These results in our studies indicate there still exists great health risk to the environment and population due to historically widespread application of PCP-Na in LY.

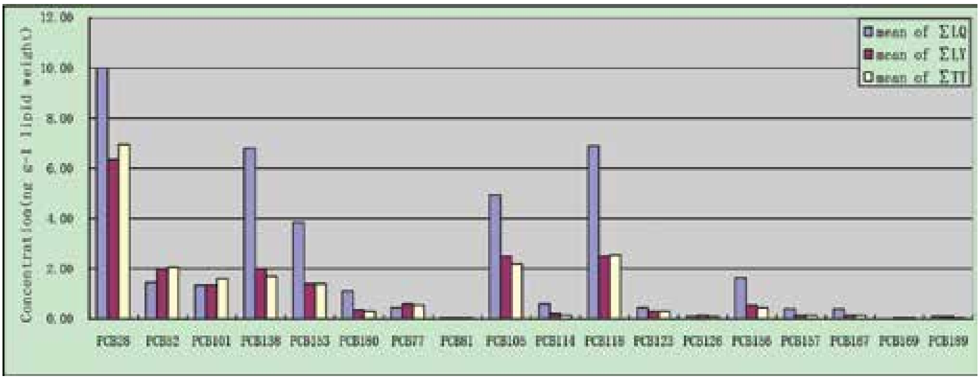

Figure 5. Comparison of PCBs concentrations (ng/g lipid) in children's blood between polluted areas (LQ) and control areas (LY and TT) [39].

Comparatively, in Korean, PCDD/Fs levels in the blood were reported to be 12.3 pg/g lipid, 10-fold less than the results of our study [23]. However, our results were comparable to the data reported in pregnant women's blood in Japan (196 pg/g lipid) [42]. Additionally, the data of LQ were comparable to those reported previously. Because of the least chance of occupational exposure for children, the data detected in children's blood more likely reflect human health effects of pollutants.

4. PCDD/Fs and PCBs pollution characteristics and correlation analysis

As stated above, POPs are persistent and lipophilic, can migrate globally via atmospheric precipitation and water flow, and bioaccumulate through food chain. In Western countries, due to a long history of production and application of PCB/PBDE, POPs levels in food are commonly higher than developing countries. It is generally believed that food consumption is the main route for human exposure to POPs. Other exposure routes include air breath, skin contact, and mother-to-child transmission.

Due to persistent property of POPs, it is speculated that POPs pollution profile in different environmental media is stable. Study of POPs in various environment media is of great significance for fingerprint analysis and understanding of sources and transport of pollutants.

In our study, systematic analysis was conducted on POPs residues in environmental media (source water, soil, sediment, air), food (eggs, rice, freshwater fish, vegetable, livestock), and body tissues (breast milk, blood, and fat). Pollution characteristic of PCDD/Fs and PCBs in different environmental media was further analyzed.

PCB congener compositions in different media are very similar. All 6 kinds of indicator PCBs and 12 kinds of DL-PCBs were detected in breast milk. The predominant congener PCB138 makes up 32.86% of total concentration. The abundance of other major PCB congeners was in a descending order as PCB153 (26.85%), PCB118 (14.43%), PCB28 (8.61%), PCB180 (5.89%), and PCB105 (5.44%). These major PCB congeners account for 94.08% of total concentration. In body fat, the abundance of major congeners was in the order as PCB153 > PCB 138 > PCB 180 > PCB 118 > PCB 28 > PCB 105, totally consisting 94.34%. In human blood, PCB28 was most abundant. Notably, the proportion of PCB180 in fat was 20.24%, higher than that in breast milk (5.89%) and blood (4.01%), which can be explained by the fact that high-chlorinated congeners more easily bioaccumulate in high-fat tissues [45].

PCBs residues in seafood, eggs, and freshwater fish which are universally consumed by local people have been analyzed to determine the sources of PCBs in human body. The major six kinds of PCB congeners make up 79.67, 88.09, and 80.71% of total concentration, respectively, in seafood, eggs, and fish. The fingerprints of the major PCB congeners in food and human body were very similar, suggesting food consumption was the main route for human PCBs exposure. In both food and human tissue samples, OCDD was the most abundant congener, and the levels of other PCDD/Fs congeners were relatively low.

Additionally, our study showed that the fingerprints of PCBs and PCDD/Fs in body fat, breast milk, and blood in general population were very similar to those in main food samples such as fish and eggs, implying the main contribution of food consumption to PCDD/Fs exposure of general population. We speculate that there is a possibility to control the hazard of PCDD/Fs to human health by adjusting the diet structure.

5. Body burden in general population and special population

Analysis of PCBs and PCDD/Fs in peripheral blood was conducted in healthy population in LQ, LY, TT, YH, and ZH. LY showed the highest TEQ value, followed by LQ, TT, YH, and ZH. The results of PCBs and PCDD/Fs fingerprints were consistent with those stated above.

Additionally, PCBs concentrations in breast milk, umbilical cord blood, and mothers' and children's blood in polluted sites were higher than the reference sites. The TEQ values of PCBs and PCDD/Fs in breast milk were also higher in polluted sites.

In the dismantling areas, cerumen from occupational population or non-occupational population was collected for analysis of PCBs and DL-PCBs (n = 30). Cerumen of farmers in TY town about 10 km far from the polluted area was considered as control group (n = 30). The detection rate was 90% in occupational population and 50% in non-occupational population in the dismantling area. No PCBs have been detected in the control groups. The difference of PCBs and DL-PCBs between the three groups was significant. Correlation analysis revealed a positive relevance between PCBs levels and seniority of dismantling workers.

6. Correlation between major POPs pollution and cancer

6.1. Statistics of cancer incidence and financial loss

Prevalence of diseases, as well as cancer-related financial loss and mortality, has been estimated in TZ and YH. In both regions, the total number of patients and total medical expense in both polluted area and control area increased over time during 2004–2010, whereas the proportion of cancer patients and cancer-related financial loss remained constant during these years. Statistical data indicated that cancer incidence during 2004–2010 was 2.6% in polluted area and 3.4% in control area. The growing number of cancer patients and increasing financial loss were hypothesized to arise from the increasingly improved social security system and self-health-care consciousness. The cost for cancer therapy in the control area during 2004–2010 totaled 8 million RMB Yuan with per capita cost of 9.2 thousand RMB Yuan, while in the polluted area, these data were shown to be higher with total cost of 17.96 million RMB Yuan and per capita cost of 12 thousand RMB Yuan.

In addition, retrospective epidemiological study was conducted to determine the morbidity and mortality of cancer and other kinds of disease in this province by stratified sampling. The statistical data indicated no significant difference between the polluted area and control area (data not shown).

6.2. Biomarker responses by exposure to major POPs

In this section, in vitro cell culture experiments, coupled with population survey, were conducted to screen the sensitive biomarkers following PCBs exposure by testing gene expression.

6.2.1. In vitro experiment

In vitro, effects of PCB153, the predominant congener in the environment, and biota in this province, on gene transcription profile in human B lymphoblasts, were investigated using gene chip technique (Human-12T Beadchip, Illumina) [46]. The data indicated PCB153 exposure caused notable change in the transcription level of 161, 191, and 1006 genes, respectively, at concentrations of 25, 100, and 200 μmol/L. Among these genes, 15 genes' expression was altered by PCBs at all exposure concentrations, specifically, upregulation in 4 and downregulation in 11 genes. These results were further validated by real-time PCR assay, and we found CCDC92 and TMEM175 were upregulated while CCL22, STK38L, and GZMK were downregulated following varying exposure periods.

It has been reported that CCDC92 and TMEM195 influence the function of B lymphocyte and T lymphocyte, respectively. CCL22 regulates immune system. Altered CCL22 expression was reported to be potentially associated with cancers. GZMK plays critical role in clearing virus and tumor cells. Altered transcription of STK38L impacted cell cycle and encouraged apoptosis. Therefore, these in vitro tests implied PCB153 potentially disrupted the transcription level of genes relevant to immune system and cancer.

6.2.2. Population survey

The expression of five genes which had altered transcription in the in vitro test, including CCDC92, TMEM175, CCL22, STK38L, and GZMK, was determined in population survey. Furthermore, the transcription levels were compared between the polluted area and the control area [47].

Peripheral blood (2 ml) from population in dismantling areas and in pollution-free areas was collected ($n = 60$). The subjects were grouped by age. Total RNA in peripheral blood from men and women aged 30–40 and 50–60 years was isolated, with three subjects in each group. Quality-inspected RNA samples from three subjects in the same group were mixed for further analysis of gene chips using Human-12T Illumina Beadchip.

The results showed that CCL22 expression declined in PCBs exposure subjects compared with the control group, consistent with the data of in vitro test [48]. GZMK and MTDH expression was upregulated, but the expression of CCDC92, STK38L, and TMEM175 had no change in PCBs exposure groups. The CCL22 gene, located on the q arm of chromosome 16, is a member of the cys-cys (CC) chemokine family, encoding proteins critical for chemotactic activity of monocyte, dendritic cell, NK cell, and T cell. CCL22 primarily functions to regulate immune system by influencing biological process of T lymphocyte, such as transfer of T lymphocyte to the inflammatory sites. Previous studies demonstrated that several kinds of inflammatory diseases, such as atopic dermatitis, rheumatoid arthritis, psoriatic arthritis, and osteoarthritis, occurred with dysregulated expression of CCL22. Moreover, aberrant CCL22 expression was reported to be related with hepatitis C virus infection, acute leukemia, lung cancer, gastric cancer, abdominal aortic aneurysm, and esophageal squamous cancer. PCBs exposure may be correlated with atopic dermatitis, rheumatoid arthritis, osteoarthritis, chronic hepatitis, lung cancer, gastric cancer, and belly aneurysm. In the present study, downregulated CCL22 gene expression was found in PCB153-exposed human B lymphoblasts and in the peripheral blood of PCBs exposure population, suggesting PCBs might disturb the function of immune system by inhibiting CCL22 and eventually cause inflammatory diseases. Nevertheless, further studies are required for investigation of the underlying mechanisms.

The transcription of 68 genes showed significant difference between PCBs exposure population and control population, including 37 upregulated genes and 31 downregulated genes. These genes were found to distribute on all except chromosomes 6, 10, 16, 20, x, and y. They are primarily involved in ribosomal peptide synthesis, pathogenic bacterial infection, cytoskeleton actin regulation, insulin signal pathway, Jak-STAT signal pathway, and endocytosis. Sexually, there were 21 genes in men showing different expression between PCBs-exposed group and control group, including 10 upregulated genes and 11 downregulated genes. These genes mainly function to regulate the signal pathway of ribosome, cytoskeleton actin, and phagocytosis. In women, 316 genes had significant change in expression level in PCBs-exposed population, including 181 upregulated and 135 downregulated genes. These genes primarily regulate ribosome, metabolism, oxidative phosphorylation, Alzheimer's disease, Parkinson's disease, cytoskeleton actin, Huntington chorea, cancer, chemokine signal transduction, small-cell lung cancer, infection pathogens, Jak-STAT signal pathway, and endocytosis. Our study demonstrated that there was sexual difference in response to PCBs exposure, and women were more susceptible. The expression of genes associated with nervous system in women was altered, which was not observed in men.

In general, the results of the present study indicated PCBs exposure caused altered expression of genes involved in nervous-system- and immune-system-related diseases and cancers, despite inconsistent results of in vitro cell culture test and population survey. Additionally, our study showed women were more sensitive to PCBs exposure, and CCL22 might serve as a powerful and effective biomarker of PCBs exposure.

6.3. Animal experiments: rat, mouse, and zebrafish

6.3.1. Toxicity of circuit board powder to male mice

In this section, circuit board powder was used to elucidate the toxic effects of pollutants in e-waste, including heavy metals and various POPs, on organs of male mice, especially the reproductive system [49]. Male ICR mice were fed either normal chow diet or mixed diet containing circuit board powder. The weight and food intake were recorded periodically. After 90-day exposure, the animals were sacrificed and the organs, including brain, heart, liver, spleen, lung, kidney, and testis, were weighed and histopathologically examined. Organ coefficients were calculated, and PBDEs levels in the liver and brain were determined. Sperm motility and the relevant kinetic parameters were measured, and the expression of Connexin43 protein in testis was tested by immunofluorescence. The acute oral LD50 of male mice after 24-h exposure to circuit board powder was higher than 10,000 mg/kg. After a 90-day subchronic exposure, the organ coefficients of liver (4.63 ± 0.39), kidney (1.72 ± 0.29), brain (1.02 ± 0.13), and lung (0.51 ± 0.04) in exposed groups were significantly higher than those in the control group (liver: 3.99 ± 0.42, kidney: 1.38 ± 0.16, brain: 0.85 ± 0.15, lung: 0.46 ± 0.06). Pathological damage occurred in the liver and kidney of exposed animals. PBDEs levels in liver (175.54 ng/g ww) and brain (29.60 ng/g ww) of exposed animals were enormously elevated compared with those in control group (liver: 2.16 ng/g ww, brain: 0.12 ng/g ww). However, no significant difference was observed between the tested groups and control group in terms of organ coefficient, pathological section and Connexin43 expression in testis, and motility and kinetic parameters of sperm. In general, oral exposure to circuit board powder caused pathological changes in the liver and kidney of adult male mice, but had no toxic effects on the reproductive system.

6.3.2. Chronic oral toxicity of circuit board powder to rat

Toxicity of circuit board powder to rats was investigated by subchronic oral exposure experiments [50]. Briefly, SD rats were fed either control diet or mixed diet containing circuit board powder at doses of 10, 20, and 50 g/kg. A chronic exposure experiment of 90 days was conducted, followed by a 45-day recovery test. After 90-day exposure period, organ coefficients in each group were calculated and blood biochemical indexes were measured. Additionally, contents of thyroxine T3, T4, and testosterone (T) were determined after 45- and 90-day exposure and 45-day recovery exposure. The results indicated that there was no statistical difference in body weight between the exposed and control groups. The organ coefficients in exposed female rats were significantly higher than those in control animals. After 45- and 90-day exposure, the contents of T3, T4, and T were significantly increased in all groups exposed to the circuit board powder when compared to the control. No difference of T3, T4, and T contents was observed between higher dose groups and control group following 45-day recovery exposure. The findings suggested that exposure to circuit board powder caused notable liver damage and significant increase of plasma T3, T4, and T levels in rats.

6.3.3. Toxicity of circuit board powder leachate to zebrafish

Chemical analysis was conducted to determine the concentrations of heavy metals in circuit board powder and leachate [51]. As expected, a large amount of heavy metals, including nickel, cadmium, iron, copper, manganese, and lead, was detected, with the top three of copper, lead, and iron. However, in the circuit board powder leachate, no lead was detected, and the concentrations of the other five metals were extremely low, suggesting less possibility of water pollution due to circuit board powder stack. Furthermore, toxicity data indicated that circuit board powder had no toxicity to adult zebrafish following 28-day exposure at the tested concentrations.

7. E-waste management in ZJ province

7.1. Status of e-waste recycling

Due to large-amount imports from developed countries, coupled with domestic use, the amount of e-waste in China has been steadily increasing in recent decades [52]. China has been becoming one of the biggest centers for e-waste dismantling and recycling in the world [53].

ZJ province is one of the most developed regions in China, where the replacement of appliances is very fast and the amount of obsolete electronic devices is quite large. In December 2003, the National Development and Reform Commission (NDRC) initiated the national pilot program for e-waste management system, and ZJ was the only province selected to implement the pilot project due to the large-amount e-waste from domestic generation and imports from developed countries [54]. Since then, a large number of e-waste recycling centers in ZJ province have been established. The e-waste recycling sites in this province are mostly distributed in the southeast coastal areas [55]. The regions of developed e-waste recycling industry include LQ and WL areas in TZ city, and ZH area in NB city. TZ is the biggest e-waste recycling center in ZJ province with a nearly 30-year history for e-waste disassembly and has one of the largest e-waste recycling facilities in the world [56, 57]. According to the statistical data, more than 100 thousand people in TZ worked on the e-waste recycling activities, and the annual e-waste amount reached 2 million [8]. The e-wastes disposed in these areas mainly include electrical machine, transformer, and electric wire and cable [56].

7.2. Management of e-waste recycling industry

Given the rapid increase of e-waste, as well as the potentially concomitant environmental effects and health risk to human and wildlife [58], it is essential to establish sound and environmentally benign management system for e-waste [59]. Legislative Affairs Office of ZJ province subsequently published Pilot Measures for Recovery Processing of Waste Electrical and Electronic Products in ZJ province. This pilot measures apply to natural person, legal entity, and any other organization engaged in production, use, sell, repair, and import of electrical and electronic equipment or e-waste disposal and recycling activities, and aim to reduce the use of hazardous chemical in electronic appliances and the pollution generated during the manufacture, recycling, and disposal of these products. Furthermore, as the biggest e-waste recycling center of this province, TZ has enforced a series of policy measures and regulations for e-waste management. The Economic and Trade Department of ZJ province also made great contribution to establishment of e-waste recycling and disposal system and implementation of the pilot project in many e-waste disposal sectors. Thus, in recent years, a great advance has been obtained in e-waste recycling management in ZJ province.

7.3. Problems in e-waste disposal and recycling

With the growing amount of e-waste, it has been widely recognized the importance of establishing a sound and regulated e-waste management system in ZJ province. Reclamation of precious materials for reuse from e-waste has practical significance for development of circular economy in ZJ province. Despite recent improvement in e-waste recycling industry, there still exist a lot of problems in e-waste disposal and recycling framework in this province. Specifically, the responsibility of the government, producer, assembler, importer, or dealer for the collection and recycling of e-waste is not very explicit. Secondly, although a great many formal e-waste recycling centers with large-scale solid waste incinerators equipped with exhaust treatment device have been established, due to lack of sound recycling network, a large amount of e-waste flows to informal small-scale family workshops for disposal and recycling using crude and primitive methods such as manual disassembly and open burning, which bring about potential detrimental environmental effects. Thirdly, the cooperative management and joint law enforcement of different sectors are not coordinated and effective. Additionally, the reward system and subsidy system in the provincial government require further improvement to ensure the benefits of business owners of formal e-waste recycling companies and encourage their initiatives. Based on these remained problems, in the future, the e-waste recycling industry should be regulated through establishing sound legislation, such as extended producer responsibility (EPR) legislation, and the informal e-waste disposal and recycling processes should be replaced by large-scale facilities.

8. Conclusion

Our study for the first time determined the residue levels of major POPs in the environmental media, local food, and human body in ZJ province. Fingerprints of PCBs and PCDD/Fs were identified in various kinds of food, body fat, human blood, and breast milk. Body burden of PCBs and PCDD/Fs in special populations (children, women, and occupational population) was compared between polluted sites and reference sites. POPs pollution and cancer incidence in polluted areas and control areas were surveyed, and the correlation was analyzed. Furthermore, the results of in vitro and in vivo tests provided evidence that the CCL22 gene could be used as a effective biomarker for PCBs exposure. Acute toxicity, subacute toxicity, and subchronic toxicity of circuit board powder to experimental animals were as well investigated.

Generally, the present study provided integrated information for the assessment of POPs pollution level in ZJ province. The data suggest that the pollution status of major POPs in the environment is undesirable and should be noteworthy. Especially, the pollution levels in east coastal areas, such as LQ and ZH, were shown to be more serious than the middle and west areas, which may result from the long history of e-waste dismantling activities in these areas. However, due to long-range transport of POPs through atmosphere and biomagnification via food chain, there was mild pollution of PCBs and PCDD/Fs in the midwest areas. In the littoral zone, rude and primitive e-waste recycling processing, such as manual dismantling and open incineration, may be one of the most important reasons for POPs pollution in the ambient environment.

In recent years, due to some techniques improvement in e-waste dismantling industry and the widespread application of pollution control measures, the environmental quality in some areas of intensive e-waste recycling industry has been improved to some extent. However, there still exist many obstacles and challenges involved in combating e-waste and improving the environment in ZJ province. In the future, more efforts should be devoted to propaganda and enforcement of pollution control regulations, and should optimize the e-waste recycling management framework, development of advanced techniques for e-waste disposal and recycling, regular monitoring of environmental pollution level, and implementation of comprehensive health surveillance of the human population for cancer control in this province.

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Chapter 4

The Generation, Composition, Collection, Treatment and Disposal System, and Impact of E-Waste

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61332

Abstract

The problem of e-waste has forced governments of many countries to develop and implement environmentally sound management practices and collection schemes for E-waste management, with a view to minimize environmental impacts and maximize re-use, recovery and recycling of valuable materials. In developed countries, e-waste management is given high priority countries, while in developing countries, it is exacerbated by completely adopting or replicating the e-waste management of developed countries and several problems including, lack of investment, technological, financial, technically skilled human resources, lack of infrastructure, little available information on the e-waste situation, recovery of valuable materials in small workshops using rudimentary recycling methods, lack of awareness on the impacts of e-waste, absence of appropriate legislations specifically dealing with e-waste, approach and inadequate description of the roles and responsibilities of stakeholders and institutions involved in e-waste management, etc. This chapter provides the definition of e-waste, and presents information on generation of –andcomposition of e-waste, collection, treatment, and disposal systems. It also discusses the overview of e-waste collection schemes in different parts of the world with regional focus, and the best current practices in WEEE management applied indeveloped and developing countries. It outlines the illegal e-waste trade and illegal waste disposal practices associated with e-waste fraction. In this chapter, the terms "WEEE" and "E-waste" are used synonymously and in accordance to the EU, WEEE Directive.

Keywords: e-waste, illegal trade, recovery, collection, treatment, disposal system

1. Introduction

The information technology (IT) industry is an important engine of growth of any country. With the rapid development of technology, manufacturers now produce superior televisions,

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new and smarter mobile phones, and new computing devices at an increasing rate. People are enjoying what technology brings, surfing the Internet on their smart phones or tablets and watching high-definition movies on their televisions at home. As more and more electronic products are produced to fulfill the needs of people worldwide, more resources are used to produce these items. Hence, the rapid growth of computing and other information and communication equipment is driving the ever-increasing production of electronic waste (e-waste) [1]. The current e-waste encompasses a particularly complex waste flow in terms of the variety of products [2-3]. Over the next few years, one billion computers will be obsolete. In 2005, 8.3-9.1 million tons of e-waste was produced across the 27 members of the European Union (EU) [4]. By 2020, the total waste electrical and electronic equipment (WEEE) is estimated to grow between 2.5% and 2.7% annually, reaching a total of approximately 12.3 million tons. The reason is that the number of appliances entering the market every year is increasing in developed and developing countries [5]. Sales of electronic products in countries such as China and India and across Africa and Latin America are predicted to rise sharply in the next 10 years. Also, it is a higher growth pattern that will be influenced not only by need but also by changes in technology, design, and marketing [1]. The diverse waste generated due to advancement of technology may have significant impacts on the environment and public, if not properly stored, collected, transported, treated, and disposed of. Thus, around the globe, e-waste generation, treatment, and disposal are becoming issues of concern to waste management professionals, innumerable non-governmental organizations and citizens, and international agencies and governments, particularly in developing and transition countries. E-waste stream contains diverse materials, which requires special treatment and cannot be dumped in landfill sites, most prominently, hazardous substances such as lead, polychlorinated biphenyls (PCBs), polybrominated biphenyls (PBBs), mercury, polybrominated diphenyl ethers (PBDEs), brominated flame retardants (BFRs), and valuable substances such as iron, steel, copper, aluminium, gold, silver, platinum, palladium, and plastics [6-7]. During the last decade, large amounts of diverse e-waste discarded by developing and transition countries, as well as a sizeable portion of the e-waste generated from developed countries and exported to developing and transition countries, has been rapidly piling up in developing countries impacting their emerging economies [8]. The management of e-waste in developing and transition countries is exacerbated by several factors, including illegal trafficking and unlicensed recycling of e-waste; lack of technological, financial, and technically skilled human resources; inadequate organizational structure required; and an inadequate description of the roles and responsibilities of stakeholders and institutions involved in e-waste management. In Africa, e-waste management is still in its infancy; characterized by little available information on the e-waste situation, the recovery of valuable materials in small workshops using rudimentary recycling methods, lack of awareness on the impacts of e-waste, and the total absence of policy specifically dealing with e-waste [9].

To describe the situation of e-waste around the world, this chapter provides the definition of e-waste. The next section of the chapter presents information on the generation, composition of e-waste, collection, treatment, and disposal systems. It also discusses the overview of e-waste collection schemes in different parts of the world with a regional focus, and the best current practices in WEEE management in developed and developing countries. It outlines the illegal e-waste trade and illegal waste disposal practices associated with e-waste fraction. In this chapter, the terms “WEEE” and “E-waste” are used synonymously and in accordance to the EU WEEE Directive.

2. Definition of e-waste

An electrical and electronic product can be classified as a product that contains a printed circuit board (PCB) and uses electricity. Much has been written about the e-waste problem, yet the definition of the term "electronic waste" is quite complex to define. Referring to scholarly literature on the topic, there is, as yet, no standard definition, as every country has its own definition of e-waste. The questions that arise, therefore is: What is to be called e-waste? Any electronic or electrical appliances, which are obsolete in terms of functionality? Products that are operationally discarded? Or is it both? [10]. Table 1 gives a list of the different definitions of e-waste.

Reference	**Definition**
European Union Waste Electronic and Electrical Equipment (EU WEEE) Directive [11]	Waste from electrical or electronic equipment refers to “*all components, sub-assemblies, and consumables, which are part of the product at the time of discarding*”. In the Directive 75/442/EEC, Article 1(a), waste is primarily defined as “*any substance or object that the holder disposes of or is required to dispose of pursuant to the provisions of the national law in force*”.
Basel Action Network [12] Puckett and Smith [13]	E-waste means “*discarded appliances using electricity, which include a wide range of e-products from large household devices such as refrigerators, air conditioners, cell phones, personal stereos, and consumer electronics to computers which have been discarded by their users*”.
Organization of Economic Cooperation and Development (OECD) [14]	E-waste can be classified as “*any appliance using an electric power supply that has reached its end of-life*”.
SINHA [15]	E-waste can be described as “*an electrically powered appliance that no longer satisfies the current owner for its original purpose*”.
Solving the E-waste Problem (StEP) [16]	“*E-waste refers to the reverse supply chain that collects products no longer desired by a given consumer and refurbishes for other consumers, recycles, or otherwise processes wastes*”.

Table 1. Different definitions of e-waste.

Many researchers have established that a clear definition of e-waste is needed due to rapid technological changes and enhancement, which are shortening the lifespan of the electronic products [8-10]. To date, the widely accepted definition in different e-waste studies is by the EU WEEE Directive, which defines e-waste as “*Electrical or electronic equipment (EEE) which is* *waste, including all components, sub-assemblies, and consumables, which are part of the product at the time of discarding"* [11]. E-waste is usually described in terms of the cost and durability of products used for data processing (e.g., telecommunications or entertainment in private households and businesses) [17].

3. E-waste generation

The major problem associated with e-waste management is its ever increasing quantum. However, the e-waste quantities represent a small percentage of the overall municipal solid waste (MSW). Data on e-waste generation may vary between areas of a country because of the definitions of waste arising, technological equipment used, the consumption patterns of the consumers, and changes in the living standards across the globe [18]. Global e-waste generated per year amounts to approximately 20-25 million tons, most of which is being produced in rich nations such as the United States (US) or European Union member countries. The US, is the largest generator of e-waste, with a total accumulation of 3 million tons per year; and China is the second largest, producing 2.3 million tons each year. Brazil generates the second greatest quantity of e-waste among emerging countries [19].

In Malaysia, the volume of e-waste generated is estimated at roughly 0.8-1.3 kg of waste per capita per day, with an increasing trend of e-waste generation, which rose to 134,000 tons in 2009. Furthermore, the volume of e-waste in Malaysia is expected to rise to 1.1 million metric tons in 2020, at an annual rate of 14% [20]. In South Africa and China, e-waste production from old computers will increase by 200-400% from 2007 to 2020, and by 500% in India. In this same period e-waste from televisions will be 1.5-2 times higher in China and India; whereas in India, e-waste from discarded refrigerators will double or triple by 2020. For India, the volume of e-waste generated is 146,000 tonnes per year. However, these data only include e-waste generated nationally and do not include waste imports (both legal and illegal) which are substantial in emerging economies such as India and China [21]. The reason is that large amount of WEEE enters India from foreign countries without paying any duty in the name of charity [22-23]. The rate at which the e-waste volume is increasing globally is 5 to 10% yearly [24].

4. Composition of e-waste

E-waste normally contains valuable, as well as potentially toxic materials. The composition of e-waste depends strongly on factors such as the type of electronic device, the model, manufacturer, date of manufacture, and the age of the scrap. Scrap from IT and telecommunication systems contain a higher amount of precious metals than scrap from household appliances [6]. For instance, a mobile phone contains more than 40 elements, base metals such as copper (Cu) and tin (Sn); special metals such as lithium (Li) cobalt (Co), indium (In), and antimony (Sb); and precious metals such as silver (Ag), gold (Au), and palladium (Pd) [25-27]. Special treatment of e-waste should be considered to prevent wasting valuable materials and rare elements. Materials such as gold and palladium can be mined more effectively from e-waste compared to mining from ore [28]. By contrast, e-waste contains PBDEs, which are flame retardants that are mixed into plastics and other components. Circuit boards found in most of the electronic devices may contain arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), and other toxic chemicals. Typical printed circuit boards treated with lead solder in electronic devices contain approximately 50 g of tin-lead solder per square meter of circuit board [7]. Obsolete refrigerators, freezers, and air conditioning units contain ozone depleting Chlorofluorocarbons (CFCs). The prominent materials such as barium, cadmium, copper, lead, zinc, and other rare earth metals are contained in end-of-life (EOL) cathode ray tubes (CRTs) in computer monitors, and televisions. For example, items such as leaded glass provide protection against X-rays produced in the picture projection process in CRTs [6]. The average lead in CTR monitors is 1.6-3.2 kg. Thus, the US and other developed countries in the EU and Japan have banned the disposal of cathode ray tubes in landfills because of their toxic characteristics. A critical challenge in designing and developing strategies to manage e-waste is the changing composition of the many constituents due the advancement of technology, particularly in the electronic components [24]. It is against this background that e-waste recycling and disposal methods ought to keep pace with the changing composition of e-waste. Several factors influence the composition of e-waste, including economic conditions, availability of a reuse market, and infrastructure of the recycling industry, waste segregation programs, and regulation enforcement. Figure 1 illustrates the distinctive materials in a WEEE.

