Chapter 5
Previous, Contemporary, and Prospects of E-Waste and Its Management

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ABSTRACT

The contemporary world is driven by electronic gadgets without which the survival of mankind is perceived to be incomplete. The uncontrolled dependence of mankind on electronic gadgets has resulted in enhanced production of these gadgets leading to the accumulation of e-waste