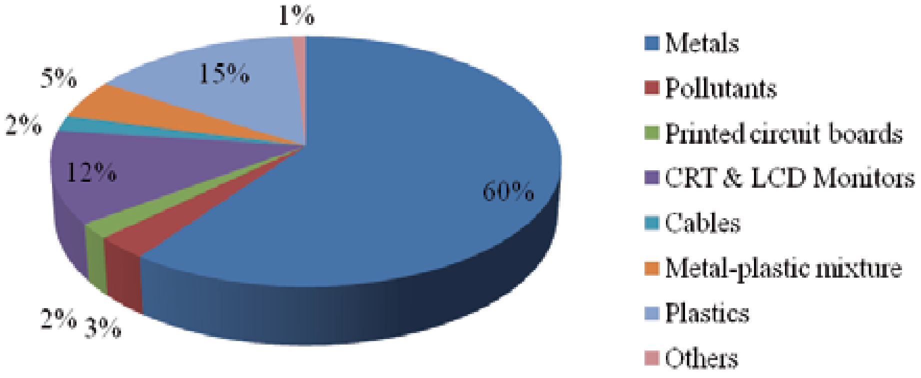

Figure 1. The distinctive contents of a WEEE. Source: Adapted from [9].

5. E-waste data for several countries across the globe

5.1. Amount of e-waste collected and treated

E-waste generated from the different diverse sources is normally collected as a whole unit or sub-unit of functional equipment. In many instances across the globe, whole units of e-waste have been categorized as e-waste. Based on the number of discarded information communication technology (ICT) devices collected in Europe, computers, cell phones, fixed-line telephones, televisions, and radios are the major electronic products, and together they amounted to 11.7 million tons in 2007. In 2004, approximately 75,000 tons of WEEE were collected, classified, disassembled, and then processed in Switzerland, compared with the collection of approximately 68,000 tons in 2003 [29].

In developing and transition countries, little consideration is given to the quantification of the e-waste collected. The reason is that in pre-reprocessing stages, collection of the e-waste is mostly undertaken by the unorganized sector of scrap dealers/traders or peddlers. As a result, this information is invisible to the statistics collection system, which makes quantification of e-waste very difficult in developing and transition countries [27]. More precise figures regarding unused electronic and electrical equipment/waste electronic and electrical equipment (UEEE/WEEE) are not available because the customs data do not distinguish between used and new equipment and the import statistics reveal only total values [29]. Based on the current understanding on e-waste management, research studies suggest that to achieve sustainable development goals associated with waste management would require successful establishment of baseline levels of information from which more informed e-waste management and policy decisions can be made [30]. Similarly, to effectively manage e-waste could require establishment of separate collection channels that would be environmentally friendly. This could result in the reduction of e-waste generated and its environmental impacts [31].

In the EU, the EU WEEE directive clearly imposes collection, recovery, and recycling targets on its member countries. Thus, it stipulates a minimum collection target of 4 kg/capita per year for all the member states. These collection- and weight-based recycling targets seek to reduce the amount of hazardous substances disposed into landfills and to increase the availability of recyclable materials that indirectly encourages less virgin materials consumption in new products [11]. Switzerland is the first country in the world to have established and implemented a formal e-waste management system that has recycled 11 kg/capita of WEEE against the target of 4 kg/capita set by the EU. One-third of electrical and electronic waste in the EU is reported as separately collected and appropriately treated. In 2006, Germany collected and treated about 754,000 tons of e-waste according to the ElektroG system, while other EU member states collected about 19,000 tons. It was also forecasted that IT and telecommunications equipment put on the market were 315,000 tons, and the waste collected and treated in the system according to ElektroG was about 102,000 tons (7,000 tons of this was collected from other EU countries) [29]. This shows the effective collection and treatment of e-waste in the EU. The introduction of the extended producer responsibility (EPR) scheme in 2003 was the most important step in South Korea, and about 70% of e-waste was collected by producers. Over the same period, the amount of e-waste reused and recycled was 12% and 69% respectively. The remainder was sent to landfill sites or incineration plants, accounting for 19% [32].

5.2. Amount of e-waste disposed

The scientific and environment friendly disposal of e-waste is critical. Relevant past studies on e-waste management confirmed that rapid growth combined with rapid product obsolescence are the most important factors making discarded e-products one the fastest growing waste fraction, accounting for 8% of all municipal waste in the EU. If not disposed of properly it could lead to significant negative environmental impacts. The average for developing and transition countries was 1% of total solid waste, which increased to 2% in 2010 [33]. Developing and transition countries, especially those in Africa and Asia, are the primary destinations for e-waste dumping, despite these countries lacking basic disposal technologies or facilities [34].

In 2012, more than 70% of the total electronic waste collected worldwide was actually exported or discarded by developed countries [35]. In the US alone, 130,000 computers and more than 300,000 cell phones are disposed each day, and an estimated 80% of the generated e-waste is sent to less-developed countries [36]. In 2007 in the US, 410 thousand tons were recycled (13.6%), and the rest was improperly discharged in landfills or incinerated. Between 2003 and 2005, approximately 80-85% of the e-waste ready for EOL management ended up in US landfills. A related study about e-waste management in the US pointed out that in 2009, enormous quantities of e-waste (82.3%) was disposed in landfill sites and incinerators, while 17.7% went to the recyclers [26]. In the EU, it is shown that two-thirds of this waste stream is potentially still going to landfills and to sub-standard treatment sites in or outside the EU. In China, huge volumes of e-waste have been discarded in recent years as people more frequently replace their old home appliances with new ones [37-39].

A relevant case-study on e-waste management pointed out that it is not possible to make an overall comparison between different countries, even if they are in the same continent, as the definitions in legislation and categorization of e-waste streams differ. Nevertheless, it is established that the main volumes of e-waste reside in developed countries [40].

6. Collection, treatment, and disposal systems

Collection, treatment, and disposal systems are critical elements of e-waste management. Most developed countries have framed conventions, directives, and laws aimed at fostering proper collection, treatment, and recycling of e-waste, as well as safe disposal of the non-recyclable components [36]. These include the EPR, product stewardship, advance recycling fund (ARF), the 3Rs or Reduce, Reuse, Recycle initiative, etc. For the EU, two directives have been promulgated to place an obligation on the producers of e-goods to take back EOL or waste products free of charge in an effort to reduce the amount of waste going to landfills [37]. However, in developing and transition countries, e-waste is treated in backyard operations, using open sky incineration, cyanide leaching, and simple smelters to recover precious metals mainly copper, gold, and silver—with comparatively low yields—and discarding the rest with municipal solid waste at open dumps, into surface water bodies and at unlined and unmonitored landfills [35], thereby causing adverse environmental and health effects. Table 2 presents a comparison of typical e-waste treatment processes in developed and developing countries.

Developing countries	Developed countries
"Informal" sector	Formal sector
Manual dismantling	Manual dismantling
Manual separation	Semi-automation separation
Recovery of metals by heating, burning, and acid leaching of e-waste scrap in small workshops	Recovery of metals by the state-of-the-art methods in smelter and refineries

Table 2. Comparison of typical e-waste treatment processes in developed and developing countries [41].

6.1. Disposal system

Disposal of e-waste is mainly through landfilling. Most often, the discarded electronic goods finally end-up in landfill sites along with other municipal waste or are openly burnt releasing toxic and carcinogenic substances into the atmosphere. In developing and transition countries the disposal of e-waste in the informal sector is very rudimentary so far as the safe techniques employed and practices are concerned, resulting in low recovery of materials [38]. Table 3 presents a comparison of typical disposal systems in developed and developing countries.

Developed countries	Developing countries
Incineration with MSW	Opening burning
Landfill disposal	Open dumping

Table 3. Comparison of a typical e-waste disposal systems in developed and developing countries [13].

E-waste management is different between developed countries and developing and transition countries. Developing and transition countries do not have guidelines and information campaigns on the fate of e-waste. Especially, less sophisticated disposal systems are used, from open burning and dumping to uncontrolled landfill sites, which pose significant environmental pollution and occupational exposure to e-waste-derived chemicals [31]. Serious challenges in the disposal of e-waste were analyzed across developing countries such as Brazil [19], China [42], and India [43], outlining the difficulty to implement/enforce existing regulations and clean technologies backed by lack of capacity building and awareness. In contrast, developed countries have devised sophisticated disposal schemes and high-cost systems, which are less hazardous to handle waste. However, a comprehensive overview of the situation is constrained by the availability of data. This means that the differences in the socio-economic and legal contexts between typical developing and developed countries' scenarios limit e-waste management in developing and transition countries. The regulations that guide the disposition of e-waste in developing countries is mostly fragmented and lack monitoring, while in developed countries the regulations are stringent and there is effective monitoring [36].

7. An overview of e-waste collection schemes in different parts of the world with a regional focus

In general, citizens must sort and segregate e-waste to divert e-waste from mixed municipal waste collection schemes and landfills due to the heteremeneous materials it contains. It needs to be stored, and then transferred to the curbside or transported to an offsite collection site [27]. Although research has supported that curbside collection is the most convenient collection system for households, offsite drop-off remains attractive to waste management authorities. This is because curbside collections are regarded as expensive, time-consuming to design, implement, and operate [28].

In essence, a separate, parallel collection and management scheme is required, organized by the authorities, the producers, or retailers. Compared to simple or commingled collection, such as single-stream collection, source separation imposes additional efforts on citizens regarding material segregation and drop-off and, thus, convenience is of paramount importance [34]. In developed countries, e-waste is collected to recover some materials of value and to be safely rid of the lead, cadmium, mercury, dioxins, furans, and such toxic materials they contain. On the other hand, in developing countries, e-waste is collected principally to recover a few metals of value. E-waste collection is logically a profit-driven activity. E-waste contains a huge volume of different engineering materials that can be reused via available and evolving technologies [9].

7.1. The Asian region

In Malaysia, a planned infrastructure is being promoted for whole units of WEEE to be collected from households, business entities, and institutions [20]. The Department of Environment (DoE) and the Japanese International Cooperation (JICA) are trying to develop an e-waste collection model for household items in Penang state for the very first time. This model is expected to be used to make a countrywide drive after the model's test run, which may happen in the next few years. However, this model has limitations, and only can ensure the collection of a small portion of e-waste. Thus, there is no engineering analysis on material characteristics, remanufacturing potential, and economic benefits, and an optimization analysis is not yet planned. Moreover, there is no reverse logistic system in this model. The e-waste collection activities in Malaysia include: DoE-licensed contractors, retailer's collection, environmental working groups, voluntary collection organization, social organizations, informal scrap collectors, street buyers, scavengers, traditional hawkers (Surat khabar lama), and manufacturers' initiatives such as Panasonic Malaysia ECOMOTO Take back, Nokia Malaysia, Dell Malaysia HP, and Pikom (National ICT) [39].

In other Asian countries, collection of most -waste materials and components remains in the hands of the informal sector. "Scavenging" or the informal sector is the predominant collection scheme of e-waste in the Asian region. Using inappropriate methods, this poses a severe threat to the environment and health of the workers [41]. For instance, in China, Taiwan, Thailand, the Philippines, Indonesia, and other neighboring countries [42], this informal stream of e-waste collection is not under regulation, and most of the e-waste ends up in landfills through the informal stream. Furthermore, collection systems and procedures in the region are very loose, and there is limited established market for finished products resulting from recycling [41]. Customers need to be given incentives to return their EOL e-products back to the collection centers. In India and China, studies equivocally state that consumers look for economic benefits for discarding their e-waste. Thus, the Chinese residents, in the likelihood of a take-back regime, reportedly seem to prefer the pay-in-advance scheme against the deposit-refund route favored by residents in India. There exists a very well networked and effective door-to-door collection network in India [43]. China has established special recovery industrial parks in Tianjin, Taicang, Ningbo, Linyi, Liaozhong, Taizhou, and Zhangzhou in order to promote efficient and environmentally friendly recovery of original and imported metals. The collection of discarded household electronic and electrical equipment in China is still dominated by the so-called informal individual collectors (peddlers). They provide a door-to-door service by paying marginal fees to e-waste owners and then sell them to e-waste dealers [44].

7.2. The European Union context

Consumers in Europe use municipal collection, retailer collection, social organization collection, and the re-use market to collect e-waste. The so-called municipal collection is performed by local authorities (municipalities or counties). It is pointed out that some municipalities collect the WEEE themselves, while others themselves, while others contract with other parties to collect to collect it on their behalf. Municipal collection activities are managed and financed by public waste management entities, whereby drop-off points and doorstep collection are used [45]. Retailer collection is performed either by the retailers themselves or by their logistics partners who deliver new appliances to consumers. Social organization collection is performed in cooperation with several members of the reverse supply chain, with the purpose of providing a material input to and a financial benefit for the social organizations. The re-use market extends the use phase of appliances, thereby delaying the final discarding by the ultimate owner/user of the appliance into municipal, retailer, or social collection [45-46]. Germany has developed a curbside collection scheme and is already achieving remarkable success in e-waste management andrecycling. The typical collection channels in the EU, from dismantling through pre-processing until end-processing, lead to the safe disposal or processing of e-waste [41].

7.3. The situation in the US and Canada

The US and Canadian provinces are increasingly adopting EPR and product stewardship (PS) schemes for WEEE. For instance, in the state of Maine in the US, the WEEE management program is based on a PS scheme, with the active participation of retailers [47]. Three American-based non-governmental organizations (NGOs) are particularly active in e-waste issues. The Basel Action Network (BAN), Silicon Valley Toxic Coalition (SVTC), and Electronics Take-Back Coalition (ETBC) constitute an associated network of environmental advocacy NGOs in the US. The three organizations' common objective is to promote national-level solutions for hazardous waste management [7]. A recent initiative has been e-Stewards, a system for auditing and certifying recyclers and take-back programs so that conscientious consumers know which ones meet high standards. Canada is among the countries developing systems based on these principles and EPR. Also, Canada has well-developed and advanced collection systems. In the US, Apple, Sony, Sharp, Mitsubishi, Samsung, Hewlett-Packard, Dell, LG, Lenovo, Panasonic, and Toshiba have free collection point or mail-in take-back programs of their products [48].

7.4. Japan and Brazil

Japan has a door-to-collection scheme to separate e-waste from being mixed with other municipalcollection schemes. The retailers and the municipality, in some cases, are obliged to transfer the collected units to the producers' designated collection points and subsequently pass on the recycling fee to the producers. The producers are mandated to collect e-waste from their designated collection points and achieve the recovery targets set under the legislation [49]. In Brazil, "e-scrap" can be disposed of and recycled through three mechanisms: social organization collection, manufacturer collection, and retailer collection [50].

Overall, the waste collection infrastructure in developing countries is characterized by a high level of informality. Thus, a certain level of informality will prevail even when a regulated e-waste management system becomes operational [41]. Evaluating the e-waste management in developing and transition countries, it has been established that the informal recyclers will continue to collect major components of e-waste with economic value from individual households. Similarly, research showed that the major challenge is to guide the informal sector toward systems that could work in a regulated environment in the future [31]. Hence, increasing attention on incentivizing individual and corporate consumers to dispose potentially harmful WEEE into formal collection systems would systematically improve the effectiveness of e-waste management systems. Consequently, financial plan could provide compensation for the return of obsolete equipment to make the system more effective and sustainable [51].

8. The best current practices in WEEE management applied in developed and developing countries

Managing the increasing quantum of e-waste effectively and efficiently-in terms of cost and environmental impact is a complex task. Thus, the adoption of best practices and implementation of mitigation measures are important steps to manage e-waste products, particularly at the EOL. Hence, developing and developed countries have responded to these growing quantities of e-waste and their potential impacts by developing various disposal pathways, several measures, and legal frameworks to properly manage such waste [43]. It is established that when developing an effective e-waste management system, the following should be considered:

- Collection of e-waste from the source of generation and transportation to disposal sites and treatment facilities require special logistic requirements [2].
- Disposal of e-waste requires specialtreatment to minimize impacts on the environment; e-waste contains many hazardous substances that are extremely dangerous to human health and the environment.
- E-waste is a rich source of precious metals such as gold, silver, and copper, which can be recovered and recycled/reused into the production cycle [50].

Significant differences exist in the management of e-waste between developed countries and emerging economies. Many developed countries have understood the importance of developing and implementing regulatory approaches (laws and regulations) to tackle the ever increasing quantum of WEEE, and framed and formulated various laws and regulations to restrict the negative impact of WEEE on occupational health and the environment [52].

8.1. The best current practices in WEEE management applied in developed countries

8.1.1. The EU context

Switzerland is the first county in the world to develop and implement a well-organized and formal e-waste management system for collection, transportation, recycling/treatment, and disposal of e-waste [28]. Thus, the EPR principle is used as a framework to manage e-waste. The EPR makes manufacturers/producers and exporters of products responsible for the environmentally sound handling, recycling, and disposal of the e-waste [53]. Two-based Producer Responsibility Organizations (PROs) are responsible for the management of e-waste. The Swiss Association for Information Communication and Organizational Technology (SWICO) and Stiftung Entsorgung Schweiz (S.E.N.S.) constitute the PROs in the Swiss system. The two PROs are responsible for the management and operations of the system on behalf of their member producers covering different parts of WEEE, as defined by the European WEEE directive [11, 53]. In the Swiss system, consumers of EEEs are required to pay ARF when purchasing new ones for the daily operation of the system such as collection, transport, and recycling/disposal. The ARF requires that the end consumer pays the recycling fee, which is equivalent to the difference between the total system cost and the total recovered value from the e-waste, and ensures that the necessary finances for the system as the fees are collected in advance. Analyses of the Swiss system showed that the consumers willing to dispose of their e-waste are free to deposit old or obsolete appliances, regardless of the brand or year of manufacture free of charge to any retail shop or 500 official collection points. The ARF prevents the illegal disposal of e-waste since consumers are willing to pay small amounts of money when purchasing the new products rather than EOL, which they will ultimately have to dispose [54].

To ensure the smooth functioning of the Swiss system, multiple levels of independent controls on material and financial flows at every stage have been formulated that check on free riding and pilferage, as well as ensure that the recyclers maintain quality and environmental standards [53]. This also prevents the illegal import and export of e-waste to and from

Switzerland. Hence, Switzerland does not permit the export of e-waste to non-OECD countries and has been a signatory to the Basel Convention Ban Amendment [54].

In July 2001, Sweden executed its WEEE management regulation to ensure the appropriate treatment of WEEE. For instance, consumers can send back old products to retailers when they buy a similar new product (old-for-new or new-for-old rule). Moreover, household consumers can leave their WEEE at municipal collection points, while institutional and enterprise consumers are responsible for covering the expense of treating WEEE. Thus, municipalities are responsible for managing these collection points for household consumers, while manufacturers are responsible for covering the costs of WEEE collection and treatment. Meanwhile, a retailer's responsibility is to accept WEEE from consumers under the old-for-new rule [55].

8.1.2. Japan

Japan has adopted a new legal framework in [56] to kick-start its own WEEE recycling system incorporating EPR with a view to establish a sound material-cycle society that promotes the 3R principle. Such a law was necessitated by the fact that proper treatment of e-waste would enable proper resource recovery and reduce dependence on landfill. A unique feature of the Japanese EPR law is that it is primarily based on the principle of shared responsibility wherein the responsibilities of different stakeholders are explicitly shared. For instance, according to the Home Appliance Recycling Law (HARL), retailers are mandated to collect used products, consumers are responsible for financing recycling and transportation by paying recycling fees to the retailer at the point of disposal, and producers are mandated with setting-up pretreatment plants and collection networks. The above law covers four major e-waste products, namely air-conditioners, televisions, laundry machines, and refrigerators [57].

On the other hand, bulk and business consumers may either engage the treatment of e-waste at their own expense or return to the retailer by paying the requisite recycling fees. The law for the management of e-waste from personal computers (PCs) from the business sector also came into effect on April 2001, while those from the household sector came under EPR law on October 2003 [56]. However, for computers, the costs of recycling are borne at the point of sale, as opposed to at the point of disposal for products under HARL. Yet another law, the Small-sized Home Appliance Law was enacted on April 2013 to cater for small electronic and electrical home appliances such as mobile phones, gaming machines, small personal computers, etc. The new law, which covers about 100 items, does not require consumers to pay recycling fees. Under this new law, the concerned municipality is responsible for setting up collection centers, from where collected waste is to be sent to certify recycling companies. Furthermore, each municipality is stipulated to design their own collection centers and identify the products to be collected [57]. Home appliances are taken back by retailers or secondhand shops according to the flow in Figure 2. However, problems with the recycling system include inelastic recycling fees, illegal dumping, illegal transfer by retailers, and the limited number of target appliances [58].

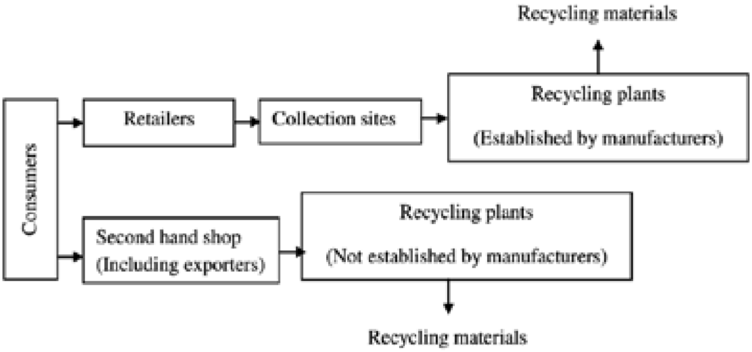

Figure 2. Flow of the take back system in Japan. Source; Adapted from [58].

8.1.3. Singapore

In Singapore, retailers have established commercial take-back schemes for their products. The retailers set prices of used mobile phones based on the quality. It is established that the mobile phones are leased during the contract period (e.g., 2 years), at a lower cost than the sales price. As a result, approximately 95% of used mobile phones are taken-back. The second-hand mobile phone market is well-developed in Singapore, with many retail shops dealing in second-hand phones [59]. This shows effective the collection of EOL e-products by retailers in Singapore.

8.2. The best current practices inWEEE management applied in developing countries

8.2.1. South Korea

Korea has promulgated the Act on the Promotion of Conservation and Recycling Resources (also called the Waste Recycling Act), which took effect in 1992. The act regulated two home appliances, television and washing machines, together with air conditioners and refrigerators. Other statutory instruments include Waste Deposit-Refund System for limited categories of home appliances, packaging materials (e.g., glass, plastics, and cans), and other items (e.g., lubricating oil, batteries, tires, and fluorescent lamps) as part of the Act in 1992; modification of the Waste Recycling Act was made to promote effective collection and recycling of materials and promulgate EPR regulation for items covered by the Waste Deposit-Refund System for personal computers and monitors; and the Act on the Resource Recycling of WEEE and EOL Vehicles, aimed at reducing the amount of e-waste going to landfills and incinerators [60]. In 2003, the EPR system was enforced to promote recycling practices [61].

8.2.2. India and China

China and India have promulgated schemes similar to the EPR. EPR involves producers taking more responsibility for managing the environmental impacts of their products throughout their lifecycle, particularly at the end of their life. Producers that manufacture the EPR products must collect and recycle an assigned quantity based on a certain percentage of their annual production volume. In India, more relevant and important regulation have been issued in the past decade by the Ministry of Environment and Forests (MoEF), and the most important is the letter no. 23-23/2007-HSDM dated March 12, 2008, the guidelines for environmentally sound management of e-waste, which aims to provide guidance for the identification of various sources of e-waste, and outline procedures for environmentally sound handling of e-waste [61]. On May 14, 2010, the MoEF issued a draft of the E-waste (Management and Handling) Rules, 2010. The rules clearly stipulate producer responsibility for the proper collection of e-waste through an appropriate take-back system on the same lines as the European EPR directive [62]. However, this regulation does not describe the specific handling and treatment practices of WEEE. The Hazardous and Waste Management Rules, 2008 and Municipal Solid Waste Management Rules, 2004 aim at addressing the hazardous and non-hazardous materials found in e-waste, but are not specific at defining the roles of the different stakeholders in e-waste management. The main problem in India is the administrative delays to enforce these regulations [63]. The Chinese government has introduced legislation and developed infrastructure on WEEE and the removal of hazardous substance (RoHS) according to EU directives [64].

8.2.3. Brazil

The Brazilian government has developed general environmental regulations applicable to e-waste management, such as Act 12.305 of August 2, 2010, which established a National Policy on Solid Waste, and "reverse logistics" obligation for e-waste, and Decree 7.404 of December 23, 2010. The Committee of the National Policy on Solid Waste (CNPSW) was established to support the structuring and implementation of this policy through the articulation of government agencies. Thereafter, a thematic group (TG) made of different stakeholders, including government departments, industries, municipalities, representatives of NGOs, and scavengers was set up. Only São Paulo state has passed its own e-waste legislation based on EPR, Law 13576, on July 6, 2009 [19].

8.2.4. The African Context

As early as 2004, several projects were successfully initiated in three South African provinces (namely KwaZulu-Natal, Western Cape, and Gauteng) with support from the Global Knowledge Partnerships in e-Waste Recycling program, which was initiated by the Swiss State Secretariat for Economic Affairs (SECO) and implemented by the Federal Laboratories for Materials Testing and Research (EMPA). It is established that some (inter)national-based IT corporations have shown increasing commitment to set up and support initiatives nationwide to address the challenge of e-waste. In order to deal with the sustainable and environmentally sound e-waste management system for the country, the e-Waste Association of South Africa (eWASA) was established on 2008. However, these initiatives lack efficient monitoring and enforcement. As a result, improper e-waste management still exists despite these initiatives [65].

Despite the absence of regulations concerning the specific collection and disposal of e-waste in developing countries some countries provide separate schemes for certain types of e-waste. Increased public awareness and government attention to the problems emanating from e-waste have prompted few manufacturers from developing countries to establish individual take-back schemes for specific products as a part of their corporate social responsibility and green image. In brief, the management schemes are categorized as follows:

- Mandatory product take-backs, as for example in Taiwan
- Voluntary take-back strategies, as for example China and India

Take-back policies in the form of disposal (or recovery) fees either at the time of disposal or at the time of purchase (advance recycling fees or advance disposal fees) have been developed. For instance, the Japanese model argues for both approaches: advance fees for computers, and fees at the point of disposal for home appliances. Conversely, the Californian and Taiwanese models favor advance recycling fees for all products, which are typically used to fund the state-controlled recycling system [66-67]. Advance disposal or recovery fees have the advantage of being visible to all stakeholders that influences better future planning at the downstream end. Additionally, fees charged at the point of disposal might lead to an indifferent disposer who, in all likelihood, might be tempted to illegally dump the used products or perpetually store them [61].

Over the recent years, regulation efforts have been implemented to remove hazardous items or optimally recover the main recyclable materials. Others are aimed at increasing the collection and recycling rates of e-waste through diverse collection programs, encouraging manufacturers to develop more environmentally sustainable products, and requiring manufacturers to take responsibility to recycle their products [41]. The Best-of-2-Worlds (Bo2W) philosophy has been introduced, which seeks technical and logistic integration of the "best" pre-processing facilities in developing and transition countries to manually dismantle e-waste and the "best" end-processing strategies to treat hazardous and complex fractions in international state-of-the-art end-processing facilities [67]. Alternatively, eco-friendly product designs can also reduce the environmental pollution caused by recycling e-waste scrap. At present, Design for Environment (DfE) is attracting much attention in the world as a new method to solve environmental pollution. DfE principle in the product design is a process to significantly reduce the environmental impact of products being put into the market. It is pointed out that DfE is intended for: easy disassembly to encourage recycling of home appliances; recycling by using recyclable materials; energy saving; and reducing hazardous material such as Pb, Hg, Cd, and hexavalent Cr [68]. If DfE, in particular, becomes more widespread, we can expect significant mitigation of environmental damage caused by recycling e-waste scrap [66].

9. An outline of the illegal e-waste trade and illegal waste disposal practices associated with e-waste fraction

9.1. The illegal e-waste trade

Across the globe, high volumes of e-waste have been discarded in recent years. Despite the fact that many countries have already organized e-waste regulations, there are additional problems with the import/export of e-waste. For instance, in industrialized countries such as the US, Japan, and the EU, recycling operations have set high environmental and social standards, which trigger the illegal exportation of WEEE to developing and transition countries [41]. The developing and transition countries lack cleaner technologies, waste minimization measures, and environmental sound management systems. As a result, the items are treated, recycled and/or reused with less consideration for environmental protection and public safety and health [42].

Several countries have ratified the Basel Convention on trans-boundary movement of hazardous waste. It specifies the relevant requirements of governments exporting hazardous waste, and stipulates the responsibility of the government of the importing country. However, because of the lack of management systems for secondhand e-products and e-scraps, these items are not covered by the convention's rules [19]. The Basel Convention does not solve the new environmental problems caused by the recycling of e-waste. Over the recent years, the exportation of secondhand electronic devices from developed countries to developing and transition countries continues through clandestine operations, legal loopholes, and by countries that have not ratified the convention. For instance, about 2 million secondhand televisions, approximately 400,000 units are exported from Japan to the Philippines, annually. However, inappropriate recycling and final treatment processes such as open burning of wires and improper crushing of CRT tubes has been observed at or near dumpsites in Manila. Amendments to the Basel Convention are necessary to prevent the exportation of hazardous from developed countries to developing and transition countries for any purpose (even for recycling) [69].

China, Vietnam, and Cambodia have built up their own legal frameworks to deal with the import of secondhand items and hazardous wastes. For instance, in 1996, Cambodia banned the importation computers because of concerns about the possibility of spreading virus infections into domestic computer systems. Nevertheless, e-waste scrap is not subjected to any legal regulations [70].

In 2000, China introduced a complete ban on the importation of secondhand EEE. It also prohibited the importation of printed circuit boards [66]. In 2001, Vietnam followed suit to introduce the ban on importation of secondhand EEE, including home appliances and computers. Between 2004 and 2006, Vietnam introduced laws to tighten the ban on the importation of secondhand EEE (with the promulgation of Governmental Decree No. 12/2006/ND-CP) and re-exportation of e-waste scrap by the Minister for Trade (Decision No. 5678/VPCP). Along with laws banning the importation of secondhand EEE, relevant prohibitions on the importation of e-waste scrap for any purpose and on the dismantling of e-waste scrap have been enacted in July 2005. Although bans on the importation of secondhand EEE and printed circuit boards have been introduced in China and Vietnam, research studies pointed out that due to the demand for used electronic products and used parts, significant proportions of these materials still find their way into these two countries. In addition, these countries lack effective implementation of policies and monitoring measures. For instance, China allows the importation of secondhand EEEs to be imported as long as they are built and then re-exported. It is predicted that annually, some 57,700 tons of e-wastes were illegally imported, of which 8,470 tons were exported again. Also, mandatory removal results in spreading of improper recycling activities to other places. Given this background, it is clear that a major portion of e-waste scrap, such as printed circuit boards, has been, and is being, recycled or smuggled into Vietnam, China, and Cambodia [71].

The illegal trade of electrical and electronic waste to non-EU countries continues to be uncovered at EU borders. Past research studies confirmed that significant proportions of materials are still exported illegally outside of the EU member states because recycling companies, scrap dealers, brokers, and the so-called re-use companies take advantage of low dumping costs and environmental standards [44]. Illegal dumping remains a serious problem in Japan, and some e-waste is exported overseas as reusable parts [37]. China, along with Peru, Ghana, Nigeria, India, and Pakistan are the biggest recipients of e-waste from industrialized countries [25, 72-73]. Other leading recipient countries of e-waste are Singapore, Malaysia, Vietnam, Philippines, and Indonesia [5, 21, 74]. Approximately 500 containers with electrical and electronic equipment reach Nigeria every month [75]. Some researchers estimate that approximately 400,000 used computers are imported every month. Of these, only approximately 50% are functional. Approximately 45% of the equipment comes from Europe and the USA each, and the other 10% from Asia. This situation was also found in Ghana, where computers, televisions, and monitors were the most common imports. According to the available data, around 300 containers of UEEE/WEEE reach Ghana every month through the ports of Tema. The highest number of equipment from the EU comes from Germany, the Netherlands, and the UK. It was established that approximately 75-80% of the imported UEEE/WEEE cannot be reused [75-76].

9.2. An outline of the illegal waste disposal practices associated with e-waste fraction

In developing and transition countries, formal recycling of e-waste using efficient technologies and facilities is rare; therefore, e-waste is managed through various low-end management alternatives, such as disposal in open dumps, backyard recycling, and disposal into the environment, such as surface water, conventional landfills, etc. The majority of the unusable components are thrown away arbitrarily, polluting the environment and water sources [73]. Developing and transitional countries have not yet established official e-waste recycling facilities. Some developing countries, such as South Africa, Indonesia, India, etc., have industrial areas where recycling facilities and plants have been built [74]. However, backyard recycling of PCs, television sets, etc. is a common practice. For instance, individuals from the informal sector usually recover precious materials from e-waste, such as gold from the integrated circuit (IC) socket or IC chipset. Using their bare hands and without wearing any personal protective clothing (PPP) for safety and health protection mask, they burn ICs and mix the residue with other chemicals (e.g., nitric acid (HNO3), selenium, etc.) to recover gold [77]. This process generates waste water containing heavy metals that exceed World Health Organization (WHO) threshold values of waste water regulations (e.g., Cu, Cr, Co, Pb, nickel (Ni), Sn, and zinc (Zn)) [41].

10. Impacts of e-waste

The uncontrolled recycling of WEEE known as “backyard recycling” by the so-called informal sector is the main concern in non-OECD countries such as India, China, etc. Informal recycling is the most pressing environmental issue associated with e-waste [78]. Relevant case-studies about informal recycling of e-waste performed by [41, 77] pointed out that primitive tools and methods such as open burning of plastic waste, exposure to toxic solders, and acid baths to recover valuable materials and components from WEEE with little or without safeguards to human health and the environment result in the pollution of the land, air, and water. Guiyu in Guangdong Province, China, is one of the widely known examples of a center of improper recycling of printed circuit boards. Health effects of crude e-waste disposal methods have been reported. These include elevated levels of exposure of toxins in air, soil, water, and human tissue. This is because there are no criteria for reusability and no legally binding guidelines aimed at providing a common understanding practices of handling in developing and transition countries to manage e-waste. Besides Guiyu, there are several lesser printed circuit board recycling areas in Guangdong Province, such as in Guangzhou, Dongguan, Foshan, Shunde, Zhongshan, and Shenzhen [79].

Recycling of e-waste scrap is polluting not only the water but also the soil and the air. A recent study on recycling of e-waste [80] pointed out that the increasing concentrations of persistent organic pollutants (POPs), such as polychlorinated dibenzo-p-dioxins dibenzofurans (PCDD/Fs), PBDEs, polycyclic aromatic hydrocarbons (PAHs), and PCBs, and heavy metals were detected in the Guiyu air because of incomplete combustion of e-waste. Higher concentrations of POPs and heavy metals compounded more favorable conditions for severe pollution of soils. Other environmental pollutions accrued from recycling printed circuit boards have been observed in some areas in Vietnam. A multitude of health consequences may result from prolonged exposure to these hazardous materials, such as negative birth outcomes, cancer, long-term and permanent neurologic damage, and end-organ disease of the thyroid, lungs, liver, and kidneys [81]. Significant environmental impacts and risks on workers by crude disposal processes were analyzed across Indian cities, such as Bangalore [10], outlining the increasing concentration of elements such as Cu, Zn, In, Sn, Pb, and bismuth (Bi) in soil near informal recycling shops. As a result, increasing concentrations of Cu, Sb, Bi, Cd, and Ag were reported in the hair samples of the workers [82]. The lax or zero enforcement or implementation of existing regulatory framework or low level of awareness and sensitization, and inadequate occupational safety for those involved in these processes exacerbate e-waste management in developing countries compared to the EU and Japan, which have well-developed initiatives at all levels aimed at changing consumer behavior [31]. Therefore, there is need for developing countries to adopt effective strategies to encourage re-use, refurbishing or recycling e-waste in specialized facilities to prevent environmental contamination and human health risks [83].

11. Conclusions

E-waste management is a great challenge for governments of many countries. It contains hazardous constituents that may negatively impact the environment and affect human health if not properly managed. Developed countries have implemented restrictive policies to manage e-waste. However, developing and transition countries harbor in their economies an entrenched business sector that use harmful methods to retrieve valuable materials from e-waste. These methods are harmful to both humans and the environment. These informal sectors in developing and transition countries may best be reformed by specifically targeting the most unfriendly environmental practices. Hence, there is an urgent need to integrate the informal sector with the formal sector in order to separately collect, effectively treat, and dispose of e-waste, as well as divert it from conventional landfills and open burning, thus minimizing public health and environmental impacts. The competent authorities in developing and transition countries need to establish mechanisms for handling and treatment of e-waste. Increasing information campaigns, capacity building, and awareness is critical to promote environmentally friendly e-waste management programs. In developing and transition countries, significant attention is needed in developing information management systems for defining what contributes to e-waste, generation and management. Increasing efforts are urgently required on improvement of the current practices such as collection schemes and management practices to reduce the illegal trade of e-waste, and also to protect the environment and public health. Reducing the amount of hazardous substances in e-products will also have a positive effect in dealing with the specific e-waste streams since it will support the prevention process.

Glossary of terms and acronyms

Ag; Silver

ARF; Advance Recycling Fund

As; Arsenic

Au; Gold

BAN; Basel Action Network

BFRs; Brominated Flame Retardants

Bi; Bismuth

Bo2W; Best-of-2-Worlds

Cd; Cadmium

CFCs; Chlorofluorocarbons

CNPSW; Committee of the National Policy on Solid Waste

Co; Cobalt

Cr; Chromium

CRTs; Cathode Ray Tubes

Cu; Copper

DfE; Design for Environment

DoE; Department of Environment

EEE; Electronic and Electrical Equipment

EMPA; Federal Laboratories for Materials Testing and Research

EOL; End-of-Life

EPR; Extended Producer Responsibility

ERP; European Recycling Platform

ETBC; Electronics Take-Back Coalition

EU; European Union

EU WEEE; European Union Waste Electronic and Electrical Equipment

eWASA; e-Waste Association of South Africa

HARL; Home Appliance Recycling Law

Hg; Mercury

HNO3; Nitric Acid

HP; Hewlett-Packard

IC; Integrated Circuit

ICT; Information Communication and Technology

In; Indium

IT; Information Technology

JICA; Japanese International Cooperation

LCD; Liquid Crystal Display

LG; Life’s Good

Li; Lithium

MoEF; Ministry of Environment and Forests

MSW; Municipal Solid Waste

NGOs; Non-governmental Organizations

Ni; Nickel

OECD; Organization of Economic Cooperation and Development

PAHs; Polycyclic Aromatic Hydrocarbons

Pb; Lead

PBBs; Polybrominated Biphenyls

PBDEs; Polybrominated Diphenyl Ethers

PCB; Printed Circuit Board

PCBs; Polychlorinated Biphenyls

PCDD/Fs; Polychlorinated Dibenzo-p-dioxins Dibenzofurans

PCs; Personal Computers

Pd; Palladium

POPs; Persistent Organic Pollutants

PPP; Personal Protective Clothing

PROs; Producer Responsibility Organizations

RoHS; Removal of Hazardous Substance

Sb; Antimony

SECO; Swiss State Secretariat for Economic Affairs

S.E.N.S.; Stiftung Entsorgung Schweiz

Sn; Tin

StEP; Solving the E-waste Problem

SVTC; Silicon Valley Toxic Coalition

SWICO; Swiss Association for Information Communication and Organizational Technology

TG; Thematic Group

UEEE; Unused Electronic and Electrical Equipment

UN; United Nations

UNEP; United Nations Education Programme

US; United States

USEPA; United States Environmental Protection Agency

WEEE; Waste Electronic and Electrical Equipment

WHO; World Health Organization

VAT; Value-added Tax

Zn; Zinc

3R; Reduce, Reuse, Recycle

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Chapter 5

Electronic Waste in Mexico – Challenges for Sustainable Management

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/64449

Abstract

The purpose of this chapter is to analyze the situation of the management of electronic waste in Mexico; it has been organized into four sections. In the first, a brief description of the problem of electronic waste based on the world vision presents the situation of transboundary movements of electronic waste from developed countries to developing countries or emerging stands out, in which it is done an incipient and inadequate management without concern about pollution, and health damage caused. In the second, the law applied to waste management in this country, concerning international, regional and national framework is presented. The third section, an analysis of the actors involved in the production, marketing, use, handling and disposal of electronic waste is presented; highlighting the role currently performed. A conceptual model of the life cycle of electrical-electronic equipment as a starting point for handling electronic waste and the model of management electronic that is now operating in Mexico, in which the actors involved in the value chain of electrical and electronic equipment waste (WEEE's), is presented. In the last section, efforts that Mexican environmental authorities have done on the management of electronic waste, and WEEE 's generation data are analyzed, a generic model is presented enhance the WEEE 's in Mexico as a first phase to move from an emerging electronic waste management to a management model.

Keywords: e-waste, handling, stakeholders, regulatory framework, Mexico

1. Introduction

The consumption of electrical and electronic equipment are increasing continuously all around the world, and therefore also the amount of waste electrical and electronic equipment (WEEE)

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at the end of useful life. This is a consequence of rapid technological advance that make electrical and electronic equipment production in a shorter of useful lifetime and/or reduction using, due a substitution by costumer. Customers are motivated for new models, thus increasing the waste flow, so electronic waste volume increase faster than rest [1]. Actually growing is three times more faster than municipal waste and estimated worldwide grows between 3% and 5%. Without prevention, control and information strategies, this problem can cause and inadequate handling and disposal practices of WEEE. Lepawsky [2], mention that since more than a decade the problem of e-waste it focus on exportations of rich countries, particularly EE.UU., Canada and European Area, poor countries and/or emergencies economies to be processed in dangerous conditions for employees, that impact into health and environment.

According to Pickren [3], rapid growing of electronic equipment, it is consider an emergent problem. A study made for Yu, et al. [4], indicate that for 2017 developing countries will start generate more electronic waste than developed countries. An UNU report [5], predicts for 2020, countries like China and other of South Africa obsolete computer generation will grows from 200% generated in 2007 to a 400%, and to a 500% in India. Despite the high consumption in electrical and electronic equipment (EEE), markets still not saturated, this means that growing of electronic waste generation it overpass an adequate development infrastructure for collection, recycle and reuse [6,7].

Electronic waste problem, is a global problem, Ogondo et al., [8], research estimate that worldwide of e-waste generation was of 50 millions of tons annually approximately, and for 2017 estimate this will increase to 65.4 millions of tons per year [9]. This implicate that toxic wastes of electronic are multiplying with uncontrolled speed. Garlapati [10], indicate that current research shows that in next eight years developing countries will producing double of electronic waste than developed countries. Therefore, estimate for 2013 developed countries discard between 200-300 millions of obsoletes computers, while developing countries discard double of this amount [11]. According to [12], Mexico is between forty countries around the world. In first places was United States and China with just more than 7,000 million of tons first one and 6,000 second one, both countries contribute with 32% of total generated worldwide, 60% of electronic waste generated all around the world is from big and small home appliances. In terms of electronic waste generation per capita there is eight European countries that are in on top list: Norway, Switzerland, Iceland, Denmark, United Kingdom, Netherlands, Sweden and France. Consider this countries average generation for Norway is 28 kilograms of electronic waste per year and France with 22 kilograms.

At global level generation of electronics increase in 2014 to 41.8 Mt., from this volume only 6.5 million of tons of electronic waste was treated formally with data collection method which is establish in some developed countries. In European Union was deposited in garbage container 0.7 million of tons of e-waste. Electronic waste quantity that deposited in containers for other regions are unknown, in addition movement of electronic waste mostly comes from developed countries through developing countries is unknown. According to [13], data shows a flow to Nigeria in 2010 of 0.1 MT. In Asia, in 2014 generated 16 millions of tons of electronic waste. Generation per capita was 3.7 kg. Europe was the continent that had highest generation per capita (15.6 kg/capita). Oceania was the continent with less electronic waste generation (0.6 Mt.); however, quantity per capita was very similar to Europe (15.2 kg/capita). Less electronic waste per capita was generate in Africa (1.7 kg/capita). Throughout the continent generated 1.9 million of tons of electronic waste.

American continent generated 11.7 millions of tons of electronic waste, of this, North America generated most of the quantity (7.9 Mt); Central America 1.1 Mt and South America 2.7 Mt, generation per capita of continent was 12.2 kg/capita. From Latin American countries, there six that have highest generation, Brazil generate 1.4 million of tons of waste, Mexico follows this list with a million, Argentina, Colombia, Venezuela and Chile also are between in the 40 countries that generate more electronic waste.

In Table 1 shows largest electronic waste generation per capita in Latin American countries. Electronic waste generation per capita is high, therefore is important that establish strategies to handle electronic waste.

Country	Generation per capita
Chile	9.9
Uruguay	9.5
Mexico	8.2
Panama	8.2
Venezuela	7.6
Costa Rica	7.5
Argentina	7
Brazil	7
Colombia	5.3
Ecuador	4.6

Source: Modify of [14]

Table 1. Electronic waste generation in Latin American countries in 2014

According to [15] electronic waste are a source of material for metal recycling market because contain a lot of the metals that demand needs, between post-consumption electronic there are computers, mobile phones, screens and kitchen appliances include. In a recent survey, Cucchiella et al. [1] note that notebooks ant tablets, along with desktops and servers are the most valuable WEEE category, because of the high of metal content in some of its major subsystems. On the other hand, electronic waste generation is a problem that requires attention Premalatha, et al. [16] point out that few developed countries around the world are scientifically able to recycle or dispose electronic waste generated. In other developed countries just a fraction of e-waste is recycle correctly, the rest either incinerated or sent to landfills that causes severe secondary problems. Even worst, a significant part of waste flow generated worldwide is exported to a developing countries where are dispose without any concern for the pollution that is causing.

In Latin American countries there aren´t WEEE management systems, only started with initiatives to address problematic, but it is necessary to work with management systems in which stakeholders involved are committed and be responsible in the cycle. According to [17], at the end of life cycle, some electronics end up in common garbage. Contaminated fields around landfills by chemical substance and heavy metals such beryllium, chromium, cadmium, arsenic, selenium, antimony, mercury in electronic equipment and/or electronic that are hazardous and required a especial final disposition in order to not pollute the environment, for this reason collection and treatment sustainable of electronic equipment is indispensable.

Another alarming situation in terms of e-waste are transboundary movements, [18] suggest that developed countries are exporting their electronic waste to a developing countries as a practice of disposition. They state that much of e-waste sent it to countries such Africa or Asia, without authorization to export unnecessary good to poor countries for reuse o refurbish; in these cases, electronic equipment that does not work wrongly classified as "used goods". A significant flow of e-waste exportation is being sending from the European Union to Western Africa, causing environment pollution and significant risks to local population health [19].

In this sense [20], say that despite the Basel Convention, transboundary movements of hazardous waste is still high, mainly from countries such as United States, Canada, Australia, the European Union, Japan and Korea trough the Asian countries such as China, India and Pakistan. America, Brazil and Mexico are the countries, which serve as destination for this waste. According to [21], it is estimate that between 60-75% of e-waste collected in the European Union is sent to the countries of Asia and Africa for recycling or dismantling. Electronic waste in Pakistan are imported from United States, the EU, Australia, Saudi Arabia, Kuwait, Singapore and the United Arab Emirates, among many other countries. Dubai and Singapore also serve as centers of pre-distribution of e-waste from the European Union (EU) and United States through countries such South Asia as India and Pakistan as the main destinations [22]. This indicate that exportation of e-waste is a flow that is still practiced, in which there are transport processes of e-waste from one country to another, where do this imply the existing of partners, including countries of origin and recipients, multinational companies, handling agents and market intermediaries.

Currently electronic waste are exported to countries that are unlikely to obtain infrastructure and security networks to prevent damage to human health and to environment, this is due to factors such lower cost of exporting and manage waste in country of origin. Markets availability for raw materials or recycling facilities among other. However, there are examples of official recycling facilities in developing countries and with economy in transition that dedicate to repair, rebuild and recycle used equipment and electronic waste in environmentally sound manner.

Although the Basel agreement objectives, countries that been added to this agreement must be into the rules established for transboundary movements control of hazardous wastes, their still some gaps in some areas. Electronic waste are subject of interest or this agreement, one of it is major problems with authorities is to establish a clear definition in order to distinguish between secondhand equipment to be repair, refurbish or direct reuse and those they are an e-waste. In addition, there are controversies to determine which an e-waste is and what does not, therefore fall within the scope of the agreement. Therefore organisms in charge are vigilant for accomplishment of disposition of Basel agreement related to transboundary movements. Sometimes is difficult and complex to determinate.

2. Legal framework of electronic waste in Mexico

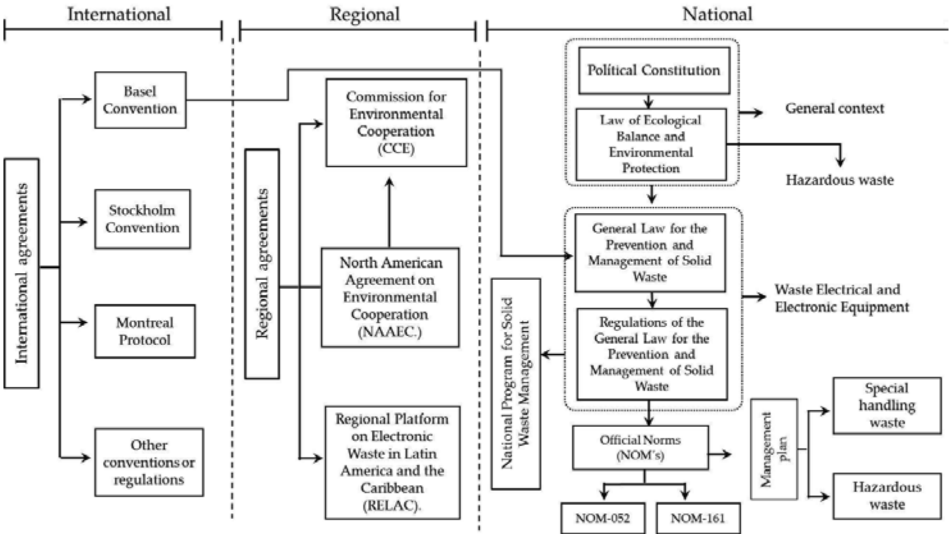
In Mexico, electronic waste begun having more importance, since that were included in the General Law for Prevention and Integral Management of Wastes (LGPGIR, by its acronym in Spanish). This law classify electronic waste in especial handling and establish obligation to make management plans and specific programs for disposition, because are this waste represents a high risk for population, environment and/or natural resources [23]. This waste contains persistence toxic substances and bioaccumulation, and materials can be recover.

The regulation of waste in Mexico is supported by an international framework that includes agreements and treaties such as Basel convention, Stockholm and Rotterdam among others. As well as a regional approach that applied for North America situation and Latin America in terms of e-waste where Mexico has participation in different programs and agreements related to topic of both zones, such Commission for Environmental Cooperation (CCE) and Waste Regional Platform in Latin America and Caribbean. As well as the national legal framework establish since Political Constitution of the Mexican United States, General Law of Ecological Balance and Environmental Protection (LEGEEPA, by its acronym in Spanish), the General Law for Prevention and Integral Management of Waste that derives regulation of LGPGIR and official standards. Figure 1 shows the legal instruments in terms of environmental protection and waste management for Mexico and also international regulations and regionals agreement that Mexico has signed.

2.1. International legal framework in terms of waste

The inclusion of the international and regional framework for electronic waste management is important because it sets a benchmark in the development of public politics on waste in Mexico. Management of e-waste in our country has gained importance because of the presence of some contaminants found in waste and when they are disposal not properly, can be freely into the environment. Electronic industry growing and technological development in this country have contributed to equipment process substitution, increasing the number of electronic waste nationally [27].

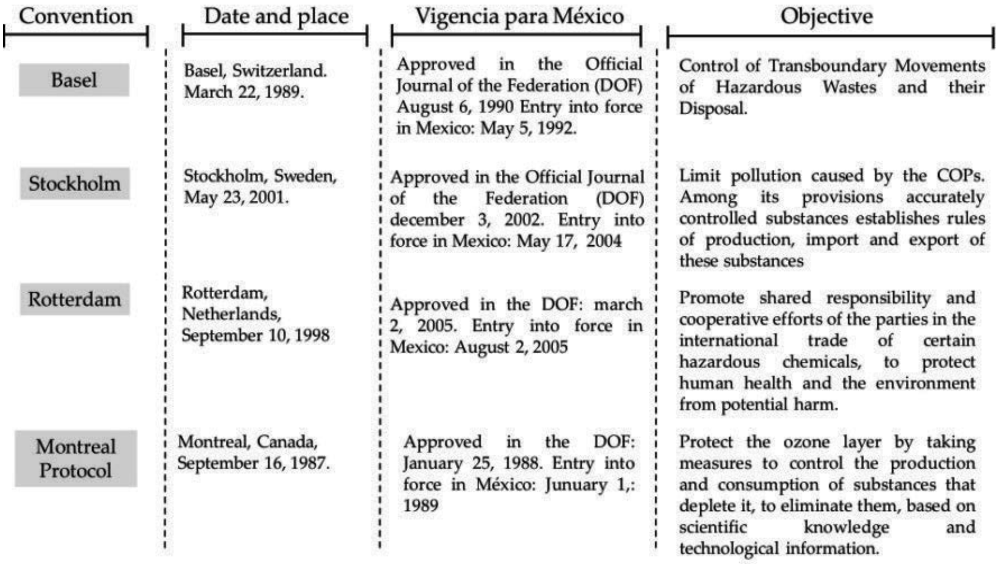
Cano [28], suggest that electronic waste topic has gained international importance from its inclusion in the agendas of different agreement between countries seeking to promote actions for reduction environmental impacts such as the Basel and Stockholm Convention among others. These actions mainly for the identification of some persistent organic pollutants (POPs), such as brominated flame-retardants as well as of heavy metals. At the end of its life cycle,



Source: Prepared by the authors based in the [24-26]

Figure 1. International and national legal framework in terms of waste in Mexico.

these contaminants can be released and cause adverse environmental and health effects. Figure 2 presents a summary of the agreements to which Mexico has acceded to protection to the environment and where management of electronic waste is involved.



Convention	Date and place	Vigencia para México	Objective
Basel	Basel, Switzerland. March 22, 1989.	Approved in the Official Journal of the Federation (DOF) August 6, 1990 Entry into force in Mexico: May 5, 1992.	Control of Transboundary Movements of Hazardous Wastes and their Disposal.
Stockholm	Stockholm, Sweden, May 23, 2001.	Approved in the Official Journal of the Federation (DOF) december 3, 2002. Entry into force in Mexico: May 17, 2004	Limit pollution caused by the COPs. Among its provisions accurately controlled substances establishes rules of production, import and export of these substances
Rotterdam	Rotterdam, Netherlands, September 10, 1998	Approved in the DOF: march 2, 2005. Entry into force in Mexico: August 2, 2005	Promote shared responsibility and cooperative efforts of the parties in the international trade of certain hazardous chemicals, to protect human health and the environment from potential harm.
Montreal Protocol	Montreal, Canada, September 16, 1987.	Approved in the DOF: January 25, 1988. Entry into force in México: Junuary 1,: 1989	Protect the ozone layer by taking measures to control the production and consumption of substances that deplete it, to eliminate them, based on scientific knowledge and technological information.

Figure 2. International agreements which Mexico has signed in environmental terms.

Mexico adheres to the Basel convention and considers that is an important advancement in environment protection, through the legal regulation of the transboundary movement of hazardous wastes, to establish a framework of general obligations for countries involved, seeking primarily to minimize generation of hazardous wastes and the transboundary movement of those. These ensure their environmentally management as well as promoting international cooperation to achieve this; establish mechanisms for coordination, monitoring and regulating the application of procedures for peaceful settlement of disputes. Also encourages their elimination, through environmentally proper management, more near from site where is generated. It also seeks to minimize the production of hazardous waste; this involves strong controls during storage, transport, treatment, reuse, recycling, recovery and disposal. Promotes substitution of hazardous substances in the production and the responsibility extended of producer (REP) from design and production of the product to the treatment of waste.

Currently, this agreement has included in its regulations, the transport of electrical and electronic waste, mobile phones and computers. Likewise, it contains fractions that specifically limit the export of electronic waste including metallic waste, electronic assemblies as circuits printed, accumulators and other batteries and cathode ray tubes glasses.

Based on the regulatory framework that provides for the LGPGIR and its rules of procedure, the Secretariat of Environment and Natural Resources (SEMARNAT, by its acronym in Spanish) applied provisions of agreement on the transboundary movement of hazardous waste. The Stockholm convention is an agreement on polluting organic persistent (POP), chemicals products with toxic and resistant to degradation, and cumulative properties in human skin, can be transported by air, water and migratory species, causing their accumulation in terrestrial and aquatic ecosystems, which makes them harmful to human health and the environment. Thus, since the problem is cross-border, it is essential to take measures at the international level.

Mexico, is committed to eliminating use of polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) in the country, for which there is a commitment to the elimination of products that contain them, including electrical and electronic waste. This agreement establishes a series of commitments and opportunities for signatory countries, such as Mexico. The obligations include formulation of a National Plan of implementation that meets objectives of convention, through an actions that will lead to the elimination or reduction of use and release into the atmosphere of pollutants.

Mexico government restricted, since 1992, the use of the PCBs, one of the compounds subject to the Stockholm Agreement, whose management began in 1988 with publication of the LGEEPA and its regulations on hazardous waste and, later, with elaboration of the NOM-133-SEMARNAT-2000, environmental protection, management of polychlorinated biphenyls (PCBs) [29], some of the electronic waste contain PCBs; in addition, incineration environment frees heavy metals such as lead, cadmium and mercury, as well as dioxins and furans, polluting the air, soil and on occasions, reaching aquifers and introducing in trophic chains; for this reason, the Stockholm Agreement represents an opportunity for signatory countries to reduce effects to health and the environment through the control of POPs [26]. With regard to the management and handling of WEEE, this agreement includes the PCBs contained in some capacitors equipment.

The Rotterdam Agreement promotes shared responsibility and joint efforts of the countries adhering to the Convention in the field of international trade of certain hazardous chemicals in order to protect human health and environment against possible damage and contribute to their environmentally rational use, facilitating the exchange of information on their characteristics, establishing a national process of decision-making about their import and export and disseminating these decisions among members.

The Montreal Protocol was signed for the purpose of standardizing on substances depleting the ozone layer, in which established deadlines for removal and consumption of the major substances that are depleting the ozone layer. Protocol establish a restriction on trade with countries that are not part of the Protocol, by prohibiting the import or export of depleting substances or products that contain them. It also gives importing countries the media and information they need to recognize potential hazards and exclude chemicals products that cannot handle safely. If a country consents the import of chemicals products, the Agreement promotes the use of this chemicals without risks according to standards of labeling, technical assistance and other forms of support.

Mexico is part of the 190 countries that are committed to the goals of production of gases chlorofluorocarbons (CFC), halons and methyl bromides which are used in industry and domestic application in cooling systems and air conditioners among others that are causing thinning of the ozone layer. The Montreal Protocol is an example of the success that may have the adoption of measures at the international level, provided there is the technological development needed to replace substances which have adverse effects on our environment, as well as the willingness of governments to cooperate in terms of transfer and exchange of information.

2.2. Instruments on waste in regional scope

At the regional level, in 1994 Mexico signed the North American Agreement of Environmental Cooperation (NAAEC). This agreement reflects the commitment of Mexico, Canada and United States to environmental improvement in the region. As a result of the NAAEC, arises the Environmental Cooperation of North America Commission, integrated by three federal environmental agencies of the signatory countries of the North America Free Trade (NAFTA) signed by the three countries.

Since 2004 the three countries have worked within the framework of the CEC to develop proper management of electrical and electronic waste projects. Commission considers that electrical and electronic waste represent an environmental and commercial issue both waste generated by flows with use and destination unknown to other regions such as Africa or Asia. So the problem of electrical and electronic waste in North America must be addressed in a way joint given the geographical vicinity and the permeability of borders. The differences in national laws and complex institutional coordination represent significant challenges that may be faced in the context of the CCA to contribute to the control of illegal electrical and electronic waste flows and efficient application of local laws to improve its management, among others.

In relation to the Regional Platform on electronic waste in Latin America and the Caribbean (RELAC by its acronym in Spanish), it is not itself a normative instrument, but a partnership project, non-profit, its aim is promotes, articulate and disseminate initiatives that promote solutions for prevention, proper management and proper final e-waste treatment in Latin America (LAC). The scope of project is prevention, reuse and recycling, its foundation focuses on identifying the social, economic and cultural peculiarities of Latin America and the Caribbean and respond to them in the initiatives of e-waste that are implemented in the LAC countries, its foundation focuses on recognize, highlight and respond to the social particularities economic and cultural of Latin America and the Caribbean in treatment of e-waste that are implemented initiatives. Undertakes overhaul initiatives to reduce the digital divide, promote social business, and promote equal access to initiatives of market for the treatment of e-waste (Figure 3).

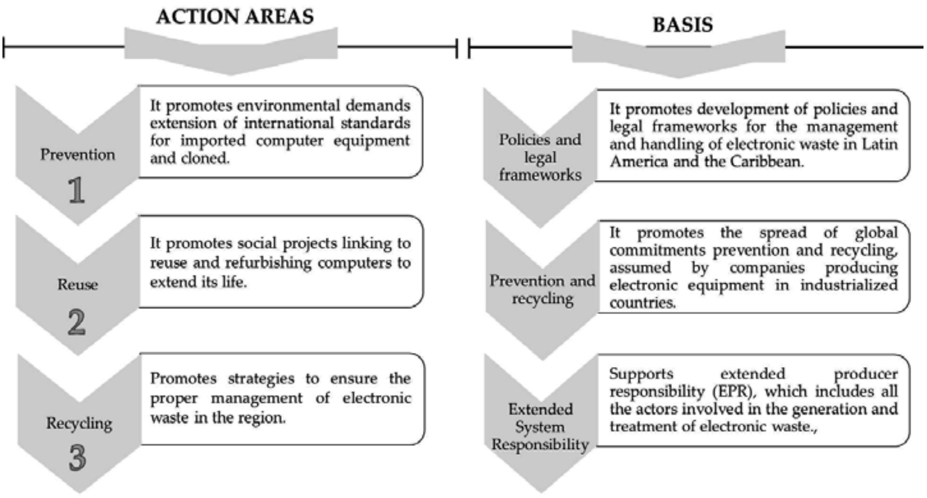


Figure 3. Basis and action areas of RELAC.

The RELAC also promotes and participates in research projects focused on solutions for management of e-waste in LAC; supporting Latin American electronic waste management projects and initiatives. Manages different sectors (public, private, academic) and from civil society the articulation in management of WEEE. It also offers legal and technical tools for dissemination of knowledge on management of e-waste, turning it into an important broadcast channel for the problem of electronic waste.

2.3. National framework on waste issue

Wastes are standard since the constitution, in its article 115, which is attributed to the municipalities' the responsibility the responsibility for providing the public service of cleaning, collection, transfer, transportation, treatment and final disposal of solid waste, this is the general framework of the issue of waste. The first environmental law that regulated specifically to hazardous waste, is the LGEEPA, this was the first specific legislation of environmental protection in Mexico, there are established specific guidelines to waste handling, as well as the distribution of powers in the three levels of government, so the e-waste generated in homes, in public and private institutions, one of the natural destinations is in the municipal waste stream, even though there are regulations which confer you the responsibility of its management to the states or to the federation, this situation makes more complex the management of e-waste, depending on the source that generates it and the composition can be an urban waste, special handling or hazardous [26].

The General Law for the Prevention and Integral Management of Wastes (LGPGIR, by its acronym in Spanish) as an instrument of environmental policy establishes a general classification for waste: hazardous, special handling and solid urban waste [23]; the first and last classification are waste whose identity has no doubt however, as regards handling special waste, has not been very clear definition and understanding, which makes more complex the management of WEEE in Mexico.

The LGPGIR set environmental policy instruments to regulate plans of waste management that need it, this official Mexican norms laying down criteria for development of management plans. The LGPGIR classified the WEEE as special handling waste, defined as technological waste from industries of computer science, electronics manufacturers and others that require a specific management after its useful life [23]. It establishes a framework of shared responsibility among various players in the industry, as well as general principles for waste management, appraisal, and shared responsibility and integrated, under the criteria of environmental, technological, economic and social efficiency management.

The regulation of the General Law for the Prevention and Integral Management of Waste defines the implementation of plans for special handling waste which represent an environmental hazard and seeks to promote the recovery of materials. It also indicates that to classify a residue of especially management in terms of the LGPGIR, it will be established in accordance with the Mexican Official Norms (NOM, by its acronym in Spanish). Regulation drives the management plans of priority trends of waste including e-waste. By NOM are defined special handling waste listings inclusion and exclusion of waste criteria and requirements for the handling plans formulation through responsibility plans [30].

Mexican Official Norm (NOM-052-SEMARNAT-2005) for management of hazardous waste, set properties, the procedure of identification, classification and includes some electronic components in the list of hazardous waste, because some of the substances contained in these possess properties of corrosively, reactivity, flammability or toxicity [31]. Official norms (NOM-161-SEMARNAT-2011) establishes criteria to classify special handling waste and to determine what are subject to management plan, the procedure for the inclusion or exclusion of special handling waste; as well as the elements and procedures for formulation of management plans. This standard lists in normative annex products which in the course of its useful life should be subject to a management plan: technological waste from computer industries and electronics manufacturers; desktop personal computers and accessories, personal laptops and their accessories, cell phones, monitors with cathode ray tubes (including TVs), screens of liquid crystal and plasma (including TVs), portable audio and video players, cables for electronic equipment and printers, copiers and multifunctional [32].

Other instruments that are framed in legislation are management plans, it aims to minimize the generation and maximize the recovery of the waste, with specific steps looking for environmental, technological, economic and social efficiency designed on principles of shared responsibility and integrated management, which considers the set of actions, procedures and viable means and involves producers, importers, exporters, distributors, traders, consumers, users of by-products and large generators of waste, as appropriate, as well as to the three levels of government.

The LGPGIR, indicates that management plan should be designed under the principles of shared responsibility, where the integral management of waste is a social co-responsibility and requires the joint participation, coordinated and differentiated producers, distributors, consumers, users of by-products, and the three orders of government, as appropriate, under a scheme of the feasibility of market and environmental efficiency technological, economic and social in Mexico the federal entities, have the power to formulate, lead and evaluate state policy as well as the programmers in e-waste topics. They are also responsible to authorize the comprehensive management of these, and identify those who may be subject to management plans.

3. Actors involved in management of electronic waste

Interest in problems associated with generation and management of e-waste has led the authorities to carry out studies to measure the problem and identify the level of participation of the actors involved in the life cycle of electronic.

In Figure 4 a diagram shows how is the release into the environment of hazardous substances, as well as the exposure of human beings and organisms of the terrestrial, and aquatic biotic in any of the stages of the product life cycle processes, services, from production to disposal [33].

Figure 5 shows a conceptual model about cycle of life EEE, proposed by United Nations Environment Programme (UNEP) by establishing the flow of materials from production, stage in which turns recycled until the final disposition or virgin material. This model is important for any electronic waste management system, because it allows establishing the flow of materials and identification of networks and chain that connects the different stages of the cycle of life of EEE and stakeholders, as well as interest groups associated with the management in the country, which is to be proposing the model.

Identifying the string sets the flow of materials; identify inputs, outputs at each stage, to quantify the WEEE in the analysis of the life cycle of the EEE. According to [34], the inventory of the WEEE in a city, region or country is the basis for management, in the model that proposes, start from the stippled line (Figure 5) from this model will identify the chain that connects the different phases of the cycle of life of the EEE and the actors involved.

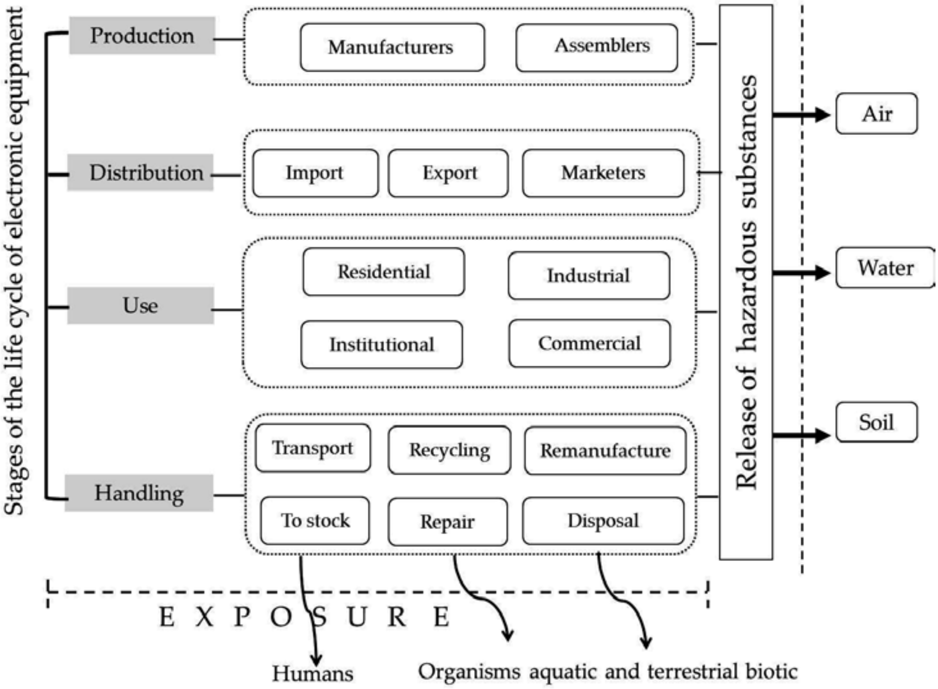
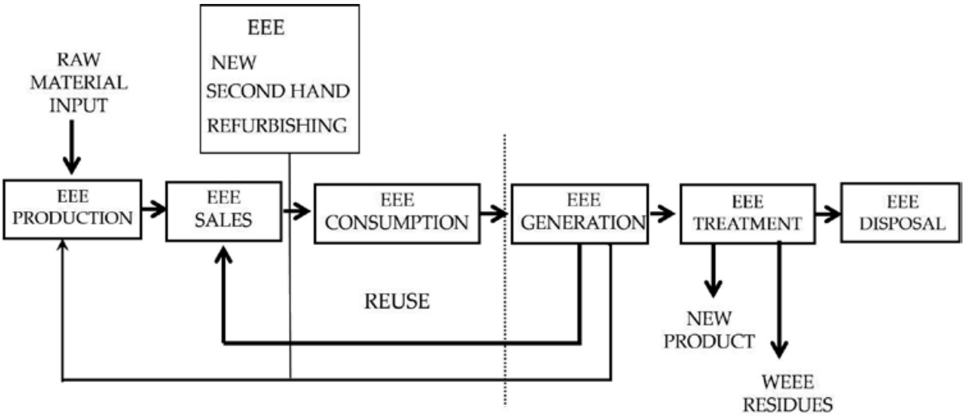


Figure 4. Environmental impacts and human exposure in life cycle of EEE.



Modified according to UNEP, 2007

Figure 5. Conceptual Life Cycle of Electrical and Electronic Equipment.

Electronic devices that are discarded, obsolete and/or not be functional, can be repaired, reused, or recycled. In Mexico there is a both formal and informal market for devices repaired and reused, mainly near the border between the United States and Mexico, which generates a large volume of used electronic products (used electronic products UEP), which eventually end up in the final disposal sites or are recycled inadequate way, presenting risks for public health and the environment. In Mexico, formal recycling of electronic waste, which is mostly limited to disassembly, is a new activity. Traditional metal recycling industry has discovered the WEEE recycling market; however, the recycled quantities are very small, since the political framework, nor the infrastructure allow larger quantities. Most of these companies do not offer a complete service; concentrate on the valuable components, such as printed circuit boards, neglecting the adequate disposal of other components such as cathode ray tubes (CRT) that have no economic value, but represent a risk to health and the environment.

Recycling of electronic products in Mexico market is mainly composed of three groups: small and medium-sized companies exclusively dedicated to the recovery and valorization of materials from collection or low tax of team programs; the scrap metal dealer, scavengers or local small that ordered recovery of components considered valuable, such as cables and printed circuits cards.

WEEE recycling is a source of employment and income for the informal sector composed of recyclers and brokers, operating in streets, small shops, disposal sites, as well as their own homes [35]. Processes carried out by the various actors, both formal and informal, in the value chain are collection, manual dismantling, refurbishment, recycling, mainly recovering, plastic, metals, cables and printed circuit boards contained in the WEEE. This process finally transformed into secondary resources for chains of production, while the unusable components, and frequently hazardous are discarded and thrown away or left on sidewalks vacant lots and illegal dumps.

In Mexico, as in other countries of Latin America collection, a network of complex and diverse actors and processes are formed for recovery, recycling and disposal of the WEEE′s. The specific legal framework for environmental management and socially sustainable of the EEE ′s at the end of its life cycle, has not been defined, there are instruments which establish very generic guidelines added to this is the lack of financing for managing post-consumer of WEEE, manufacturers/importers, consumers and others involved in the chain. So the management of WEEE, is emerging, there is a differentiated and heterogeneous management by region according to the efforts that have been made by actors involved in the chain of recovery. Once an EEE life cycle, whether functional or not, in Mexico, involved an important network of actors by value electronics such as printed circuit cards, as well as materials that constitute the devices. Figure 6 shows actors involved in the value chain of e-waste.

The chain begins with the actors who manage the electronic equipment in the stages of production and use, in Mexico the producers of EE are the manufacturers of original equipment (OEM), which may be national or transnational and companies providing services manufacturing (Electronics manufacturing Services EMS) ; according to the Ministry of Economy [36], Mexico is one of the leading exporters and assemblers countries in the world, it is located nine of the 10 largest transnational companies manufacturing service. Our country is the leading exporter of flat panel TVs, the computer room and eighth in cellular globally. The flow of the EEE, are presented in two directions, can be manufactured in Mexico for export or sold on the domestic market, there is also a flow of electronic equipment that are acquired primarily in

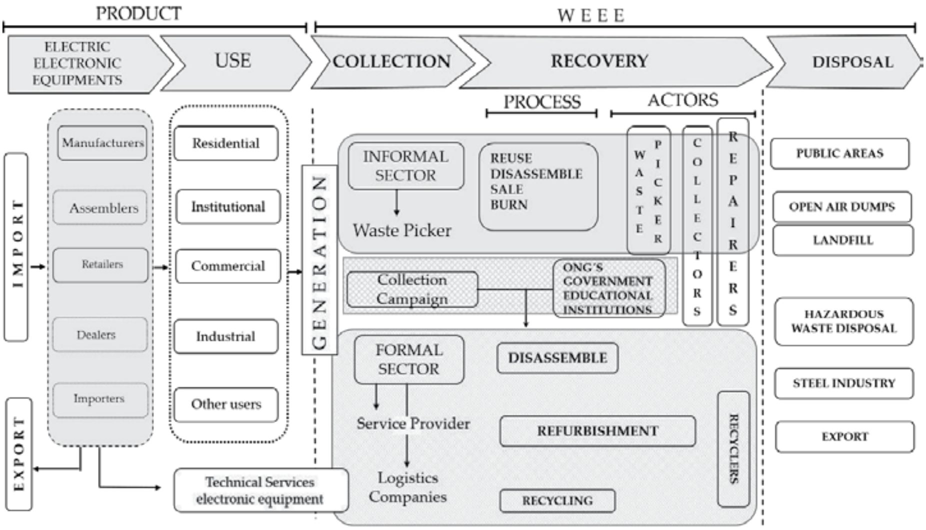


Figure 6. Actors involved in the value chain of electronic waste.

the United States, the actors involved in the flows described are retailers, distributors and importers.

The next step is to use, in which the actors belonging to the sectors shown below this stage (Figure 6), buy the US for use, so they are also generators of WEEE´s, from this time the waste flow continues to be valorized. Among the collection and use stage it is inserted the actor who have called technical, some are distributors, retailers of electronic equipment and simultaneously perform repair functions, so that also generate electronic waste.

In the collection stage involving both the informal sector and formal; in the first are the street scavengers who separate the waste from the streets to segregate materials and / or components which have market value; to retrieve the value the disassembled, sell them to collectors and / or recyclers; when the EE still works sell at outdoors markets or reuse; it is also common to burn cables to recover metals. The materials that have no market value dispose them in open dumps or abandoned in vacant lots.

The formal sector is also involved in the collection stage through companies dedicated to providing the collection service WEEE's service sectors, commercial and industrial which by law must prove that has been prepared in accordance with the regulations logistics companies that are contracted by companies engaged in recycling electronics and provide service including users in the sector also participate residential who can request to collect at home electronic equipment in use, it is important to clarify that it is not a common practice. In the collection stage also involved NGOs, government institutions, educational institutions and some companies dedicated to the recovery of WEEE, through collection campaigns, in which citizens can bring their obsolete electronics. Which are sent to companies that are formally registered to provide treatment and proper disposal of the WEEE, components with value are sold and e- scrap is disposed at authorized sites.

In the recovery stage the formal sector makes disassembly processes, equipment refurbishing and recycling of components. The actors involved are the assemblers, repairers and recycling companies. Some of the collectors and repairers are part of the informal sector because they are not registered to provide those services, but there is also a group that works in formality compliance with the standards established.

The waste recycling companies that have a presence in Mexico, most of them limit their operations to the dismantling of equipment, recovery of useful parts, grinding and separation of materials. As a result, the national recycling activity focuses on the reprocessing of plastic, glass and copper, while the valorized material is sent abroad for the recovery of precious metals [37].

As for marketing, unlike developed countries, recovery is an activity in which the informal sector is actively involved in the chain coexisting with actors that have made e-waste business. There is a significant flow of secondhand electronic equipment that are marketed, so in the recovery chain is an important link repairer who perform activities of repair, refurbishing and reselling used equipment. All this impacts on a significant prolongation of the life cycle of the equipment. As shown in Figure 6, there are chain actors who share working spaces in formality and informality. Depending on the sector involving the final disposal has several streams in the informal sector the actors have in public places such as vacant lots and open dumpsites, also arranged in the flow of urban waste to be disposed in the landfill, whereas the formal sector, must dispose compliance with regulations, the waste is hazardous they must be disposed in an approved this site, components and parts that have market valorize are sent to companies that buy metals, plastics or exported for processing in raw material.

Figure 7 shows the flow of the life cycle of electronic waste and the participation of stakeholders to long cycle is presented. EEE production, begins with the use of virgin materials to produce them subsequently is marketed for sale and consumed by various actors. From generation stage becomes WEEE, when the equipment is discarded and still works, re-enter the market with secondhand equipment to be marketed and consumed again. When the WEEE enters the treatment stage

In the management of WEEE's, the recovery chain starts when a user and owner of an electrical or electronic equipment (EEE), intends to dispose of WEEE, for several reasons:

1. Obsolescence of EEE, which may be for functionality, underperformance compared with recent patterns, fashion, technological, etc.

2. Technological replacement of all or part thereof, change of systems, software requirements or updates.

3. Break, damage or loss of function in this factor are included from producers, assemblers, importers, distributors, corporate users and government, to private consumers of EEE.

One of the purposes of the stage of recovery of WEEE's, is the recovery of disused equipment functions in this activity involved from remanufacturing or multinational technical services to NGOs promoting the reuse of EEE disused even work. Among the functions reclaims, highlights companies specializing in maintenance and updating which exclude or receive

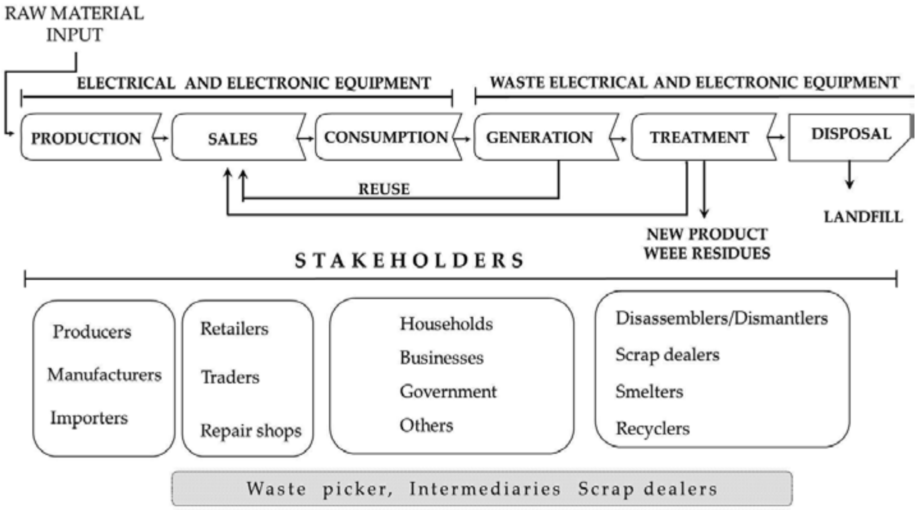
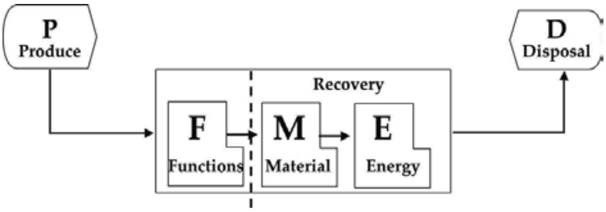


Figure 7. Stakeholders in the life cycle of e-waste.

equipment market and sloughed them or incorporate new devices to prolong its life. One of the problems associated with the recovery of functions is that the actors involved refurbishing EEE to incorporate them back into the market, as repairers or waste pickers, not considered parts of EEE as potentially hazardous substances since the usually they handled without caution, with low technological support without concern that accumulate debris discard obsolete equipment or parts. In this sense it is important to consider the Swiss model for electronic recycling in which they propose three principles, recovery function, material and energy. (Figure 8).



Source: [38]

Figure 8. Principles for the recovery of disused electronic equipment

4. Generation and electronic waste management

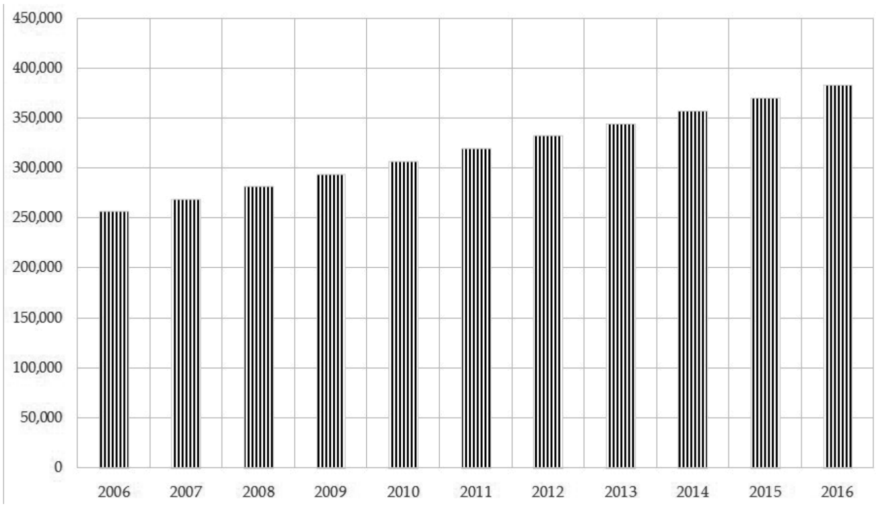
The interest in the problems associated with the generation and management of electronic waste has led authorities to conduct studies to go dimensioning the problem, SEMARNAT, in the field of environmental research through the National Institute of Ecology (INE, by its acronym in Spanish) currently National Institute of Ecology and Climate Change (INECC, by its acronym in Spanish) has conducted diagnoses of electronic waste generation to estimate the generation of these wastes by region and propose strategies for handling.

The first national study on the generation of electronic waste was made by the INE in 2006, in which the potential of televisions, personal computers (desktop and portable), recording devices or sound reproducing equipment, fixed and mobile phones generation was estimated. The estimated generation of these wastes in 2006 was 257,000 tons amount to be discarded, generating an indicator of 1.5 to 1.6 kg / year per capita [39]. The inventory made provided the elements for an approach to the magnitude of the problem; however, there are still gaps regarding more precise information on consumption patterns and particularly storage alternatives and end of life electronic waste. Roman [40] notes that despite the lack of formal infrastructure to manage these wastes in its various stages, the informal market is a reality in the management of WEEE in Mexico.

The next step that followed the authorities was to develop a guidance document for the development of management plans for it were classified into three sources generating electronic waste: postconsumer waste of society, post-consumer waste companies and organizations and waste production electronic equipment (obsolete and waste). They conducted a material balance for the amount of electronic waste from the three critical currents, desktop computers, mobile phones and televisions and representing more than 65 percent of the estimated in the first study of overall generation. The result of this document was integrated into a Model Program for Electronic Waste Management in Mexico, oriented to support decision makers involved in the management of WEEE, primarily the SEMARNAT and the private sector. It focused on these players because they are the ones who could develop a management plan nationwide. From this work we would be prepared to specify the responsibilities, activities, functions and interactions of the various actors involved [40].

Subsequently updated WEEE generation data through regional studies, the first of these was held in 2007 in the northeast region of the country, the aim of this study was to characterize the generation of WEEE 's (computers, mobile phones, TVs, fixed phones, audio and video) in border cities in the northeast region of Mexico through a flow analysis coupled materials with an economic study to develop proposals for proper handling that can be implemented as public policy, in this study it was estimated to be generated annually in the region 48,331toneladas [27]; for 2009 a study was conducted in the area of the northern border, including the border cities of Tijuana and Ciudad Juarez ; the WEEE's generation for this region was between 32,000 and 40,000 tons per year [41]; in 2010 the study of generation Metropolitan Area of Mexico was performed in this study WEEE 's generation was 94.203 tons / year,[42]. Studies in Mexico to evaluate the generation and management of electronic waste at the end of its useful life, seeking to propose a policy option according to national conditions and existing infrastructure for future recovery of WEEE's present a policy according to national conditions and existing infrastructure in the country.

Figure 9 generation WEEE's a national level is presented without considering technological change to digital television, according to the study of Roman [39], in 2006 257 000 tons per year were generated from this study estimated that by 2016 the generation will be 383, 424 tons in the year, these data generations are conservative, mainly because it has not included the volume of analog televisions discarded by the analog switch, which ended on December 31 2015. In this regard Roman [43], indicates that generate 400,000 Ton by changing television between 2015 and 2016.



Source: [44]

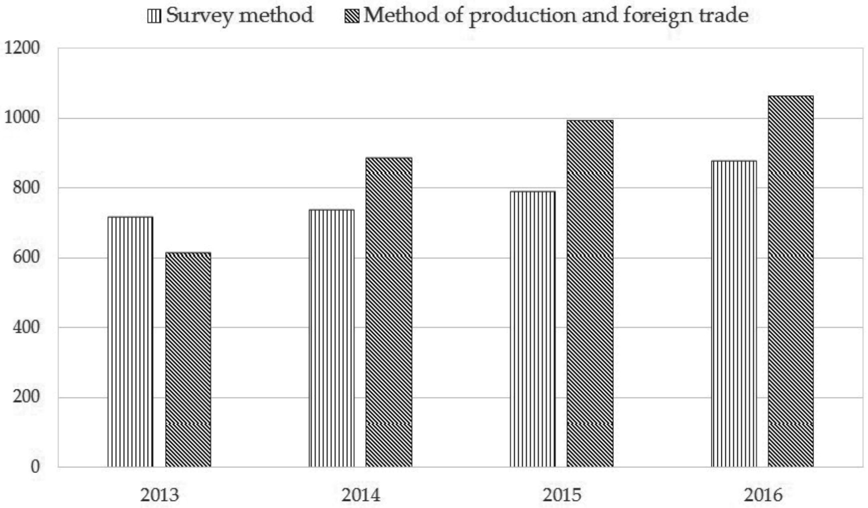
Figure 9. Generation of electronic waste in Mexico.

The method used to estimate the generation also influences to determine the tonnage in Figure 10 estimated between 2013 and 2016 by two methods, employed by National Institute of Statistic and Geography (INEGI) generation occurs, the first results from the national survey, which shows the EEE data in use, the other method used is based on production data and foreign trade [43].

From the experience of INECC in recent years on the issue of electronic waste, is to strengthen the technical capacity for actors to generate information on the subject and industry can access best management of these wastes. Among the actions was the need to develop management tools and implementation of management plans at all levels, in this case, states and municipalities set a target.

The valorization of WEEE's, is critical to the use of raw materials, which also avoids the high environmental and energy impact by obtaining them through traditional methods. That is why recycling of WEEE is an important issue not only from the point of view of waste treatment, but also from the perspective of material recovery.

Decisions on strategies in the management of WEEE should be designed to maximize the welfare of the population. The waste management affects people in three areas; economic through tax management concept, due to environmental emissions and derivatives and psychological effects due to the location of facilities management. In the search for better



Source: [43]

Figure 10. Estimed annual generation of electronic waste in Mexico.

strategies for managing WEEE's and determination of impacts associated with it is important to consider a whole range of factors related to both the product and the consumer and post-consumer keeper's management. In the case, electronics can be analyzed and evaluated environmentally in each stage of the life cycle. From a consumer perspective we might consider aspects such as the level of environmental awareness, consumption habits, socioeconomic status, disposal practices, etc. Also important to consider that a management model will be influenced by population issues such as: economic status, geographic location, cultural level, etc.

In Figure 11, a universal model for the recovery of electronic waste is presented to formalize the process of recovery of components WEEE's has value and market to subsequently implement more complex and comprehensive models. The rate shown represents the practices currently being carried out, which have not been systematized or have been ordered. This scheme can be adopted by municipalities and assemblers who perform recovery informality.

It is important that those involved in the recovery chain, at different levels work on responsibility for WEEE's management models are developed, taking advantage of the wills of the actors who are already recovering some components and materials for recycling and reuse and evolve to management models that are applicable to the locale. The model presented takes up two of the functions proposed by the Swiss model, which is the recovery of materials and functions.

Since 2006 the first national generation WEEE's diagnosis was made, it caused concern and interest in the problem of WEEE's, this process has been slow, although much work is required stakeholders, including the authority, producers, retailers, distributors and generators. Work is required in the formulation of a unique legal regime for the integrated management of

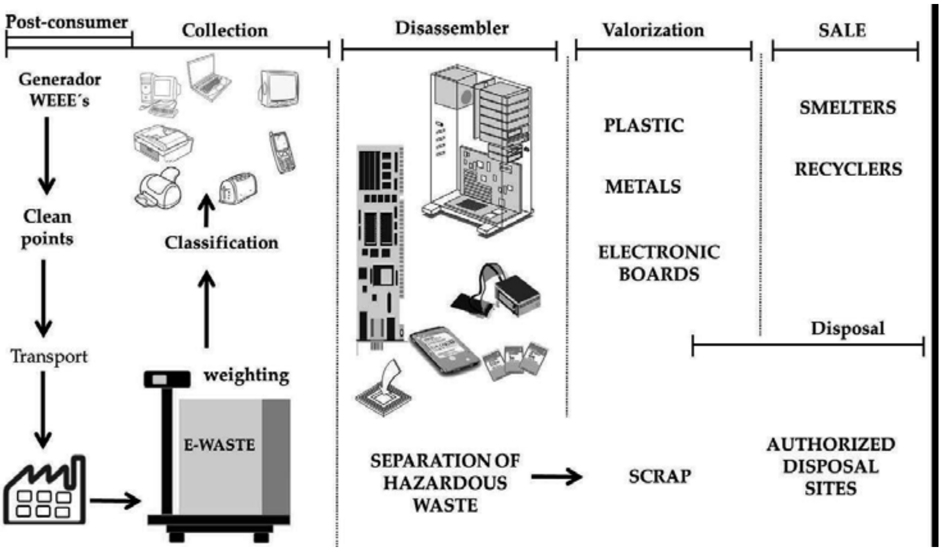


Figure 11. Flow for the recovery of electronic waste in Mexico.

WEEE's. Informal recycling is an issue that must be addressed by the environmental implications and associated health this common practice in our country.

5. Conclusions

The increase in the generation of electronic waste and insufficient formal mechanisms for handling it involves promoting schemes participation of society and decision makers involved in the value chain, giving greater opportunity to use materials, reducing environmental impacts and minimizing exposure to the informal sector in recovery WEEE's.

It is important to emphasize the topic about the management of electronic waste in rural areas it has not yet been extensively studied, it is known that there are no programs for collecting electronic waste, there are not reported generation statistics and handling practices in these communities. Therefore it is a topic of research that should be included in the agendas of experts and authorities at all three levels of government.

The existing regulations in Mexico, is not enough to develop management schemes WEEE's, so it is essential to promote a specific legal framework for the management of electrical and electronic waste equipment in which the extended producer responsibility is included, to hold manufacturers and other actors who are producers, as importers, assemblers and distributors to organize and finance the recovery and management of waste from electronic equipment put on the market. It should work on norms for WEEE's involving the three levels of government in the management process WEEE's. Also missing homogenizes the regulations of each state to avoid inefficiencies and inequities that exist in the management of this waste. It is important to work with WEEE's large generators to assume the commitment to be socially responsible and sustainable companies.

Should be promoting among the community the recycling culture of obsolete electronic equipment to recover materials can be recycled, as well as useful components and equipment. The recycling practice of WEEE's impact the reduction in the virgin materials in the manufacturing and therefore contribute to the reduction of environmental pollution.

In the process of WEEE’s managing a series of social and environmental problems arise that Mexico, like other emerging and developing economies must face. Among them are the practices of disposing of the WEEE's mixed with the municipal waste stream, without any handling for disposal. This action causes contamination in soil, air and water with toxic substances for health and environment. Another problem is the management that the waste pickers make it on this waste, which is unsafe, because the only purpose for them is to obtain plastics, metals and other materials such as printed circuit boards, facing the serious health risk to have contact with toxic substances contained in components WEEE's. The absence of extended responsibility for the producer is another problem.

Finally, it is essential that in Mexico programs integrated management of WEEE's should be established from the federal to the municipal level, where to promote private participation and are adaptable to the municipality, with the aim of implementing Integrated System Management WEEE's at a national level to promote sustainable management of WEEE's. Within these management processes as are collecting, reconditioning, repair, reuse, storage, and disposal should involve all stakeholders from the value chain, including those involved are producers, traders, consumers, carriers, collectors, repairers, and recyclers.

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Chapter 6

A Review of Technology of Metal Recovery from Electronic Waste

Vidyadhar Ari

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61569

Abstract

Electronic waste, or e-waste, is an emerging problem with developed nations as with developing nations. In the absence of proper collection and disposal systems, awareness, and proper regulations, the problem is rather more acute in developing nations. These wastes are environmentally hazardous on one hand and valuable on the other. They contain substantial amount of metal value, including precious metals. Personal computers are the biggest contributors to e-waste, followed closely by televisions and mobile phones. The growth in their consumption pattern indicates a manifold increase in the volume of e-waste and calls for immediate attention to the management of e-waste in general and their recycling and reuse in particular.

Their recovery, recycle, and reuse have become mandatory. Research and development work on their recycling has led to several technological options. However, a close investigation of the options reveals that there is no universally acceptable model for management of e-waste and they are still evolving. The technology for recycling depends on the economic status of the region along with several other factors. R&D efforts towards the management of e-waste and its recycling is seriously lacking in India.

There are three main constituents of e-waste, namely, glass, plastics, and metals. The glass may be re-melted for production of glass or for recovery of lead. The thermosetting plastics are difficult to recycle. The other types of plastics can be recycled for use as fuels or production of chemicals. The metals may be separated from the plastics and processed for recovery of individual metals. It may be said that physical separation techniques followed by metallurgical treatment is the best proposition for the recovery of metals. Detailed technology development needs to be taken up for the recycling of e-waste that may serve the interest of the region best.

Keywords: Electronic waste, collection and disposal, recycling practices, metal recovery

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1. Introduction

Safe and sustainable disposal of End-of-Life (EOL) electronic waste has been considered to be a major sphere of concern both by the government and public as well, due to its perilous impact on human life and environment, arising from its hazardous and highly toxic constituents. Disposal of such heterogeneous mix of organic materials, metals, etc., entails a scientific approach and special treatment to prevent exposing the inhabitants to the consequential damage implications arising from leakage and dissipation of the same for effectively mitigating the emerging risk phenomena escalating with the passage of time [1–6]. The threat perception arising over the last decade from accelerated accumulation of e-waste on account of the emerging consumption patterns across all sections of the society, influenced by the associated advantages ranging from affordability to comfort in day-to-day utility with respect to computers, cell phones, and other personal electronic equipment has been found to be phenomenal. It is now imperative for the society at large to evolve safe and scientific methodologies, both as a deterrent to the impending damage potential to the environment and also for recovering economically the embedded valuable and rare metals in contributing to immense value addition to the waste, which otherwise leads to large scale environmental and ground water pollution. Recycling, recovering, and reusing of obsolete electronics in new product cycles have now been globally recognized as a formidable challenge, taking into account the inherent value addition potential of metals such as gold, silver, copper, palladium, including rare metals, etc., which has immensely contributed to the concept of recycling to be a very lucrative business opportunity in both developed as well as developing countries. Also, the sheer volume of such waste generated on account of the present-day usage pattern poses a formidable problem in terms of storage handling and disposal space, which as a natural corollary, happens to be a major trigger across the globe for processing these wastes aimed at effectively extracting the metal values and remove the non-metallic constituents.

According to the United Nations (UN), the initiative to estimate e-waste production, the world produced approximately 50 million tons of e-waste in 2012, on an average of 15 lbs. per person across the globe. In 2012, the UN also stated that, the United Kingdom (UK) produced, 1.3 million tons of e-waste. China generated 11.1 million tons of e-waste that was followed by the United States (US) that accounted for 10 million tons in 2012 [7]. In Western Europe, 6 million tons of electric and electronic wastes were generated in 1998. The amount of this waste is expected to increase by at least 3–5% per annum [1]. This study also indicated that in the US, over 315 million computers would be at EOL by the year 2004. The same scenario applies to mobile phones and other hand-held electronic items used in the present society. In 2007, over 130 million mobile phones were discarded alone in the US and by 2010 in Japan, 610 million mobile phones will be disposed off. Every year, a European Union citizen leaves behind nearly 20 kg of e-waste [2]. The problem of e-waste is global, for example, in China about 20 million consumer electronic and electric equipment (EEEs) and 70 million mobile phones reach EOL each year [8] and in India computer ownership per capita grew 604% during the period 1993–2000 far exceeding the world average of 181% [9]. About 4000 tons per hour of e-waste is generated worldwide [10]. The printed circuit board (PCB) is a major constituent of these obsolete and discarded electronic scraps. The typical composition of PCB is non-metals (plastics, epoxy resins, glass) >70%, copper ~16%, solder ~4%, iron, ferrite ~3%, nickel ~2%, silver 0.05%, gold 0.03%, palladium 0.01%, others (bismuth, antimony, tantalum, etc.) <0.01% [11].

Veit et al. [12] reported a combination of magnetic and electrostatic separation for removing metallics from non-metallics. The authors reported that it is possible to obtain a fraction concentrated in metals containing more than 50% of copper, 24% of tin, and 8% of lead. Zhang and Forssberg [13] have done extensive work on liberation and classification of electronic scrap. In this work, liberation and its impact on the separation of computer scrap and PCB scrap has been studied. In Taiwan, research is being carried out on the processing of scrap computers with a view to recycling. It is reported that a recycling plant can recover useful materials from the main machines and monitors of scrap computers to the extent of 94.75 wt % and 45.99 wt%, respectively [14]. This study also deals with the processing of cathode ray tubes (CRTs) and PCBs separately. Zhang and Forssberg [15] studied electrodynamic separation and reported that copper products with the grade ranging from 93% to 99% and recovery from 95% to 99% can be achieved by this technique.

An excellent review by Williams [16] presented the current scope of technology, recycling process design, and controls. The author also indicated the direction of future research emphasizing the needs of automated processes, controls, and optimum data acquisition. Kang and Schoenung [17] have also presented a review of technology options for recovery of materials from e-waste. Various recycling technologies for glass, plastics, and metals that are present in electronic scrap are discussed. The authors emphasized the need for a stable supply of scrap, a cost-effective technology for recycling, and a stable demand of recycled materials for the success of the electronic scrap recycling industry.

In spite of having several technological options, it appears that a quest for a cost-effective technology for processing electronic scrap is still on. Yokoyama and Iji [18] have invented a dry separation method for recovering valuable metals from PCBs. Their method is based on two-step grinding of the boards, followed by air current centrifugal classification for gravity separation and electrostatic separation. Menad et al. [19] suggested that plastics contained in the electronic scrap may be used as combustible in some metallurgical processes. However, the authors cautioned that during combustion, halogenated flame retardants present in them would produce dibenzo-dioxins and dibenzo-furans, which are hazardous. Zhang et al. [20] have proposed an eddy-current method for recovering aluminum metals from PCB and personal computer scrap. It is reported that materials on the High-force eddy-current separator, an aluminum concentrate out of personal computer scrap can be obtained with a purity of 85%, while maintaining a recovery in excess of 90%, with the feed rate being up to 0.3 kg/min. Sinha-Khetriwal et al. [9] compared the recycling of e-waste in Switzerland as one of the few countries with long-term experience in managing e-waste in India, which handles huge amounts of imported e-waste, but is continually experiencing problems. Market players are taking measures to recycle e-waste in order to reduce the pollution and environmental hazards caused by it. In June 2014, Dell, a leading computer manufacturer, launched its first computer that is made of plastics obtained from recycled electronics. The company has started selling its first computer "the OptiPlex 3030", which is made up of old electronics using the closed loop recycling process. Recently, Dell has also started using recycled plastics in its other desktops and monitors. Millions of refrigerators, TV sets, and cell phones are replaced with newer versions due to the users' growing inclination towards technologically advanced gadgets [7].

Developed countries such as the US, Europe, and Japan have adopted fully automated, high-cost technology for e-waste recycling [21]. E-waste is crushed, shredded in total, followed by the separation of metals and non-metals by adopting unit operations/metallurgical principles. The disposal and recycling of e-waste, particularly computer and related wastes, in India, has become a serious problem since the methods of disposal are very rudimentary and pose grave environmental and health hazards. The situation is aggravated as current e-waste management and disposal methods suffer from a number of drawbacks such as inadequate legislations, lack of funds, poor awareness, and reluctance on the part of the governments and the corporate organizations to address the critical issues. In view of the dwindling reserve of good quality metallic ore for production of metals, environmental pollution, and need for recycle, an indigenous technology for processing this waste is certainly necessary today. In India, e-waste management assumes greater significance not only due to the generation of its own e-waste but also because of the dumping of e-waste from developed countries. Solid waste management, which is already a mammoth task in India, has become more complicated by the invasion of e-waste. There is an urgent need for exploring different options of e-waste recycling in developing countries.

The present review article provides an overview of India's current e-waste scenario, environmental and health hazards, current disposal, collection, and recycling. It also provides a comprehensive view of the technologies available in the developed countries as well as the developing countries for the recycling of e-waste. The review research methodology as adopted by the researcher and proceeds encompasses reliability factor designed to deliver a balanced view from both macro and micro perspective of process feasibility and economics as well, based on authentic information about growth and forecasts.

2. E-waste and its composition

2.1. Definition of e-waste

Electronic waste or e-waste, according to the WEEE directive of the European Commission, is defined as waste material consisting of any broken or unwanted electronic appliance. Electronic waste includes computers, entertainment electronics, mobile phones, and other electronic items that have been discarded by their original users. Despite its common classification as a waste, disposed electronics is a category of considerable secondary resource due to its significant suitability for direct reuse (for example, many fully functional computers and components are discarded during upgrades), refurbishing, and material recycling of its constituent raw materials [22].

2.2. The key benefits for recycling EOL e-waste

E-waste is the most rapidly growing segment of the municipal waste stream and the Global E-waste Management Market is expected to reach $49.4 billion by 2020, with compounded annual growth rate (CAGR) of 23.5% (2014–2020), with maximum share of e-waste management market attributable to information technology (IT) and telecommunications, followed by household appliances and consumer electronic goods. E-waste contains many valuable, recoverable materials such as aluminum, ferrous metals, copper, gold, and silver. In order to conserve natural resources and the energy needed to produce new electronic equipment from virgin resources, electronic equipment should be refurbished, reused, and recycled whenever possible. E-waste also contains toxic and hazardous waste materials including mercury, lead, cadmium, chromium, antimony, and many other chemicals. Recycling will prevent them from posing an environmental hazard.

2.3. Health and environmental impact of e-waste

EOL of electrical and electronic equipments comprise numerous components, many of which are inherently hazardous and highly toxic in nature, which if not arrested through scientifically sustainable recycling and disposal, can lead to a disastrous impact on life, environment, and climate as well. Certain examples of sources of e-waste and their related adverse health impacts are listed in Table 1 [23]. However, if handled in a controlled environment and disposed-off adopting safe and sustainable methodology, these e-wastes provide immense value addition and new product cycle, driving great economic prospect, without posing risks to life, environment, and climate. However, haphazard recycling and disposal of e-waste by the unorganized sector without access to adequate technology and resources, guided by profit-only motive can have damaging consequences to inhabitants and the environment, including but not limited to the workforce engaged in this trade, groundwater pollution, etc., especially on account of highly toxic release into the soil, air, and ground water [23].

E-waste sources	Constitutents	Health effects
Solder in PCBs, glass panels, and gaskets in computer monitors	Lead	Causes damage to the nervous system, circulatory system, and kidney. Also affects brain developments in children.
Chip resistors and semiconductors	Cadmium	Causes neural damage.
Relays and switches, PCBs	Mercury	Cause chronic damage to the brain and respiratory and skin disorders.
Corrosion protection of untreated galvanized steel plates, decorator, or hardener for steel housing	Hexavalent chromiun	Causes bronchitis and DNA damage.
Cabling and computer housing	Plastics including PVC	Affects the reproductive system and immune system and lead to hormonal disorder.
Plastic housing of electronic equipments and circuit boards	Brominated flame retardants	Disrupts endocrine system functions.
Front panel of CRTs	Barium, phosphor, and heavy metals	Causes muscle weakness and damage to heart, liver, and spleen.
Motherboard	Beryllium	Carcinogenic in nature causing skin diseases

Table 1. E-waste sources and their health effects.

Landfilling, being one of the widely prevalent methods of e-waste disposal, is as such prone to hazardous implications attributable to leachate that often contains heavy metals, and this equally applies to the state-of-the-art landfills methodologies that are adopted or sealed for the long-term. The older landfill sites and uncontrolled dumps factually pose a much greater danger of releasing hazardous emissions, since mercury, cadmium, and lead comprise the most toxic elements of the leachates (Table 1). Mercury, for example, will leach when certain electronic devices such as circuit breakers, etc., are subjected to disposal and recycling; lead has been found to leach from broken lead-containing glasses, such as the cone glass of CRTs from televisions and monitors; when brominated flame-retarded plastics or plastics containing cadmium are landfilled, both PBDE (polybrominated diphenyl ethers) and cadmium may leach out into the soil and groundwater. In addition, landfills are also prone to uncontrolled fire, release source for toxic fumes [23].

The toxicity is due in part to lead, mercury, cadmium, beryllium, Brominated Flame Retardants (BFRs), PVC, and phosphorus compounds and a number of other substances. A typical computer monitor may contain more than 6% lead by weight, much of which is in the lead glass of the CRT. Up to thirty-eight separate chemical elements are incorporated into e-waste items. Though some of the materials are used in small quantities in each computer, the net volumes being recycled are significant and have a huge impact on both environment and human health. The unsustainability of discarding electronic items is another reason for the need to recycle—or perhaps more practically, reuse e-waste. Quantification of some of the toxic elements present in an average computer, weighing approximately 31.5 kg [24] shown in Table 2.

Element	Quantity
Plastics	7.24 kg
Lead	1.98 kg
Mercury	0.693 g
Arsenic	0.4095 g
Cadmium	2.961 g
Chromium	1.98 g
Barium	9.92 g
Beryllium	4.94 g

Table 2. Toxic elements present in an average computer.

Given the diverse range of materials found in WEEE, it is difficult to give a generalized material composition for the entire waste stream. However, most studies examine five categories of materials: ferrous metals, non-ferrous metals, glass, plastics, and others. Figure 1 shows the material fractions in e-waste [2]. Metals are the major common materials found in e-waste representing about 60%. Plastics are the second largest component by weight representing about 15%. Figures 2—4 shows the material composition of a personal computer [25, 26], followed by television sets [27] and mobile phones [28].

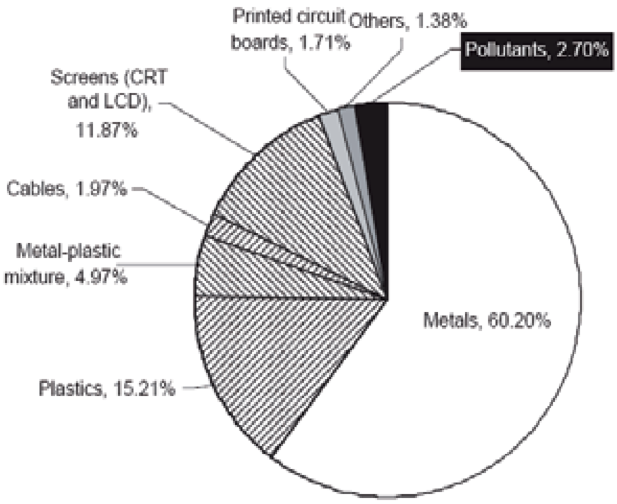

Figure 1. Material fractions in e-waste [2].

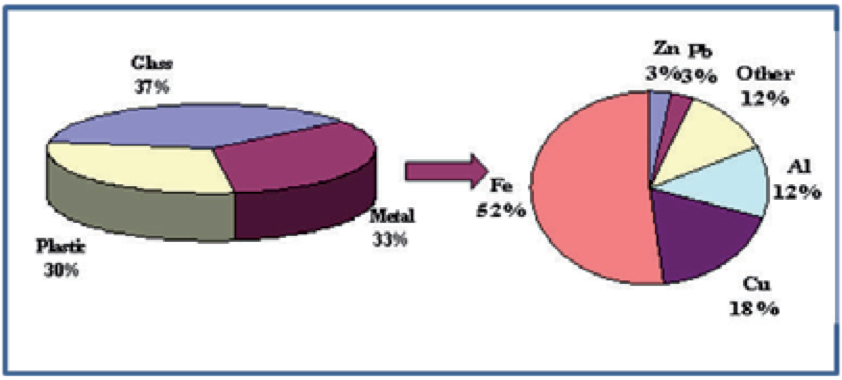

Figure 2. Material composition of a typical computer.

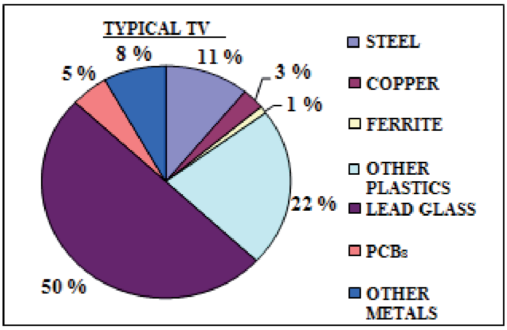

Figure 3. Material composition of a typical TV.

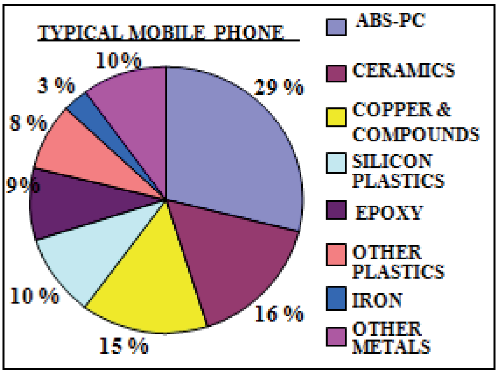

Figure 4. Material composition of a typical mobile phone.

3. E-waste scenario

3.1. Global scenario

Accelerated generation of e-waste with passage of time happens to be the natural outcome of incremental penetration of IT in diverse spheres of day-to-day activities, adding up to the municipal solid waste stream. E-waste equals 1% of solid waste on average in developed countries and ranges from 0.01% to 1% in developing countries [29], and the same is expected to inch up considerably in the near future. Some of the developed countries such as the US, UK, Germany, Japan, and New Zealand have already developed advanced processing techniques for recycling of the e-waste and patented them, as well. The Union Miniere Company in Belgium [30] and Boliden Mineral in Sweden [31] have, since quite some time, been operating recycling plants to process e-waste, while in China [32–36], Taiwan [14, 37], and South Korea [38] proactive measures are being pursued to recycle metal from e-waste, but in India, no concrete or notable steps have been initiated so far in the large scale or in structured format. Das et al. [39] developed a flowsheet using a combination of wet and dry processes to produce a rich concentrate with significantly high recoveries of metals from ground PCB powder.

Every year, 20 to 50 million tons of electrical and electronic equipment wastes are discarded worldwide and Asian countries discard an estimated of 12 million tons [40]. The share of the developing economies of China, India, etc., with respect to consumption of computers in particular, is likely to surge ahead, surpassing 178 million in case of China and 80 million in case of India, out of the estimated 716 million new computer users' global total [41]. E-waste generated in developed countries such as the US, etc., is often exported for recycling in developing countries where labor is relatively cheap, apart from the prospect of ending up as landfill, and as a result, the pollution menace is accelerating at very fast pace, especially in countries such as China, India, and Pakistan, posing severe health and environmental hazard.

Rampant approach of open-air burning of plastic wastes, toxic solders, river dumping of acids, and widespread dumping and landfill in general [25]. A report from the International Association of Electronics Recyclers states that around 3 billion units are expected to be scrapped in the remaining years for the decade to end in the US alone, which works out to an average of about 400 million units a year, that includes 200 million televisions and 1 billion units of computer equipment. According to Basel Action Network (BAN), about 75% of old electronics are in the offing to be scrapped in near future, which at present have been kept in abeyance by the consumers, with the expectation being nurtured by them that they still have some usage value left and at the same time remaining uncertain about its disposal methodology to be adopted [42]. Most of the e-waste produced by developed countries is dumped in developing and under-developed countries.

3.2. Indian scenario

As there exists no dedicated or systematic collection provision for e-waste in India, no clear data is available on the quantity actually generated and disposed off each year and the extent of resultant environmental risk. The MAIT-GTZ study [43] reported that a total of 330,000 metric tons of e-waste (computers, televisions, and mobile handsets only) was generated in 2007. An additional 50,000 tons were unscrupulously imported into the country, mostly mislabeled as charitable donations or scrap, and not specified as electronic scrap, generating a annual e-waste of about 380,000 metric tons. Of this, only 19,000 tons were recycled, which was factually complemented by the demand for refurbishing and reuse of electronic products in the country and poor recycling infrastructure set-up in the unrecognized sector with profiteering motive. Generation of e-waste in India is estimated to far exceed 470,000 metric tons as on 2011, out of which Mumbai generates around 11,000 tons of e-waste, Delhi 9000 tons, Bengaluru 8000 tons and Chennai 5000–6000 tons each year. Maharastra State (including Mumbai city) alone produces 20,270 tons of e-waste annually [44]. The Electronic Industry Association (ELCINA) in India has predicted that e-waste will increase by 11 times as on 2012, since the average lifespan of a personal computer is reduced to around 2 years. The per capita waste production in developing countries such as India and China, is still relatively small, estimated less than 1 kg per capita per year. In India electronic goods such as computers, washing machines, televisions, and refrigerators will drive the future growth of the electronics hardware industry. The e-waste generated from these four items during 2004–2005 was found to be 1,46,180.00 tons and it was expected to exceed to about 16, 00,000 tons by 2010 [45].

In India, the problem of e-waste generation and disposal is steadily attaining an alarming dimension with passage of time. It has been reported that 900–1000 computers are dismantled every day in New Delhi alone. In 2005, about 1000 tons of plastics, the same equivalent of iron, 300 tons of lead, 0.23 tons of mercury, 43 tons of nickel, and 350 tons of copper were expected to be generated as e-waste in Bengaluru alone [46]. These figures are set to increase by ten-fold by 2020. In India, Maharashtra, Tamilnadu, and Andhra Pradesh head the list of e-waste generating states. Cities such as Delhi, Chennai, Kolkata, and Bengaluru contribute significantly to the e-waste generation as well. A study done by Toxics Link in 2007 [47] estimated that Mumbai alone produces 19,000 tons of WEEE annually. Another study had done jointly by Toxics Link and the Centre for Quality Management Systems, Jadavpur University, Kolkata estimates around 9000 tons of WEEE generation in the city of Kolkata [48]. The future projection of e-waste in India as per the Department of Information Technology is shown in Figure 5.

Figure 5. State-wise e-waste generation in India.

The results of a field survey conducted in Chennai, a metropolitan city of India, to assess the average usage and life of the personal computers (PCs), televisions (TVs), and mobile phones demonstrated that the average household usage of the PC ranges from 0.39 to 1.70 depending on the income class [49]. Although the per-capita waste production in India is still relatively small, the total absolute volume of wastes generated is gigantic, and it continues to grow at an alarmingly fast rate. The growth rate of mobile phones (80%) is very high compared to that of PCs (20%) and TVs (18%). The public awareness on e-wastes and the willingness of the public to pay for e-waste management, as assessed during the study, based on an organized questionnaire revealed that about 50% of the public are aware of environmental and health impacts of EOL electronic items. The willingness of the public to pay for e-waste management ranges from 3.57% to 5.92% of the product cost for PCs, 3.94% to 5.95% for TV and 3.4% to 5% for the mobile phones [50].

4. E-waste sources and growth pattern

4.1. E-waste sources

The main sources of e-waste in India comprises the government, public, and private (industrial) sector discards, which account for almost 70% of the total e-waste generation. The growth in the government sector alone has been a staggering 126% as of 2006 [26]. Important government departments such as Railways, Defense, and Healthcare have been estimated to generate large volumes of e-waste. In India, most organizations upgrade their hardware infrastructure at an interval of 3–5 years, and at times much earlier influenced by the benefit in rate of allowable depreciation. Electronics goods are high price items and hence are not dumped in streets or garbage yards. These are stored in houses or warehouses for a long period of time and subsequently either passed on to or sold to scrap dealers for monetizing, however, this practice is set to change with time. The contribution of individual households is relatively small at about 15 % while the balance is contributed by the commercial or business segment. Though individual households are not large contributors to computer waste generation, large-scale consumption of consumer durables such as televisions, refrigerators, air conditioners, etc., are certainly attributable to this segment. The trend of extended usage is also changing with rapid advancements in technology and further complemented by lower product costs, which is leading to scaled-up generation of domestic e-waste.

Another major source of e-waste is unscrupulous import, which is adding to the volume of waste being generated within the country, however, accurate data on such imports are not available, owing largely to the nature of the trade. Developing countries, including India, have been the destination ports for various types of hazardous waste from the developed world and e-waste is no exception. Industrialized nations are scrounging for space for landfills to dispose of huge amounts of e-waste being generated by them and with strict environmental regimes being put to practice, especially in European countries, thereby, adding to the cost of disposal [51]. As per available data, the cost of recycling a single computer in the US is US$20 while the same could be recycled in India for only US$2, a gross saving of US$18 if the computer is exported to India [51]. Most developed countries stand to benefit economically by dumping e-wastes in developing countries.

The lack of stringent environmental regulations, weak enforcement mechanism, cheap raw materials and labor, and ill-informed population in combination with the unorganized nature of the trade contributes significantly to the growing imports of e-waste in India. Even though the import of e-waste is banned in India, there are many reports of such waste landing in Indian ports under different nomenclature, such as mixed metal scrap or as goods meant for charity [51]. However, estimates suggest that unscrupulous imports of e-waste are equal to or even more than that being generated in the country.

4.2. Growth of e-waste

Electronic and electrical goods are largely classified under three major heads: ‘white goods’, comprise household appliances such as air conditioners, dishwashers, refrigerators, and washing machines; “brown goods” such as televisions, camcorders, cameras; and “gray goods” such as computers, printers, fax machines, scanners, etc. These gray goods are comparatively more complex to recycle due to their multi-layered configuration and higher toxic composition. The last decade has also witnessed major growth in the gray goods market and India is expected to achieve a PC penetration rate of 65 per one thousand by the year 2008 [52].

The PC sales figure in India has been very impressive, showing a huge growth from a mere 14,05,290 in 1999–2000 to 46,14,724 in 2005–2006 and is conservatively projected to touch 56,00,000 by 2006–2007. The expected annual average growth rate in the PC is likely to be 21%, while consumption of PC in the top four cities (Delhi, Mumbai, Kolkata, Chennai) grew by 25% as on 2006 [48]. For the laptop segment, the growth is more impressive; the sales figure has jumped from 50,954 in 2002–2003 to 4,31,834 in 2005–2006 having registered an astonishing growth rate of 143% in 2005–2006 [48,52]. The overall PC sales in 2012–2013 considerably slowed down and the sales figure are well below the expectations. The overall sales figures touched 11.31 million in 2012–2013, registering a growth of 5% over the last fiscal. Desktop PCs continued to dominate the sales proceedings contributing around 60% of the sales although it is somewhat lesser than last year's contribution of 63%. Notebook sales posted a muted growth rate of 10% in 2012–2013 compared to the 22% rate in the previous year. Tablet PCs witnessed a massive growth rate of 424%. The sales for 2012–2013 stood at 1.9 million units as against 0.36 million units in 2011–2012 [53]. 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 in India [54]. 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 (Figure 6). According to forecast, based on a logistic model and material flow analysis [55], the volume of obsolete PCs generated in developing regions will exceed that of developed regions by 2016–2018. By 2030, there would be two obsolete PCs in the developing world for every obsolete PC in the developed world. Similar forecasts have been arrived independently [56]. The advent of LCD, plasma, and larger screens has changed the way India views television and this has translated into phenomenal growth in sales, resulting in a considerable surge in rate of disposal as well.

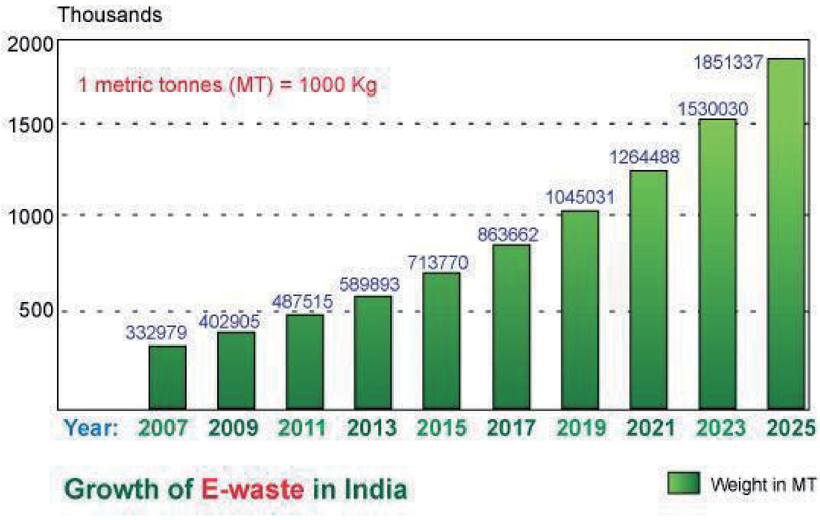

Figure 6. E-waste generation in India: Past and forecasts for the future.

There are over 75 million mobile users and the number has increased to 200 million as of 2008 [57]. An estimated 30,000 computers become obsolete every year from the IT industry in Bengaluru alone [58]. India has about 15 million computers and the base is expected to grow to 75 million computers by 2010 since the life cycle of a PC has come down to 3–4 years from 7 to 8 years a few years back, and the segment is suffering from an extremely high obsolescence rate of 30% per year [58]. The rapid growth in industrialization is immensely contributing to the generation of huge quantities of waste. Some of the recent studies on e-waste generation clearly reflect that this trend is likely to grow at a phenomenal rate, while penetrating to smaller towns and cities.

Another important contributing factor to incremental waste generation is the high obsolescence rate of these products and the inability of technology to support upgradation from the perspective of economic viability. This consumption pattern and programmed obsolescence is a part of business management strategy in planning in-built product design with limited life that promotes a high-waste economy targeted at people with higher disposable income. Every two years, a new computer model is introduced in the market, rendering the previous one obsolete. The Indian mindset has so far been able to prolong the usage of such products by devising innovative solutions; however, this approach is undergoing gradual change after being bitten by the new bug of consumerism.

5. E-waste disposal methods and recycling practices

5.1. E-waste disposal methods

Computer scrap in India is handled through various approaches in management alternatives such as product reuse, conventional disposal in landfills, incineration, and recycling. The recycling of computer waste requires efficient and advanced processing technology, which apart from being capital intensive, entails high-end operational skills and training of the processing personnel. However, the disposal and recycling of EOL computers in the country has become a menacing problem compounded on account of rudimentary methodology for disposal and recycling by entrepreneurs in the unorganized sector drawn more with profiteering motive, despite not having adequate access to sustainable technology, thereby posing grave environmental and health hazards. Apart from having to handle its own burden arising from the accelerated accumulation of EOL-EEEs, India now faces the herculean task in managing the waste being especially dumped by developed countries, leading to rapid escalation of the risk phenomena associated to solid waste management, particularly computer waste. Taking advantage of the relative slackness on environmental standards and working conditions in developing countries, vis-à-vis stringent environmental norms followed in the developed countries, e-waste is being sent or dumped for processing in India and China—in most cases, illegally. The random open-air disposal of e-waste, including incineration, is factually contributing to the rapid escalation in pollution menace, affecting both life and environment. Currently, the likely modes of disposing e-waste discussed in the following sections.

5.1.1. Product reuse

Refurbishing used computers and other electronic goods for reuse after minor modifications, apart from the prevalent trend of passing on the same to relatives and friends, is a common societal practice. Apart from this, being lured by the retailers to monetise the old gadgets by exchanging against new gadgets, in the form of additional discounts, are factually marketing gimmicks for accelerating sales volume. The actual benefits to the customer in the new for old exchange exercise, more often than not, are notional in reality, when viewed in perspective from commercial angle. There are instances when educational institutes or charitable institutions receive old computers for reuse. Such deemed unhealthy practice adopted for product reuse, despite their limited life span, which sooner or later ends up as waste, contributes significantly to the burgeoning burden of computer waste.

5.1.2. Conventional disposal in landfills

The product is dumped in landfill sites, where it may remain indefinitely. According to the Environmental Protection Agency (EPA), more than 3.2 million tons of e-waste ended up in US landfills in 1997 [59]. The extremely low biodegradable characteristics of plastic components in computers gets further compounded in dry conditions, which complements landfills and in strictly regulated landfill sites, degradation is even slower. The highly toxic constituents found in the different components of a computer contributes to metal leaching, leading to large-scale soil and groundwater pollution, and the situation worsens with passage of time for sites subjected to dumping for prolonged periods of time. When disposed off in landfills, the multi-layered configuration of computer waste becomes a conglomeration of plastic and steel casings, circuit boards, glass tubes, wires, and other assorted parts and materials. About 70% of heavy metals (including mercury and cadmium) found in landfills come from electronic discards [60]. In 2001 CRTs were banned from municipal landfills in California and Massachusetts because of their recognized hazardous nature, while no such regulatory measures are enforced in developing countries such as India, China, etc.

5.1.3. Incineration or open-air burning

After manual separation of components, motherboards are introduced to open pit burning for extracting the thin layer of copper foils laminated in the circuit board, which after charring, is distilled through a simple froth floating process. The ash is washed out and the copper, with some carbon impurity, goes to the next recycling stage. The defective IC chips and condensers, which do not have a resale value, are burned in small enclosures with chimneys for extracting the embedded metallic parts [26].

5.1.4. Recycling

Recycling practices for discarded personal computers are highly local and rudimentary, albeit, the metal value recovered from computer waste lessens considerably the disposal burden and consequent financial costs. Though a good fraction of computer waste is recycled in the process, the unscientific methodology adopted for material salvaging has an extremely high environment and health hazard impact attached to it as a natural corollary to the deployment of rudimentary recycling and recovery process and its damaging implications both on life and environment. Apart from the challenges explained, such method of recycling has its inherent limitations with respect to recovery of both metals and non-metals e.g., copper, gold, silver, aluminum, iron, tin, lead, and plastics are recovered to some extent while such processing technique does not aid value addition in a true sense, keeping in mind the fact that many vital metallic components, such as germanium, barium, platinum, antimony, cobalt, nickel, etc. remain unrecovered.

6. Recycling practices of e-waste

Recycling of e-waste, especially EOL-EEEs, such as computers and mobile phones, provides lucrative business opportunity for extraction of valuable metals such as gold, silver, copper, lead, etc. Currently, e-waste recycling in India, especially processing, to a large extent, almost 95%, remains confined to the unorganized sector, which due to its inaccessibility to scientifically focused and sustainable processing technologies with added constraints of limitation in processing capacity, contributes significantly to pollution and environmental degradation. This trade has mostly grown on the fringes of metropolitan and larger cities surrounding the industry hub, however, with incremental growth in processing of e-waste, a shift to the periphery of smaller towns has also been observed of late. The phenomena of e-waste processing comprising dismantling and recycling for extracting valuable metals from PCBs, including CRT re-gunning, etc., adopting crude process methodology such as open-air burning or incineration, use of acid bath, etc., is primarily focused upon profiteering motive with minimal capital investment. This leads to escalating the grave damage implications for both life and environment, apart from endangering both the lives of workers engaged in the processing activities and the residents of the surrounding localities.

The recycling operations, as explained above, employs a large section of the underprivileged population, especially migrant unskilled laborers, including women and children, depending on this trade for their day-to-day livelihood. The role of the unorganized sector involved in the processing of such highly complex waste, exposing the life and environment to toxic pollution, has since long been a subject of debate in the scientific sphere and the society at large. Effectively, the real cause of concern for the escalating scenario emerging from such ill-focused trade undertaken by the unorganized sector, hinging on primitive process methodology, as adopted by them, and not on the trade or the stakeholders per se. However, it also needs to be appreciated that the unorganized trade activities undertaken in this connection contributes to the retrieval of a large percentage of the waste material and circulating back the same to a new product cycle, based on its innovative and economical techniques, albeit rudimentary, as developed by them, thereby, circumventing tons of e-waste being sent to landfills, while generating wealth from the huge waste. Open-air burning of plastics, PVC-coated wires, and PCBs are known to produce carcinogens such as dioxin and furan emissions [61]. The recovery of lead from circuit boards also emits dioxin and other chlorine compounds into the air. Broken picture tubes, contaminated with lead and barium, land up in glass manufacturing units. Thus, CRT glass, with a significant percentage of mercury and lead, re-enters the consumer's domain as a new recycled product [62], while most of the population unfortunately continue to remain ignorant about the grave health and environmental risks associated with rudimentary processing of e-waste. On the other hand, non-recyclable components are either dumped as landfill or burned in the open, releasing toxins into the environment.

Recycling of EOL PCs is a very complex process on account of its multi-layered configuration comprising numerous materials and components aimed at recovering the valuable metals and other ingredients factually entails deployment of advanced processing technology and skilled technical personnel. This can effectively meet the pre-requisite safety norms for arresting the damage consequences, as explained, which as such is not generally accessible by recyclers in the unorganized sector, who are engaged in salvaging the wealth from waste, on account of multiple constraints ranging from finances, scalability factor, etc., including but not limited to ignorance as well. Technology limitations notwithstanding, each PC component is either refurbished for reuse or disassembled and recycled in India. However, liquid crystal displays (LCDs) are rapidly replacing cathode tubes, but the menacingly escalating implications, especially with respect to TV and PC waste, essentially needs to be encountered in the decade ahead; therefore, safety and solution to the impending environmental disaster lies in recycling of the same in industry scale by the organized sector [63, 64]. Computer monitors and TVs are disassembled to recover CRT, copper yoke plastic casing, and plates. The functional CRTs are sold for re-gunning as re-charged tubes, which has a potential sale value among local manufacturers. The defective CRTs are broken down to recover iron frames, which are sold to the scrap merchants. The copper recovered from deflection yoke coils and transformers mounted in the circuit boards are sold to copper smelters. The circuit tray contains a number of condensers of different sizes, which are disassembled to sell at secondary markets based on their functionality. Defective condensers are sold along with the motherboard for recovery of precious metal. The casing of monitors and TVs, including the insulator of copper wire and cable, comprises of either PVC (polyvinyl chloride) or a combination of both PVC and ABS (acrylonitrile-butadiene styrene), however, PVC is not recyclable due to the presence of high silicate percentage. ABS is recycled into high impact plastic, mostly for consumption by toy manufacturers. The recovery methods followed [26] by the units in the unorganized sector in India for various components are described in the Table 3. The recovery of the components from e-waste depends on their market value, while the residue and leftover such as ashes and plastic residues from charred IC chips, condensers, etc., are disposed off in landfills.

The recycling process broadly involves shredding, sorting, grading, compacting, bailing, or processing clean plastics and scrap metal. After segregating at source, physical separation, identification, and testing are carried out. Present recovery practices, however, broadly comprises glass, plastic, copper, aluminum, iron, etc., and do not cover precious metals. Recovery of precious elements, albeit being a very technologically challenging task, is vital from the economic perspective and presently, electronic waste in the form of populated PCB components is exported to various countries to accomplish the objective of recovering these elements, on account of technology limitations in India. The recovery aspects of certain valuable elements such as silver (Ag), gold (Au), palladium (Pd), tantalum (Ta), ruthenium (Ru), indium (In), gallium (Ga), beryllium (Be), etc., which are present in traces, have not been explored so far since the economy of scale and processing feasibility is factually determined by the recoverability aspect, taking into account the quantitative presence of the same (in

Items	Recovered Module /Component / Materials	Methods employed
Computer monitor, TV	• Cathode ray tube • Circuit board • Copper, steel • Glass • Plastic casing	• Dismantling manually using screwdrivers and pliers • Nonworking CRT broken with hammer
CPU/Hard disk of computer	• Metals (steel, aluminum) • Non-metals parts • Actuator (magnet) • Platter • Circuit board • Disk, floppy drive • SNPS (Power supply)	• Manual with help of screwdriver, hammer, and pliers
Populated PCB	• Capacitor & condenser • Gold • Copper • Lead, IC, CPU • Chipped board	• After preheating plate, removed with the help of pliers • Acid treatment/bath • Heating, incineration • Crushing of boards by custom-made crushers
Computer printer	• Motor • Plastics • Cartridge	• Dismantling using screw drivers
Cables and wires	Copper, aluminum	• Incineration or stripping
Computer hard disk, floppy drive, and power supply (SNPS)	Copper and brass alloys, aluminum, iron, and magnet	• Melted after manual separation of each part
Capacitor and condensers	Aluminum	Incineration to extract metallic part

Table 3. Techniques and tools used for e-waste recovery.

traces), as explained. However, the recovery of the said elements may be feasible if large quantities of concentrated e-waste are processed for recovery, deploying suitably advanced technology by striking a balance between desirable recovery vs. yield.

The recycling/recovery of valuable substances by industries in the organized sector with access to requisite technology and manpower is carried out in protected environment, adopting adequate preventive methodology to minimize damage to life and environment. The merit of a focused approach by the stakeholders factually complements the efficacious recovery of metals, including rare and precious metals present in traces, aided by advanced process technology, wherein the processing capacity or volume plays a pivotal role in contributing to the viability aspect, keeping in mind the high cost of capital investments for infrastructure built-up and affordability for accessing technology advancements in the sphere. Every stakeholder across the board, especially the government policy makers, the scientific community, the industry engaged in the trade, and the society at large, need to introspect at depth and contribute proactively with their respective contribution. This is imperative for arresting the crisis-ridden scenario with tangible solutions, apart from putting forth their best of efforts for raising the consciousness level in the society.

6.1. Authorized e-waste recyclers/reprocessors registered with central pollution control board

For a developing country such as India, long identified as a potential scavenger of the developed world's discarded waste, we have now embarked on a path to discard this concept and identity, at the earliest. This is abundantly clear from the swift and quiet banning of a whole host of imports, including e-waste from overseas, and this per se serves the purpose of putting in place a multi-pronged waste management ethos in the country by regulatory enforcements for productive utilization of domestic e-waste, as generated. Majority of the e-waste in India is channelised through the unorganized sector, and on the flip side, the organized recyclers are battling grossly inadequate input materials for recycling. In order to address the issue, the MoEF had introduced adequate safeguard clauses in the Hazardous Wastes (Management Handling & Transboundary Movement) Rules, 2008 [65]. The MoEF had advised all the government departments/offices that e-wastes generated in various offices and establishments need to be essentially disposed off in an environmentally safe and sound manner, in accordance with the extant rules. The occupiers are now accountable for environmentally safe and sound handling of such hazardous wastes generated in their establishments. The MoEF has notified E-waste (Management and Handling) Rules, 2011 on 1st May, 2012 to provide collection, handling, storage, dismantling, and recycling facilities. CPCB has notified guidelines for implementation of e-wastes rules 2011 and also a list of registered e-waste recyclers/dismantlers, that are in possession of e-waste recycling capabilities [66]. As of November 2014, there were a total of 138 registered e-waste recyclers/dismantlers with CPCB in the country that have recycling/dismantling capacity of 349,154.6 metric ton per annum (MTA) for environmentally sound management of e-waste [67].

6.2. Existence of e-waste recycling plants in India

6.2.1. E-Parisara Pvt. Ltd

E-Parisara, an eco-friendly e-waste recycling unit on the outskirts of Bengaluru, has the capacity to recycle 3 tons of e-waste every day and is expected to be scaled up to achieve a 10-ton capacity in five years [68, 69]. The plant, which is India's first scientific e-waste recycling unit, will reduce pollution, landfill waste, and recover valuable metals, plastics, and glass from waste in an eco-friendly manner. E-parisara works on manual dismantling and segregation, and it separates the materials containing toxic heavy metals such as cadmium, lead, mercury, and so on. Plastic and glass wastes are sold to recyclers authorized by Karnataka State Pollution Control Board (KSPCB) [69]. The metal content can be safely recycled and reused for other processes, while the dust and other wastes can be safely land filled [69]. The process of recycling involves non-incineration technology, consisting of manual dismantling, segregation, shredding, crushing, pulverizing, and density separation, which includes crushing assured destruction, precious metal recovery, and consumer-friendly methodology [70]. E-parisara Pvt. Ltd. has shared its data of industrial operation, which indicates that 1ton of computers can recover 20kg of ferrous and 29kg of non-ferrous metals, 50kg of cable, and 40kg of PCBs [6]. The volume and cost of the metals recovered from 1 ton of PCBs are indicated in Table 4.

Recovered metal	Weight	Approximate cost (in US$)
Gold	279.93 g	6115 (@ 685.00 per 31 g)
Precious metals (Pt, Pd, In)	93.31 g	3852 (@ 1284.00 per 31 g)
Copper	190.512 Kg	1470 (@ 3.50 per 453.59 g)
Aluminum	142.152 Kg	448.00 (@ 1.28 per 453.59 g)
Lead and Tin (Pb/Sn)	30.844 Kg	144.16 (@ 2.12 per 453.59 g)
Silver	450 g	213.15 (@ 14.70 per 31 g)

NB: Data recovered on average recovery of one ton of populated PCBs and value is taken from the prevailing rate at that point of time. These are only to give a perception of value from the metal recovery from e-waste.

Table 4. Market value of the metal recovered from 1000 kg of PCBs.

E-Parisara has developed a low-cost circuit to extend the life of tube lights. The circuit helps to extend the life of fluorescent tubes by more than 2000+ hours and can also function at low voltage supply of less than 180 V. It can also be used for fused CFLs (compact fluorescent lamps). No starter is required for these tubes, only regular choke is used [69]. E-Parisara also acquired an export license and for the first time sent a consignment of e-waste to Umicore Precious Metals Refining in Belgium. Umicore operates as one of the world's largest precious metals recycling facility [30]. E-parisara not only recycles wastes in an efficient manner but also provides employment opportunities to the rural and unorganized population and creates public awareness by setting up e-waste collection boxes in and around educational institutions and public places [71].

6.2.2. *Ash recyclers*

Ash Recyclers is a Bengaluru-based environmentally compliant electronic waste recycling organization, which received KSPCB authorisation at around the same time as E-parisara in 2005. Their e-waste recycling and disposal solution consists of creating a balanced mix of reusing and recycling e-waste in order to arrest, to a very large extent, the damaging life and environmental impact while maximizing value addition from the processing of e-waste, which serves the purpose of converting waste to wealth. It is known to encourage second-hand sale through retrieval of working components and refurbishing of old equipment through manual segregation of reusable components and dismantling of e-wastes to recover useful raw materials, in a reasonably controlled environment [69]. They are now in the process of setting up a new plant for e-waste management (including hydro metallurgical operations) in Mulbagal, about 120 kms from Bengaluru.

6.2.3. K.G. Nandini Enterprises

K.G. Nandini Enterprises (KGN) has started operations in Bengaluru and is India's first fully integrated electronic waste recycling plant [72]. The plant is located in Bidadi and has a capacity of 1ton per hour. KGN has taken the license for a capacity of 7200 MT/annum and does accept all kind of e-waste (PCBs, computers, electric cables, electric transformers, small house hold appliances, etc.). In a first step, hazardous wastes or elements are removed manually at the loading point of the plant comprising the shredder. The reduced material then passes through a magnet where Fe parts are removed. Thereafter, the material enters the delamination mill, which is the heart of the process. Very high impact forces affect the composite materials, leading to reduction and delaminated as well. The material is pneumatically transported from the mill to a cyclone, which, after discharge, is transferred to a screening machine. The classified material is subsequently introduced into a battery of separators, wherein non-ferrous metals are separated from plastics. All process steps are interconnected by an automated, visually-monitored conveying system. A central filter system, which is equipped with explosion and fire safety measures, de-dust the entire process. The equipment reflects the state-of-the-art technology that had been developed and provided by swissRTec AG from Switzerland.

7. Existing e-waste recycling technologies

The recycling methodology broadly comprises of shredding, sorting, grading, compacting, baling, or processing segregated plastics and metal components, followed by separation, identification, and testing as relevant. However, on account of non-availability of suitable recovery technology in the country for some valuable elements such as palladium (Pd), tantalum (Ta), indium (In), gallium (Ga), beryllium (Be), etc., present in traces, the processing of populated PCB components are outsourced overseas at present, despite its significant economic potential and value addition prospect. Evolving suitable scientific technology alone can facilitate the recovery of the valuable elements from the waste PCBs, subject to the availability of large amount of concentrated e-waste containing the said elements.

7.1. CRT recycling

The risk-prone consequence and intense cost implications associated with the disposal of obsolete or malfunctioning CRTs containing highly toxic and hazardous materials such as lead, cadmium, mercury, etc., poses a severe threat to the region. Two major constituents of CRT comprises of glass components (viz., funnel glass, panel glass, solder glass, neck) and non-glass components (viz., plastics, steel, copper, electron gun, phosphor coating), wherein, the CRT glass components consists of SiO_2, NaO, CaO, coloring, oxidizing and X-ray protection components (K_2O, MgO, ZnO, BaO, PbO) and the lead content (Pb) in CRT entails safe handling for its disposal to avert the contaminating impact on air, soil, and ground-water. The glass-to-glass and glass-to-lead recycling, being the two technology route available at present for CRT

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(generated from obsolete computer monitors, television, etc.) recycling, converting the old to new CRT glass, happens to be the preferred option, as of date, wherein, isolating the CRT cover needs to be removed prior to depressurization of the CRTs at the Materials Recycling Facility (MRF). Preceding dispatch to CRT recyclers for glass-to-glass or glass-to-lead recycling, separation of metals and shredding of plastics is a processing essentiality.

It is an economical process as compared to smelting, which prevents hazardous waste landfills as well has been successfully evolved for recycling of CRT by Envirocycle–USA, wherein, absterged and sorted glass is utilized as a feedstock in manufacturing new CRT glass by the glass manufacturers, the eventual capacity constraints in processing, however, poses a major disadvantage. In Germany, the unidentifiable glasses are used as productive recycling avenues such as in mines filling, producing sandpaper for scrubbing, the striking surface on matchboxes, etc. Cent-percent conversion of all recyclable components in commercial exploitation and value addition is adopted by PERDI (a company in the USA), wherein, CRT glass is recycled 100% into CLEAN-BLAST sandblasting aggregate for detoxification of lead paints. Circuit boards are outsourced to vendors overseas for recovering valuable and non-ferrous metals. Copper reclaimed from insulated wires, plastic sorted and processed into 'regrind' for utilizing in conjunction with virgin plastic for conversion to new products. Polystyrene recycled into stuffing for new products, corrugated boxes baled and outsourced for producing insulation stuff and cartons. The sheet metal and other ferrous metals are sent to steel mills for smelting and re-used to enter the new production line.

7.2. Glass-to-glass recycling

Glass-to-glass recycling is considered a closed loop process where the collected glass serves as the feed material for producing new CRTs. After the separation of metals, whole glass is ground into cullet without isolating the panel and funnel glass and the said cullet is used for manufacturing new CRTs; however, the disadvantage associated to unknown lead composition in mixed grinding cullet on account of varied CRT glass compositions depending on the manufacturer and its origin, especially for paneled glass is a potential risk. The deployment of a special sawing method or tool to separate the paneled glass from funnel glass prevents the breakage of the paneled glass, thereby keeping it intact and identifiable in contrast to the conventional method of simultaneous breaking of all glass components leading to a mix, is a sustainable approach in reducing risk of contamination [73].

7.3. Glass-to-lead recycling

In the glass-to-lead recycling process, metallic lead (Pb) and copper (Cu) are separated and recovered from the CRT glass through a smelting process. Variably, CRTs generally contain 0.5–5kg of lead (in the glass) [74], which is a potential deterrent against X-ray emission exposure. The recovered CRT glasses processed in the lead smelter also acts as a fluxing agent in the smelting process. This process is automated with high overall throughput and is also cost effective as compared with the glass-to-glass recycling process, apart from protecting the work force from hazardous lead dust contamination on account of the automated nature and its inherent emission control system, the deteriorating value of quality glass, however, is a disadvantage.

7.4. Metals recovery

The separation of metallic components through magnetic and eddy current separators are in vogue, wherein, ferrous components are separated, aided either by a permanent magnet or electromagnet, while metals such as aluminum and copper from non-metallic materials are separated in eddy current separator. Table 5 shows the materials that can be separated by eddy current separator. The main separation criteria is σ/ϱ [75]. On the basis of information provided by the Union Miniere Company [14], Figure 7 presents a copper-smelting flowsheet for recycling of scrap IC boards that is ideally carried out in a primary copper smelting plant, however, such facilities are not well-established in most parts of the world. Thus, removal of the non-recyclable materials (e.g., epoxy resin and fiber glass) from the IC board to enhance the value of recyclable material is preferable since post-separation provides higher metal concentration in lesser volume, thereafter the enriched metal content can then be sold and transported to an appropriate recycling facility for further processing [14].

Metal	σ	ϱ	σ/ϱ	Metal	σ	ϱ	σ/ϱ
Al	0.35	2.7	13.1	**Cu**	0.59	8.9	6.6
Zn	0.17	7.1	2.4	**Brass**	0.14	8.5	1.7
Ag	0.63	10.5	6.0	**Pb**	0.05	11.3	0.4

ρ: density (10^3 kg/m^3), σ: electrical conductivity of material ($10^{-8}/\Omega$m).

Table 5. σ/ϱ values for some metals.

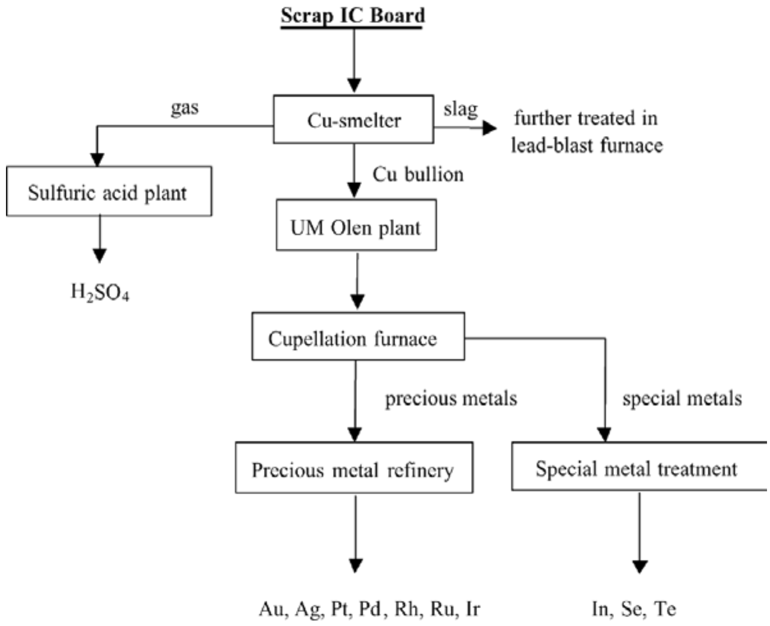

Figure 7. Union Miniere Company's copper-smelting flowsheet for recycling of scrap IC board [14].

Generally, this type of separation plant comprises of a series of physical treatment units devoted to processes such as crushing, grinding, screening, magnetic separation, air classification, eddy-current separation, electrical-conductivity separation, etc., wherein varied metal fragments of various size and content are obtained, depending on the separation technique and units deployed. The varied metal fragments, except iron, usually contain multiple types of metals, thus, identifying appropriate recycling markets for such mixed metal fragments is imperative [14]. There being no necessity of either water or chemical additive in the processing method, there is no wastewater-associated pollution issue, however, special attention should be provided with respect to dust and noise pollution. The low capital and operational cost in a physical separation plant for IC board recycling, being much less compared with a copper-smelting plant, is undoubtedly an added advantage of immense significance. On the basis of information provided by Huei-Chia-Dien Company, Taiwan [14], Figure 8 presents a physical separation flowsheet for the recycling of scrap IC boards.

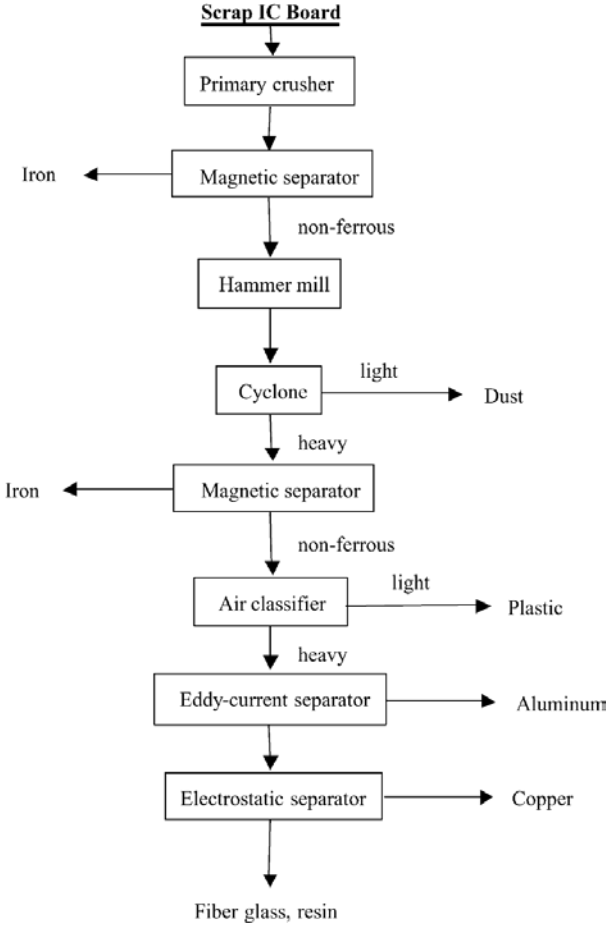

Figure 8. Huei-Chia-Dien Company's physical separation flowsheet for recycling of scrap IC boards [14].

Processing technology has been successfully developed for the recycle and reuse of e-waste at Council of Scientific and Industrial Research–National Metallurgical Laboratory (CSIR-NML), Jamshedpur, India, in which metal bearing e-waste components were shredded and pulverized at the initial operation stage. Subsequently, the metals are separated from the plastics in the particulate mass, adopting a series of physical separation processes. The process does not require much specialized and sophisticated equipment for processing of waste PCBs, since the said equipment and machinery required are readily available, however, its efficiency, especially with respect to commercial viability needs to be further worked upon [76].

The natural hydrophobicity of non-metallic constituents is effectively exploited by a flotation process and a continuous operation at plant level can reasonably be expected to minimize the loss of ultrafine metal values to a negligible level. The operation is simple and the overall processing cost is low, taking into account the comparatively inexpensive physical separation processes deployed. The techniques used are purely physical in nature and thus generate no additional harmful effluents. The process enables the recovery of both metallic and non-metallic constituents separately. Pilot plant scale demonstration was done to recover precious metals from 1 metric ton of e-waste with a recovery rate of 95%. The process flow chart developed for precious metals is depicted in the Figure 9 [39, 77]. Very recently, metal extraction processes from e-waste, particularly the existing industrial practices and routes, have been reviewed [78].

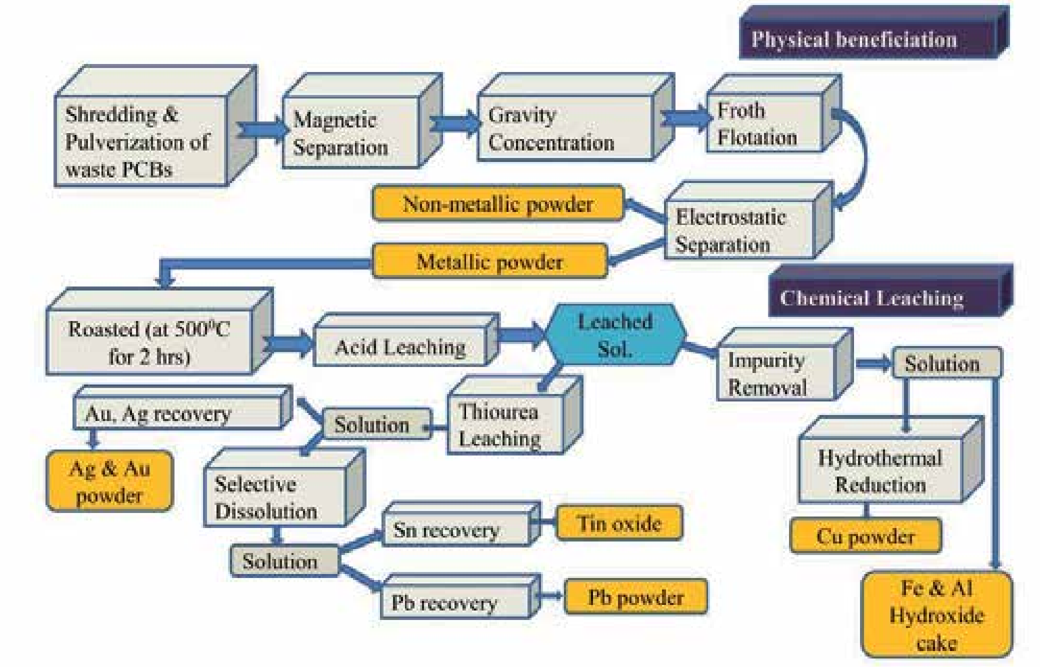

Figure 9. Process flow chart for the technology developed for precious metals at CSIR-NML, Jamshedpur [77].

7.5. Precious metals recovery

In the precious metals refinery setup, gold, silver, palladium and platinum are recovered. The anode slime from the copper electrolysis process is subjected to pressure leaching, followed by drying of the leach residue and the same after addition of fluxes is smelted in a precious metals furnace, leading to the recovery of selenium. The remaining material, primarily silver, is cast into a silver anode, subsequently when subjected to a high-intensity electrolytic refining process, a high-purity silver cathode and anode gold slime are formed while leaching of anode gold slime leads to precipitation of high-purity gold, as well as palladium and platinum sludge. Figure 10 shows the precious metals recovery process. Recovery of precious metals from electronic scraps factually is the key to its commercial exploitation by the recycling industry, for profiteering, in the backdrop of the fact that e-scrap contains more than 40 times the concentration of gold content in gold ores found in the US [79], which is almost one-third the precious metal recovered in e-waste processing. The extraction of the precious metal is carried out by the well-established techniques that are discussed in detail in various articles [80–83]. Various methodologies such as pyrometallurgy, hydrometallurgy, and bi-hydrometallurgy technologies are analyzed for the recovery of gold and also the evaluation of recovery efficiency of gold from e-waste has been reviewed [84].

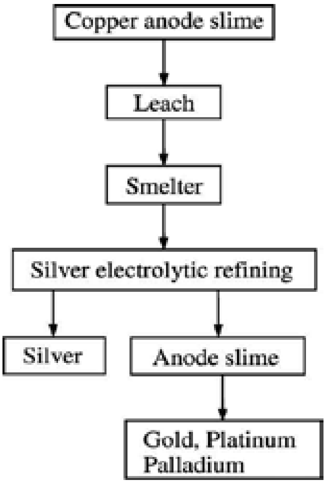

Figure 10. Precious metals recovery process [17].

7.6. Recovery of metals by pyro- and hydrometallurgical processing

Pyrometallurgical processing techniques, including conflagrating, smelting in a plasma arc furnace, drossing, sintering, melting, and varied reactions in a gas phase at high temperatures for recovering non-ferrous metals, as well as precious metals from e-waste, happens to be the conventional method deployed in the past two decades, wherein, the crushed scraps are liquefied in a furnace or in a molten bath to remove plastics and in the process, the refractory oxides form a slag phase together with some metal oxides.

From the process review undertaken by Cui and Zhang [5] with respect to recovering metals from e-waste, the emerging view indicates that both hydro- and pyrometallurgical processes were evaluated in-depth and discussed at length. The process review suggests that hydrometallurgical processes have certain benefits and merit as well when compared with pyrometallurgical processes on account of it being less of a hypothesis or more exact, predictable while also being advantageous from the view point of its ease in control [5]. On the flip side, though hydrometallurgical routes have been adopted successfully to recover PMs from e-waste, from the efficacy perspective, these processes are attributable to certain limiting disadvantages including but not limited to scale-up constraints, which poses to be deterrent to their application at the industrial scale. The review suggests that pyrometallurgical routes are comparatively more economical, eco-efficient, apart from being advantageous from the perspective of maximizing the recovery of PMs [5].

Veldbuizen and Sippel [85] reported the Noranda process at Quebec, Canada as illustrated in Figure 11. The smelter recycles about 100,000 tons of used electronic waste per year, representing 14% of total throughput while the balance percentage comprises mostly of mined copper concentrates. Materials entering the reactor are immersed in a molten metal bath (1250 °C), which is churned by a mixture of supercharged air (up to 39% oxygen), effectively reducing energy consumption in the process since the same is compensated by the energy produced through combustion of plastics and other inflammable materials in feeding. In the process, impurities including iron, lead, and zinc are converted to oxides, forming silica-based slag aided by the agitated oxidation zone, followed by cooling and milling of the slag for further recovery of metals prior to its disposal. The precious metals content of the copper matte is removed before being transferred to the converters, which after upgrade yields liquid blister copper, and this after further refinement in anode furnaces is cast into anodes with purity as high as 99.1%. The precious metals, including gold, silver, platinum, and palladium, along with other recoverable metals, such as selenium, tellurium, and nickel constitute the balance of 0.9%, which is recovered through electro-refining process of the anodes.

Pyrometallurgical processing for the recovery of metals from e-waste is applied by Boliden Ltd. Rönnskar Smelter, Sweden [31]. Purity-linked multiple step feeding of e-scraps, is illustrated in Figure 12. The scraps with high copper content scrap is processed in the Kaldo Furnace and around 100,000 tons of scraps including e-waste was reportedly being processed in the Kaldo Furnace year-on-year, as per an APME report during the year 2000. E-waste blended with lead concentrates is processed in a Kaldo rector with skip-hoist assisted feeding [86] and the required oxygen for combustion in oil-oxygen burner is provided through an oxygen lance in the system, while off-gases are subjected to additional combustion air at around 1200 °C post-combustion. A standard gas handling system recovers thermal energy assisted by a suitably configured steam network. The mixed copper alloy produced by the Kaldo Furnace is processed in a copper converter for recovery of metals (Cu, Ag, Au, Pd, Ni, Se, and Zn), while the dust content (containing Pb, Sb, In, and Cd) is subjected to other processing operations for the recovery of relevant metal content. However, the publications lack detailed discussions on environmental issues, such as emission of pollutants in air and water.

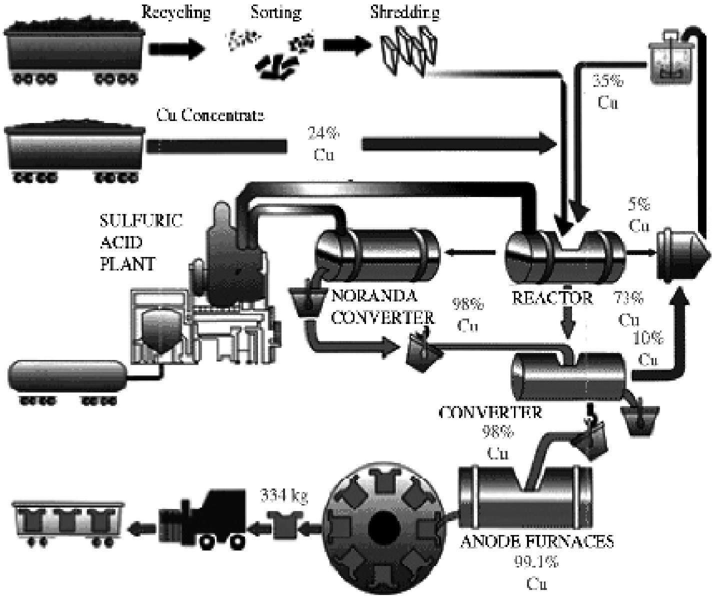

Figure 11. Schematic diagram for the Noranda Smelting Processing [85].

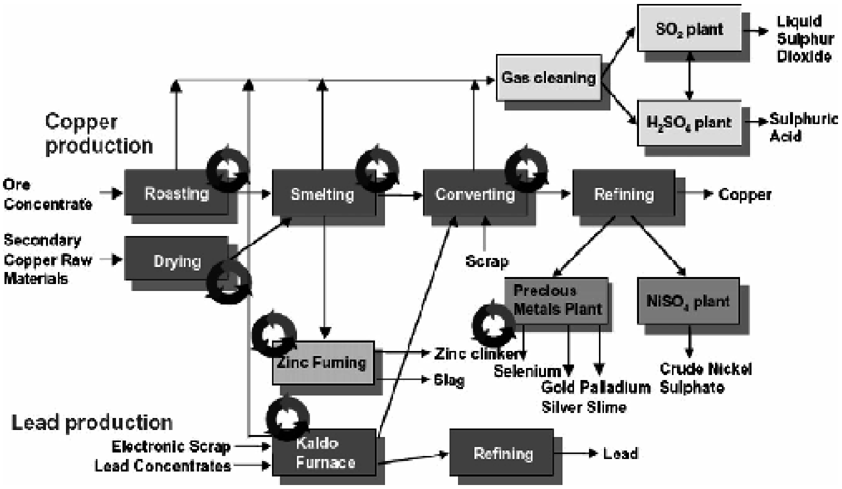

Figure 12. Schematic diagram for the Rönnskar Smelter [31].

Umicore published [30, 87] its precious metals refining process at Hoboken, Belgium, which is primarily focused on the recovery of precious metals from e-waste. Various industrial wastes and by-products from other non-ferrous industries (e.g., drosses, matters, speiss, anode slimes), sweeps of precious metals and bullions, spent industrial catalysts, as well as consumer recyclables such as car exhaust catalysts or PCBs are acceptable for the integrated metals smelter and refinery process. The plant treats around 2,50,000 tons of varied wastes per annual, out of which electronic waste presently comprises up to 10% of the feed [30]. It is the world's largest precious metals recycling facility with a capacity of over 50 tons of PGMs, over 100 tons of gold, and 2400 tons of silver [88]. The first step in the precious metals operations (PMO) is smelting by using an IsaSmelt furnace. Plastics or other organic substances that are contained in the feed partially substitute the coke as a reducing agent and energy source. The smelter separates precious metals in copper bullion from most other metals concentrated in a lead slag, which are further treated at the Base Metals Operations (BMO). The copper bullion is subsequently treated by copper-leaching and electrowinning and precious metals refinery for copper and precious metals recovery.

The Base Metals Operations process by-products from the PMO. The main processing steps are lead blast furnace, lead refinery, and special metals plant. The lead blast furnace reduces the oxidized lead slag from the IsaSmelt together with high lead-containing lead bullion, nickel speiss, copper matte and depleted slag. The impure lead bullion, collecting most of the non-precious metals, is further treated in the lead refinery (Harris process). Special metals (indium, selenium, and tellurium) residues were reported [30] to be generated in the lead refining process. Consequently, pure metals are recovered in a special metals refinery. In the Umicore's plant, following complex flowsheet with several steps including pyrometallurgical techniques, hydrometallurgical process, and electrochemical technology are employed in the recovery of base metals, precious metals, as well as platinum group metals and special metals are shown in Figure 13 [87].

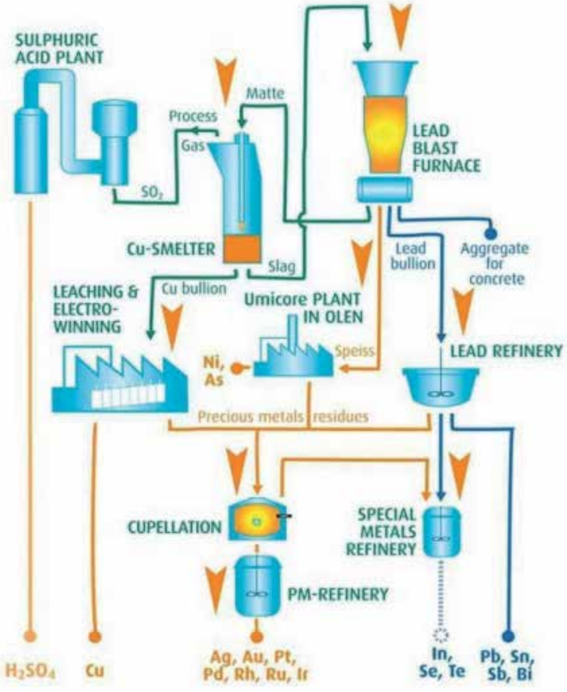

Figure 13. Flowsheet for Umicore's integrated metals smelter and refinery [30].

7.7. Composition and recovery of metal value from scrap mobile phones

The content or substances in cellular phone are variable to some extent, based on the model and its manufacturer, with no fixed formula or list of contents applicable as such, thus, the list of substances in an average mobile phone may also be misleading since varied substances might be used as additives in very minimal quantities or traces by different manufacturers in the production of microelectronic components. However, the general composition of cellular phones and other small electronic goods as well, is identical in nature. Table 6 presents the fractional composition of a modern cell phone [89]. Recovering metals of higher percentage concentration like copper and metals of precious value or worth like gold, palladium and silver is factually the underlying objective for metal recovery from EOL or obsolete cellular phones and aluminum or magnesium cases of cellular phones wherever applicable, contribute further to value addition or generation through its recycling.

Cell phones	Plastics	Pb	Al	Fe	Sn	Cu	Ni	Zn	Ag	Si	Hg
Fraction (wt%)	46.0	0.9	9.0	8.0	1.0	19.0	1.0	3.0	0.9	4.0	1.0

Table 6. Fractional compositions of mobile phones.

The flowchart (Figure 14) shows two methods of recycling scrap mobile phones developed in Korea [38]. The first method (process I) involves shredding of waste PCBs and shipment to a copper smelter. The second method (process II) comprises of shredding, conflagration, melting or converting to copper alloy containing precious metals, and subsequent refining adopting the hydrometallurgical route. However, the systemic operation of recycling for e-waste processing operations in Korea does not in true sense function effectively since the majority of waste mobile phones collected are exported or conflagrated and landfilled, while only 2.5% of the waste mobile phones collected are actually processed for recycling. A pilot plant to recover cobalt from spent lithium-ion batteries of waste mobile phones is under operation, taking into account the high-valuation of cobalt.

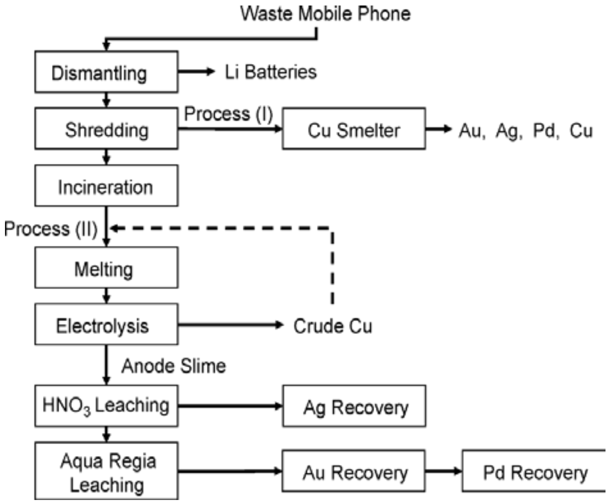

Figure 14. Flow sheet for the recycling of metal values from waste mobile phones in Korea [38].

8. Summary and conclusions

The phenomenal transformation in the lifestyle pattern of consumers of electronic goods, in the emerging scenario, is triggered by their contribution to the convenience and ease in everyday life. This is attributable to the concerted efforts of the global scientific genre, especially focused upon scientific developments in sync with modern era living comforts of the target consumers. Incremental rate of obsolescence and subsequent upgrades of product quality are key psychological impacting factors factually influencing the consumers' mindset in contributing to the faster turnaround of the product life cycle. This aspect is proving to be a potential trigger in accelerating the pace of accumulation of huge EOL-EEEs (e-waste) such as computers, mobile phones, televisions, etc., contributing to the solid waste stream. The said devices contain various non-ferrous and ferrous metals such as lead (Pb), copper (Cu), gold (Au), aluminum (Al), silver (Ag), palladium (pd), which as such gets disposed off as waste, even though it has immense potential of being converted to wealth from waste, including but not limited to serving the purpose of catering to as vital inputs in new product cycle. These valuable and precious metals comprising e-waste, when subjected to processing by the unorganized sector with limited perspective of profit motive, by adopting, more often than not, scientifically unsustainable methodology such as manual sorting, grinding, and incineration, leads to catastrophic environmental implications and health hazard to the workforce as well, especially emanating from its consequent and collective toxic impact of both gas and metal components.

Safe and scientific disposal management with respect to EOL-EEEs continues to remain an uphill task, in both developing and developed countries, and in the process, the former, more often than not, gets cannibalized by the developed countries on account of their illegal and irresponsible approach of shipping the same to developing countries, as an easy escape. Advancement in technology for the sustainable recovery of valuable materials from e-waste needs to be an evolving process to resolve this escalating problem with respect to environment and life. However, usage of the technology comprises many processing techniques of thermal processing, bioleaching, hydrometallurgy, pyrometallurgy, etc., deployment of which is interdependent upon the intended processing and recovery objective, commercial feasibility of the process involved, mandatory and regulatory issues in place, etc. The developing countries as well are gradually tightening the enforcement of regulatory norms in facing the challenges ahead, apart from the developing countries in the European Union, for sustainable, eco-friendly handling, collection, and disposal of e-waste. As is known, the developed countries have technology and infrastructure superiority, the developing countries, on the other hand, have the advantage of economy with respect to labor cost, considerably impacting both handling and processing cost and the prospect of accomplishing a win-win situation based on one's inherent strength or advantages has the potential for being commercially exploited with scientific temperament, complement each other in making this world a safer habitat.

The conventional methods of e-waste management by disposing in landfills or incineration or exporting to developing or underdeveloped countries are becoming redundant since this is already in the process of being banned in absolute terms with consciousness about its hazardous and life-threatening implications dawning upon the stakeholders, with passage of time, which to some extent is also influenced by print and media. This can be furthered by active interaction between the scientific community and the stakeholders, including the industry and public at large, since it is ethically incumbent upon the scientists to play their role in arresting the highly detrimental consequences to nature and life. Stringent and mandatory norms are being put into place, even by the underdeveloped countries, for protecting its citizens and the environment, contrary to the slackness that earlier existed, thereby exposing to exploitation by the developed countries. The presence of precious metals in e-waste recycling makes it an immensely attractive business potential, both in terms of environment and economics. There is need for evolving fool-proof solution, which addresses the limitations of current technologies, provides accessible and comparatively cost-effective techniques, efficient and eco-friendly methodologies in addressing the menacingly escalating threat to environment and life, including but not limited to the carcinogenic impact of the toxins released in crude processing of e-waste. CSIR-NML has developed a processing technology with certain advantages vis-à-vis conventional techniques with respect to metal recovery from EOL-EEEs and the laboratory is looking for interested parties for further investigation, development, and commercialization of this technology-based solution.

Increased public awareness and active participation among stakeholders across the board, including government and regulatory authorities about the damaging implications of crude recycling processes borne out of unscrupulous profit motive and incentivise the tremendous business potential of environmentally safe recycling through sustainable methodology, based on scientific techniques, is essentially imperative. Focused participation and change in mindset among all stakeholders including the industry and inhabitants at large for tangible accomplishment of the “two-pronged” intended goal and objective is unequivocally essential from larger perspective, i.e., safe and sustainable recycling while converting waste to wealth in adding to the country's economy.

Keeping in mind the rapidly escalating scenario and change in lifestyle pattern, future safety with respect to environment and life, evolving sustainable and scientific e-waste management in a focused manner with sufficient infrastructure and financial resources is imperative. On the other hand, evolving effective legislations and monitoring mechanisms for enforcement of the same by countries is equally vital, in accomplishing the herculean task that lies ahead.

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Chapter 7

Increasing the Use of Secondary Plastics in Electrical and Electronic Equipment and Extending Products Lifetime – Instruments and Concepts

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/62778

Abstract

While secondary plastics arising at the manufacturing and processing phases are recycled to the production process in large measure due to its high purity, the market share of secondary plastics remains low and recycling is often dominated by thermal recovery. Energetic recovery of plastics in waste electrical and electronic equipment (WEEE) has been dominating for a long time. At the same time reuse of WEEE is not well developed at EU level; with few exceptions at Member State level.

Against this background we want to discuss in this book chapter several policy instruments that aim to increase the reuse of WEEE as well as the use of secondary plastics in electrical and electronic equipment. Taking the case study of Germany we evaluate instruments theoretical quantity effects and their feasibility. In reality, instruments are often weak and scattered implemented. To identify a policy mix without the risk of creating expensive policies with the potential for inefficient outcomes, we make two complementary conceptual proposes, which first open up perspectives for possible synergies of instruments and second allow an integrated understanding of the regional context in which instruments are implemented. The discussion of the case study of promoting reuse within this framework makes clear, that such an integrated understanding is the basis for any appropriate, targeted and efficient stimulation and bridges the gap between theoretical policy formulation and practically implementation.

Keywords: WEEE, use of secondary plastics, reuse, policy instruments

1. Introduction

Waste electrical and electronic equipment (WEEE) can be considered as one of the most urgent waste management challenges and has raised significant political attention over the last years.

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Electrical and electronic products contain substances, which are valuable as well as often also critical (e.g. mass metals: copper, aluminium etc.; precious metals: gold, silver etc.; critical metals: indium, gallium etc.) and pose risks to the environment and human health (e.g. heavy metals: mercury, cadmium etc.; flame retardants: pentabromophenol etc.) [1, 2]. Furthermore WEEE has become one of the fastest growing waste streams. In Europe, therefore it exist high political interest for converting waste into a resource and a proper management of this waste flow. This chapter puts a specific emphasis on plastics contained in WEEE. While secondary plastics accruing at the stages of production and processing are largely redirected to the production process because of their high fraction purity, secondary plastic waste accruing after product use is recovered on a significantly smaller scale. Instead, energetic recovery of plastic waste is still dominant in the Federal Republic of Germany. This is in clear contradiction with the emerging circular economy policy framework where the value of products, materials and resources is maintained in the economy for as long as possible [3]. The life cycle environmental impacts of post-consumer plastics production from mixed, plastics-rich WEEE treatment residues from the perspective of the customers delivering the residues and the customers buying the obtained post-consumer recycled plastics is clearly superior to the alternatives (i.e. municipal solid waste incineration (MSWI) and virgin plastics production) [4].

Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE Directive) aims to address this issue by implementing inter alia the principle of the extended producer responsibility and collection, recovery as well as joint recycling/preparing for reuse targets. The achievement of the recovery and recycling/preparing for reuse targets shall be calculated, for each category, by dividing the weight of the WEEE that enters the recovery or recycling/preparing for re-use facility by the weight of all separately collected WEEE for each category (Art. 11, Directive 2012/19/EU).

Accordingly, recovery or recycling/preparing for re-use rates do only consider the recovered mass without looking at the type of waste treatment operation (e.g. no favouring of preparing for reuse because of joint recycling/preparing for reuse target), the recovered material (e.g. no difference if mass metals such as copper or critical metals such as indium, (dissipative used) are recovered) and its quality (e.g. impurity vs. material with high quality). Due to these conceptional gaps, the current system misses significant opportunities of a more circular economy that promises "an opportunity to reinvent our economy, making it more sustainable and competitive" [5].

Figures for recycling/preparing for reuse and recovery performance in 2012 – considering large household appliances (LHA), small household appliances (SHA), IT and telecommunications equipment (ICT) and consumer equipment (CE) – reported by each Member State to Eurostat highlight that all except a few fulfil the targets valid in 2012 (recovery and recycling/preparing for reuse targets according to Directive 2002/96/EC: LHA 80 and 75 %, SHA 70 and 50 %, ICT 75 and 65 %, CE 75 and 65 %) [6]. However, currently only one third of WEEE generated by EU-28 plus Norway and Switzerland are officially reported as collected and proper treated [7].

In Germany, 1.73 million tons of EEE were put on the market in 2010 [8] and around 777,000 tons of EEE were collected [9] – thus the required amount of 4 kg per capita was quite easily exceeded with an average amount of 8,8 kg per capita.

Due to the revised WEEE Directive the collection targets will be significantly increased with 45% (2019: 65%) of the amount put on the market. Against this background collection rates in many of the 1.500 responsible municipalities will have to be increased as well as the often difficult coordination with EPR systems has to be improved [10]. Right now collection rates differ significantly due to different collection systems (bring or pick-up systems, collection intervals etc.) but of course also due to different amounts of discarded products: Especially in the metropolitan regions with smaller households more products are discarded per capita. Until now there is no direct obligation for the municipalities to fulfil the higher targets – they have to be met on the aggregated national level and also against this background new policy instruments will become necessary to set additional incentives for high quality – separate and destruction-free – collection.

Besides the problem of low collection rates, the recycling rates of plastics are very low [11,12], although the legal requirements are met. Accordingly many problems are not solved by the implementation of the WEEE Directive [13]. Plastics are a considerable fraction of WEEE and contributes to the total generation of post-consumer plastic waste in the EU-27, Norway and Switzerland in 2008 at 5% [14], but the presence of brominated flame retardants (BFR) as well as various plastic types and missing incentives (e.g. economic benefits of energy recovery) hampers the recycling of plastics in WEEE [9,11].

Today the in Germany collected amount of WEEE contains around 193,000 tons of plastic, but only 18,000 tons of plastics from WEEE were recycled [9,15]. In Germany, no secondary plastics were used to produce new EEE [9]. But also conserving resources through prolonging products lifetime by reuse is not well developed at EU level, with a few exceptions at Member State level [16]. In Germany, some local initiatives to prepare WEEEfor re-use exist, but a wider application is missing. The joint target for both preparation for re-use and recycling, do not prioritize and promote reuse, since EU Member States might only increase their recycling efforts in order to reach prescribed targets.

Against this background we want to discuss in this book chapter several policy instruments that aim to increase the reuse of WEEE as well as the use of secondary plastics in EEE. Taking the case study of Germany we evaluate instruments theoretical quantity effects and their feasibility. In reality, instruments are often weak and scattered implemented. To identify a policy mix without the risk of creating expensive policies with the potential for inefficient outcomes, we make two complementary conceptual proposes, which first open up perspectives for possible synergies of instruments and second allow an integrated understanding of the regional context in which instruments are implemented. The discussion of the case study of promoting reuse within this framework makes clear, that such an integrated understanding is the basis for any appropriate, targeted and efficient stimulation and bridges the gap between theoretical policy formulation and practically implementation [17].

The chapter is structured as follows: After a brief description of the methodological approach, four specific instruments to increase the circularity of plastics in EEE are described and analysed. This is followed by an assessment of strengths and weaknesses of the instruments as well as conceptual considerations withregard to the formulation of a policy mix. Based on this analysis the chapter ends with conclusions for policy formulation and further research.

2. Approach and methodology

Starting point for this book chapter has been an empirical analysis of central barriers for the gaps between possible potentials for the application of secondary plastics and the currently disappointingly disrupted material loops. Despite a rising trend in prices for primary raw materials (see [18]) and the associated incentives for recycling, the area of plastic waste presents recycling rates far below technical potentials. Amongst other things, this can be traced back to a series of systematic market failures, which result from different economic, informatory, legal and institutional characteristics of waste (e.g. the current competition with energy recovery or insecurities about the actual quality of plastic wastes).

Building upon the analysis of potentials for an increased material recovery of plastics from WEEE and the obstacles identified, the following will outlines measures and instruments that consign the different types of plastics to high-quality recovery and promote their application as secondary raw material.

The objective is, however, to develop integrated sets of measures whose individual elements support each other and altogether aim at the development of a self-supporting innovation dynamic. Against this background, economic, legal and informatory/ institutional instruments have been discussed and tested for their legal feasibility. Clearly no single instrument is capable of addressing the complexity of constraints. Thus it is necessary to develop a policy mix that addresses these different aspects. In the following, the individual instruments have been investigated taking into account the following aspects:

- Description of the general mechanism of action,
- examples for successful implementation,
- specification of the instrument,
- estimation of the effects depending on arrangement and finally the
- feasibility of implementation.

3. Description and analysis of instruments

Based on a first preliminary analysis of available instruments, four approaches have been selected that seem to offer the most relevant potentials with regard to the closure of plastic loops. Nevertheless the analysis also shows the challenges and limitations.

3.1. Plastic-specific recycling targets

Description of mechanism / reference to barriers and motives

Although the existing mass-based requirements in the Directive 2012/19/EU guarantee a recycling of the WEEE product categories, they do not allow a selective control of materials contained in this waste stream.

The Green Paper on a European strategy on plastic waste in the environment describes the unspecific targets for plastics recycling in view of the growing environmental impact of plastics as inadequate EU legal consideration of plastics. Against this background, the European Commission decided, "that it will conduct a wide ranging review of the existing waste legislation and the various targets " [19].

Examples for successful implementations

In Germany, so far material-specific recycling targets are only implemented in the German Packaging Ordinance (for wood, plastics, metals, glass, paper and carton). As a study show, the impact of these differentiated requirements is reflected in technical advancements and efficiencies [20]. International experiences with the implementation of specific recycling targets for plastics exist for example in Belgium: In Belgian law, the implementation of the targets prescribed by the WEEE Directive are not only differentiated by product category, but also material-specific requirements are made. So, in total, the following targets have to be fulfilled (by weight relating to the collected material fraction): plastics 50%, iron / steel 95%, non-ferrous metals 95% (Milieubeleidsovereenkomst betreffende de aanvaardingsplicht voor afgedankte elektrische en elektronische apparatuur (AEEA) C-2009/35519 Art. 10).

Specification of instrument

Ideally, the level of the recycling target should be chosen so that on the one hand the maximum ecological effect is achieved to provide incentives for a high level of material recycling, on the other hand the target have to be feasible for the addressees. Therefore it requires a differentiation between different product categories. When determining material-specific targets for a product the content of this material has to be considered; is this too low, it has an aggravating effect on recycling. Second, the distribution of the material is important, since the more a material is distributed over the product - as opposed to a concentrated form in a single component - the more difficult is the recycling.

Large household appliances (LHA) contain, due to their size and with an average plastic content of 19 % by weight [21], relatively large plastic parts and the presence of brominated flame retardants seems to be less relevant compared to other EEE (1.5% share compared to 60% in ICT devices, see [21]). The definition of a material-specific recycling target based on the experiences in Belgium with 50 % by weight relating to the collected plastic fraction, results by considering the average share of plastics in LHA (19 % by weight) in a target proposal of 9.5 % by weight relating to the product weight. In the course of a target proposal it has to be investigated, to what extent LHAs differ from one to another with regard to their recyclability and it should be considered whether a differentiated target or focusing one product group would be more appropriate. For instance, in practice, only 45% of the plastics contained in refrigerators (2.8 kg with a total plastic content of 6.2 kg) are available in a high purity and are suitable for recycling [22]. Accordingly, it has to be considered to what extent the recyclable fraction is increased by setting a recycling target or whether a limitation actually exists.

Estimation of effects depending on specification

For an estimate of the potential recycled plastic amount the proposed recycling target of 50 % by weight relating to the plastic fraction (according to the targets in Belgium) / 9.5 % by weight relating to the average weight per product is used. It is assumed that this is a conservative estimate because the target-setting in Belgium relates to all EEE, which in principle have a worse starting position for a material recycling compared to LHA alone. Based on this, the potential recycled plastic amount in Germany can be calculated to 23,750 tons. By comparison, the actual recycled plastic amount of all EEE in Germany is so far only about 18,000 tons (see chapter 1).

Concluding evaluation

The introduction of plastic-specific targets for the recycling of WEEE would allow a selective control of material flows, while giving investment security for the recycling industry. Plastic-specific recycling targets would therefore clearly lead to an increase of secondary plastics supply. The extent of the use of secondary plastics, however, depends on the quality of recovered materials and ultimately determines the actual environmental impacts [14].

However, by the binding material-specific recycling targets a critical mass could be achieved that makes it economically possible for the producers within the producer responsibility to invest in a recycling-friendly product design. Flanking instruments could be specific requirements in the eco-design directive to limit the use of a variety of different types of plastics.

The feasibility of the instrument is generally considered as high, since the legal framework and the recycling infrastructure is given as well as the integration of the plastic-specific recycling targets would be possible from a legal perspective. The administrative barriers are characterized rather by the actual selection of the focus (different product compositions of WEEE do not allow an universal target for all WEEE), as through the establishment of the level of the recycling target itself (in the case of a suitable focus). The level of the recycling target could be modified continually by a self-learning target-model. Basically, when introducing such an instrument it is worth considering taking account of other materials by specific targets.

3.2. Minimum recyclate quota in the electronics sector

Description of mechanism / reference to barriers and motives

The classic approach towards waste management activities has always been the establishment of mandatory recycling targets – regulating the treatment of waste and avoiding environmentally harmful disposal. Although mass-based product-specific or waste stream-specific targets ensure material recycling of these two categories, they do not allow a targeted control of materials contained in the product. Against this background a mandatory recyclate quota could be introduced especially for plastics. With the specification of minimum recyclate quota for plastic-containing products, the demand would rise significantly for high-quality secondary raw materials and thus provide incentives to capture a greater share of separated plastic wastes (i.e. in the sense of high-quality recycling) which will be recycled and not utilized for thermal recovery.

Examples for successful implementations

Experiences with minimum recyclate quotas have already been made in particular for the case of packaging in the 1980's as it became clear that the recycling sector needs to be supported. After the emergence of different scandals concerning the dispose of waste in California, Oregon and Wisconsin, different regulations on recyclate quotas had been introduced in the U.S., while each of these instruments had a different result [23]. In Oregon the recycling law does only apply if the recyclate quota for plastics drops below 25%. In fact, the recyclate quota has always exceeded this value through mandatory deposit-refund schemes, meaning that the law was never actually applied. In Wisconsin, the inclusion of plastic waste from production was allowed by the law. According to general assessments, this has undermined any effect on the actual management of plastic waste.

The by far most stringent regulation has been applied in California and has received a lot of criticism for its bureaucratic burdens and the associated administrative costs and monitoring problems. The adoption of this law however has led to a significant stabilization, especially in the market for HDPE product waste [24]. The Rigid Plastic Packaging Container Law (RPPC) was fundamentally revised in 2012, manufacturers or marketers of plastic packaging must confirm complying with a minimum recyclate quota that is being controlled by a sample system [25]. The scope has been expanded significantly over beverage packaging. Simultaneously, manufacturers may comply with the law via design changes (-10% material input or minimum use of 5 times), a 45% recycling rate, or through a 25% share of secondary resources. Similar regulations are, for example, currently planned in Europe under Guidance of the European Packaging Directive [26].

Specification of instrument

The specification of the instrument is challenging because specific content quotas for plastics in specific products would have to be defined: On the one hand, the quota must be set sufficiently high to trigger actual effects on product design and the management of plastic waste. On the other hand, it must be technically achievable without impeding the final quality of the products. Against this background, the Japanese Top-Runner approach could be used: In this case the best available quota on the market today would be used as minimum threshold value for a certain time period like three or five years (see relevant considerations to a resource based Top-Runner approach in the research project "Material Efficiency and Resource Conservation (MaRess)" [27]). Thus, the technical feasibility of the quota would already be proven. At the same time, the possibility of strategic monopolization approaches needs to be taken into account since products with recycled material of up to 100% exist in the market (as opposed to energy efficiency without an upper limit). Considering similar examples e.g. in the construction sector, a minimum recyclate quota of 30% seems appropriate for all plastic-based components. This quota has also been mentioned in a BioIS study and termed as a realistic target for PVC [28].

Within the "MaRess" project the instrument of minimum recyclate quotas has been examined for ICT products and in particular contained critical metals. It has been proven that the Ecodesign Directive could provide the legal foundation for such an instrument.

Estimation of effects depending on specification

The introduction of minimum recyclate quotas would allow direct control of the use of secondary raw materials and thus mechanical recycling. Instead of defining technological standards, this approach would be based on market consideration how these standards can be met at the lowest cost level. Electronic products offer good conditions for the introduction of a recyclate quota because many of the employed components are used in the „non-visible range" meaning that the frequently cited problems of colour fidelity of secondary plastics only play a minor role (i.e. [29].

Concluding evaluation

Despite the potential benefits, the actual implementation faces severe challenges: The proof on the utilization of secondary plastics for certain products without the cooperation of all relevant actors will hardly be realized. This will require a comprehensive monitoring of complex international material flows and the certification of recycling processes. It is also obvious that the proposed changes in production processes require not only a national but also an EU-wide approach.

From an ecologic standpoint, it should also be taken into account that plastics might be replaced by raw materials with probably higher resource consumptions along their entire life cycle just to avoid complying with the quota. As long as such an integrated view over the "resource footprint" is missing, manufacturers could start using secondary raw materials of inferior quality that would affect the life cycle of products causing even a higher consumption of primary resources.

3.3. Mandatory deposit for small electric and electronic devices

Description of mechanism / reference to barriers and motives

The instrument of a mandatory deposit aims to lead back products after use into a controlled system for reuse or recycling. A deposit is charged when selling the product (in addition to the purchase price), which will be paid back upon return of the product again. This results in an economic incentive for the purchaser to return products.

Deposit schemes on selected plastic-containing products can firstly lead to an increase of the collection rate and, secondly, to a more homogenous collection in comparison to a collection of a variety of plastics-containing products with many different types of plastic. Consequently, the supply of economically recyclable fractions can be depending on the amount of the deposit significantly increased and thus incentives for the recycling of plastics are set.

According to the German Advisory Council on the Environment deposit shemes are in particular for mobile phones and computers, owing to their wide use (100 households own 57.8 laptops and 160.9 mobile phones), an effective tool for a high-quality collection of the products [30]. Also in the public consultation on the Green Paper on a European strategy on plastic waste in the environment the majority of interviewees considered a deposit shemes as meaningful. However, the estimates also show that general statements about the effectiveness of a mandatory deposit are not possible and must be investigated specifically: "Any proposals in this area should be mindful of the differing situation across the member states and also they must be considered by specific product sector / application" [31].

Examples for successful implementations

In Germany, a mandatory deposit scheme exists for beverage packaging and automotive batteries. Also in the USA – in 11 states - a deposit scheme for batteries is established [32]. Up to the introduction of the WEEE Directive in 2005 (general obligation to take back products) in Austria and Italy a deposit was charged on several EEE. In Austria, for instance, 10 schillings were collected on lamps and 1,000 schillings on refrigerators. After abolition of the deposit scheme in Austria only one-fifth of the outstanding amounts of deposits was picked up (even without the return of the products possible). At the end of the year 2008 (abolition 2005) still 39 million euros were managed by the foundation [33]. Obviously, the deposit was too low and has been lost from the consciousness of consumers due to the long-term capital commitment.

Specification of instrument

Against the background of the experience in Austria it is reasonable to focus those EEE that have a relatively short useful life (presence of the deposit in the minds of consumers). For instance, mobile phones, which have an enormously low collection rate, contain a number of valuable raw materials and have a relatively short useful life with an average of 2 years [34].

Basically, the deposit amount has to be addressed to the consumer. Fehling 2010 (cited in [35]) is proposing to undertake retailers to collect the deposit. The return should be possible at all retailers, regardless at which retailer the products were purchased (possibly with deposit tokens). By means of a clearinghouse raised deposits could be managed.

[36] have identified three key criteria that must be considered when determining the level of deposit: social criteria (effort for the consumer e.g. temporally, spacial), ecologic criteria (raw material consumption, types and amount of hazardous substances) and economic criteria (expected price development of raw materials, raw materials values, static lifetime of raw materials, possibilities of deposit-fraud). For instance, the green political party in Germany "Alliance '90/The Greens" propose a deposit of 10 euros [37], the German Advisory Council on the Environment propose up to 100 euros deposit for mobile phones [30]. Obviously, so far, it is not sufficient investigated, which level of deposit is appropriate.

Estimation of effects depending on specification

An investigation by Germany's digital association (BITKOM) has revealed that 86 million unused mobile phones are stored in German households [38]. Assuming that with a deposit amount of 10 to 100 euros 50 to 90% of these mobile phones are collected, 43 to 77 million mobile phones could be additionally collected and made available for reuse and recycling (at this level once; afterwards such storage at best no longer take place and a continuous return establish). However, it is still unclear which deposit amount on mobile phones induces its corresponding steering effect, while the related efforts (administratively e.g. clearinghouse, at an individual level e.g. capital commitment) are in proportion to the benefits.

The actual effects of a mandatory deposit for mobile phones on their recycling practices are also not clearly foreseeable. Due to the complex material composition of EEE and its short innovation cycles, even a product-specific collection allows only to draw conclusions on a higher recycling rate in total, but not a recycling of specific materials such as plastics. However, in principle, it is assumable that the starting position for a comprehensive recycling will improve, the higher the collection quantities are.

Overall, in terms of the economic and environmental effects of a mandatory deposit on mobile phones, it remains an enormous need for research.

Concluding evaluation

The concrete implementation of the instrument can be assessed – particularly with regard to the bureaucratic and infrastructural efforts – as problematic. For mobile phones an administrative structure has to be built up. Moreover, it is still completely unclear, which level of deposit and involved capital commitment is reasonable and what economic and ecological effects are actually to be expected from a mandatory deposit on small EEE.

3.4. Obligatory ecodesign standards for reuse and repair-ability

Description of mechanism / reference to barriers and motives

The instrument of mandatory eco-design standards for reuse and repair of selected products encourage producers to take the future repair and reuse of a product into account when designing the product by considering issues like whether it can be easily dismantled and reassembled, and whether it is set up in such a way that faults can be easily identified. Producers put than only such products on the market that do not prevent the reuse of whole products or its components and their repair.

Examples for successful implementations

So far almost no experience with standards on reuse and repair exist, but the instrument has been very successfully used in the energy efficiency sector. In the course of the Ecodesign Directive (2009/125/EC) mandatory ecodesign standards for energy-related products are introduced to reduce the energy consumption and other negative environmental impacts of products. Although the Ecodesign Directive cover a wide range of environmental aspects such as energy, water and other resource consumption, most of the "Implementing Measures" (which are set for every product group separately and have to be fulfilled by the industries) focused so far primarily on parameters to energy efficiency during the use phase [39]. In this respect, an analysis and assessment of impacts of the implementation of the Ecodesign Directive on GHG emissions in the EU until the year 2020 shows „that the GHG emissions can be reduced by 211 to 265 Mio. t CO2eq. compared to business as usual (BAU) development" [40], if all implementing measures are in place (Status: June 2010). One of the most famous implementing measures within the Ecodesign Directive is the regulation on household lamps, leading to the phase out of incandescent light between 2009 and 2012 [41]. According to [42] the Directive has the potential to be also a powerful policy instrument for resource efficiency and the circular economy such as it is for improving energy efficiency.

Specification of instrument

The implementation of mandatory ecodesign standards for reuse and repair through the existing European Ecodesign Directive is proposed by several studies [39,43,44]. Especially the feasibility – since the Directive is already in place - is one reason for using the Directive for promoting reuse and repair on an European level [45]. But [46] argue for instance that the agreement procedure of the implementing measures takes too long in order not to be technically outdated. In average the procedure takes 55 month; but the innovation cycle of EEE is often shorter. In addition the data quality is poor, since manufactures are not obliged to provide specific technical or economic information of their products. Also market surveillance is inefficient, because of too few employees, insufficient budget, inadequate surveillance infrastructure and sanctions. Insufficient cooperation of Member States as well as within industry and the absence of standardised measure methods are further reasons for the inefficient market surveillance. These issues have to be considered in specifying the instrument.

Furthermore, appropriate parameters are required that could be used to practical measure the reuse-ability and repair-ability. According to [47] determining technical criteria for the assessment of the reuse-ability of EEE are the kind and variety of parts and materials used, suitability for disassembly, cleaning and testing. In [43] within a JRC project have proposed a threshold for the time for disassembly of products components under a standardized procedure. Further parameters can be for instance a limited number of bolds, the avoidance of glue or welding of parts and the availability of spare parts.

Estimation of effects depending on specification

As result the durability of products will be extended through repair and reuse and therewith the life cycle of products can be managed in an environmentally friendly and cost-effective way. Since it is estimated that more than 80 % of all product-related environmental impacts are determined in the design phase [48], relevant resource saving potentials can be covered with the implementation of this instrument. However, so far, almost no experience with standards on reuse and repair and knowledge about its effects exist.

Concluding evaluation

Implementing mandatory eco-design standards for reuse and repair of EEE through the existing European Ecodesign Directive can be a promising approach, but possibly, as described above, not the most effective, if no flanking measures are implemented.

Moreover, the throw-away culture in which a quick turnover of (often cheap) goods and low acceptance of reused products (e.g. social stigma arising, trust regarding quality and safety) have become deeply routed become a barrier on the consumer side. Thus may lead to low demand for even eco-designed products. For instance, according to a 2011 Eurobarometer survey the most common reasons for not buying second-hand products were related to concerns about product quality and usability (58 % of mentions) [49]. However, some best practice examples (e.g. Kringloop in Flandern, Revital in Austria) verify the fact that repair and reuse can be practiced successfully with a strong support of reuse activities [50]. In this respect the linking of mandatory product ecodesign standards with a strong support of reuse activities will contribute towards a greater cost-effectiveness of repair, but also awareness and demand for repair and reuse and therewith promote reuse, leading to circularity according to the waste hierarchy.

4. Building a policy mix: from theory to practice

4.1. Preliminary assessment of impacts and feasibility

Looking at the different instruments it becomes clear that there is no lack of ideas, the key challenge is obviously the implementation phase. The following table provides a general overview over the investigated instruments and the evaluations of quantity effects (+++ high quantity effects) and their feasibility (+++ generally high feasibility) carried out in the process. There is a clear trade-off between these two analytical dimensions: Instruments with potentially high quantitative effects often seem rather unrealistic to implement. Feasible instruments on the other hand let expect so low effects that the transaction costs of policy developments maybe equal or higher, preventing e.g. the change of regulatory frameworks.

	Case Study: Germany	
Instrument	Quantity effect	Feasibility
1. Plastictype-specific target for large household appliances	++	++
2. Minimum recyclate quota in the electronics sector	++	+
3. Mandatory deposit for small electric and electronic devices	+(only plastics), +++(additional consideration of all materials)	+
5. Obligatory ecodesign standards for reuse and repair-ability	+	+++

Table 1. Assessment of the selected instruments, Source: Own illustration

4.2. Bundling the instruments into core strategies

The analysis of the various instruments clearly shows that the complex technical, economic, regulatory and informational barriers can not be overcome by a single instrument if an increased use of secondary plastics in closed material loops is intended. In fact, a long-term process adjusting various central levers is required to achieve this goal. Against this background specific instruments could be integrated into three core strategies aiming at a continuous improvement. The integration of the individual instruments that all aim to close plastic loops linked to electronic products to these three core strategies highlight the need for coordinated action and thus provides a glimpse into possible synergies.

Core strategy 1: "Push"

The first core strategy aims at increasing the collection rate of separated plastic waste according to type, which then becomes available for the mechanical recycling. An increase of these quantities may be regarded as a necessary condition for an increased use of secondary raw materials but as previously shown, this alone will not result in a higher use of secondary raw materials under the given conditions. Nevertheless, this push-strategy may lead to economies of scale, that increase incentives for the use of secondary plastic at lower unit costs. Deposit schemes have proven to be an extremely effective instrument for this strategy.

Core strategy 2: "Pull"

The second core strategy is focused on increasing the demand for secondary plastics. The theoretically available potential for secondary plastics exceeds the demand by far. Obviously, economic incentives of switching to secondary plastics are not yet significant enough for most plastic types and uses. The instrumental approach of a mandatory recyclate quota here presented is therefore intended to either lower prices of secondary plastics or strengthen the public sector as its major consumer.

Core strategy 3: "Market development"

In addition to the more traditional approaches of increasing supply and demand of mechanical recycling ("push" and "pull"), the need of a third strategy, which relies on a continuous market development, becomes clear. With regard to the recycling of plastic waste, the need and effectiveness of such measures was for instance, identified by the OECD: "Encouraging ever-higher recycling rates in an imperfect market may impose very high social welfare costs. In such cases it may be far less costly to address the imperfection within the market than to try and bring about increased recycling rates through increasingly ambitious recycling programmes.“ [51].

Figure 1. Core strategies towards increasing the use of secondary raw materials, Source: Own illustration

The following above illustrates the necessary interplay of the three core strategies and their different approaches. A successful policy mix must include specific instruments aiming at both the demand and supply side. Additionally, the framework conditions must be strengthened enabling the efficient exchange between the two market sides.

4.3. An analytical framework for an integrated understanding of material flows, the underlying socio-technical system and environmental effects

In order to avoid the implementation of single instruments with inefficient outcomes, it is necessary to base instruments on an integrated understanding of material flows, the underlying socio-technical system and environmental effects. For this purpose in the following an analytical framework for the integrated understanding of this institutional-ecological nexus taking the example of reusing WEEE is developed. It is possible to apply this framework to any other waste treatment operation or waste fraction.

The framework is based on the socio-ecological research perspective and considers the material and structural dimension of reuse: Environmental benefits of reuse depend not only on the product (and its production), but also to a large degree on consumption patterns (e.g. displacement of new product, additional consumption), the use phase (e.g. usage time) as well as collection (e.g. destructive) and repair practice (e.g. availability of adequate tools, knowledge). Regulatory frameworks, incentives structures and policy approaches influence these production, consumption and end-of-life activities. In consequence, resource consumption depends on technical, but also social aspects like the institutional context, in which the waste is generated and managed. This makes clear that it is not sufficient to look for "one size fits all" approaches when aiming to promote re-use with an appropriate mix of policy instruments.

According to [52] socio-technical regimes can be described as "the whole complex of scientific knowledge, engineering practices, production process, technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology". Drawing on [53], these socio-technical regimes exist of stabilised trajectories and share regulative rules (e.g. laws), normative rules (e.g. behavioural norms) and cognitive rules (e.g. problem definitions) that coordinate action. These rules "enter in decisions and actions, because actors are embedded in regulatory structures and social networks" [53].

Following this a systematic identification of relevant influencing factors and their interdependencies is required to achieve a comprehensive understanding of the institutional-ecological nexus of reuse. For this purpose the framework was developed considering the product/material flow alongside the supply chain from the first to the second user (including the collection of products, the checking, cleaning, repairing and testing of products, and the sale of the products). Three types of influencing factors were defined: product-technical factors (material dimension), product-flow-related factors (material dimension) and context factors (structural dimension). The interplay of these factors result in incentive structures, which coordinate action and bring product/material flows along specific pathways. A context-specific resource consumption results.

http://dx.doi.org/10.5772/62778

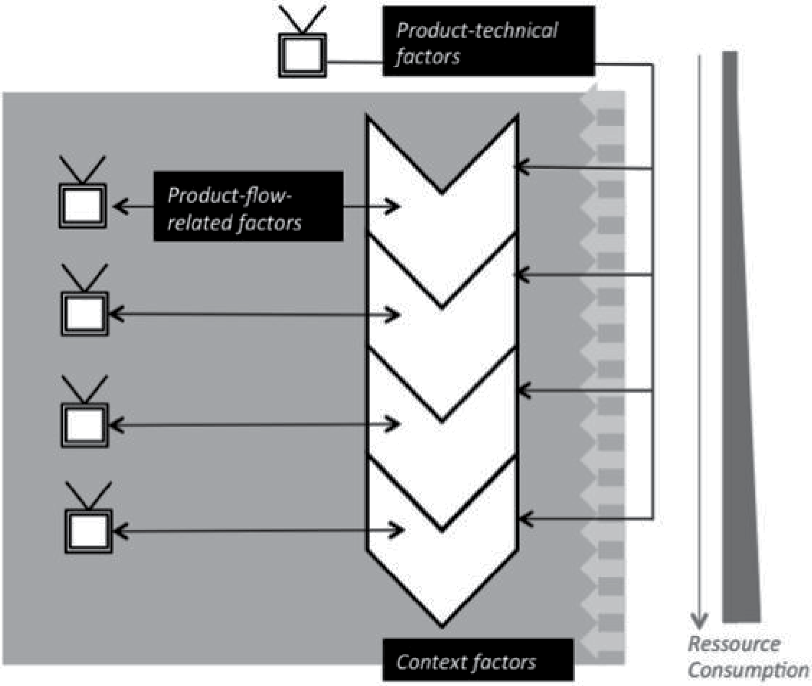

Figure 2. Analytical framework for an integrated understanding of material flows, the underlying socio-technical system and environmental effects – example of reusing WEEE, Source: Own illustration

For a comprehensive understanding the concept differs between the following types of factors:

- **Product-technical factors (material dimension)** concern a specific character of a product such as the product size. These factors are considered to be rather technical and are detached from e.g. waste infrastructure or user behaviour and are comparable for one product no matter in which region the product is used or waste generated.

- **Product-flow-related factors(material dimension)** relate to aspects, which result from the practice of users, collectors, repairmen etc. (e.g. condition of product) and can be studied by tracing the handling of a given product throughout the whole chain. These factors are dependent from the specific waste management context.

- **Context factors (structural dimension)** such as infrastructure, political or economic aspects, cover all context-specific factors, from which – together with the influence factors of the material dimension – incentive structures results, which coordinate action.

The influencing factors interact and thus multiply or mutually reinforce one another. A promising approach to analyse the structures would be therefore the acquisition of actors along the supply chain and expert knowledge – a suitable starting point to gain transparency on complex regime characters.

5. Conclusions

Based on the considerations towards the development of a policy mix to increase the use of secondary raw materials, it can be noted that on the one hand a number of potential approaches can be identified and on the other hand none of the instruments identified is able to address the multiple barriers to the desired extent single-handedly. In this respect, the need for a coordinated, long-term approach becomes apparent.

The described push, pull and market development strategies can be viewed as the basic structure to develop the identified technical potential for systematically boosting the closure of plastic material loops. At the same time, the increased use of secondary raw materials requires a functioning market process for which the right framework conditions must be set without enforcement. Secondary plastics still lack economic competitiveness in many areas for various reasons, therefore processes may be initiated which will only be reflected in the form of higher market share in the medium term.

The developed framework to base instruments on an integrated understanding of material flows, the underlying socio-technical system and environmental effects highlights the institutional-ecological nexus – the waste regime, in which the waste is generated, forms the way in which the waste is managed by the actors and therewith the environmental effects. The technological waste management perspective is shifted to a version, in which social aspects are no exogenous factors, but elementary parts of the system [54]. Analytical approaches to increase the transparency in these systems can be seen as a crucial element for transformation towards a circular economy that avoid the implementation of single instruments with inefficient outcomes.

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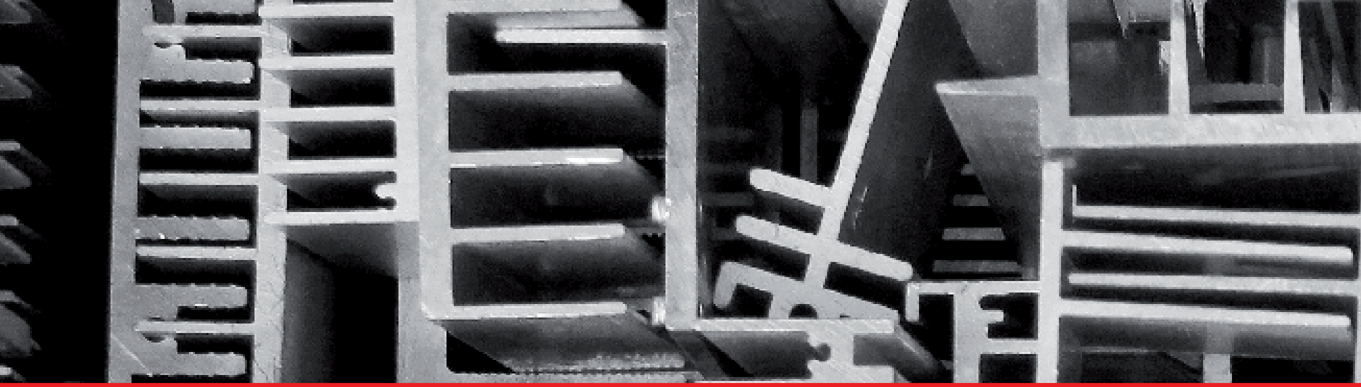

Edited by Florin-Constantin Mihai

E-waste management is a serious challenge across developed, transition, and developing countries because of the consumer society and the globalization process. E-waste is a fast-growing waste stream which needs more attention of international organizations, governments, and local authorities in order to improve the current waste management practices. The book reveals the pollution side of this waste stream with critical implications on the environment and public health, and also it points out the resource side which must be further developed under the circular economy framework with respect to safety regulations. In this context, complicated patterns at the global scale emerge under legal and illegal e-waste trades. The linkages between developed and developing countries and key issues of e-waste management sector are further examined in the book.

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ISBN 978-953-51-6660-3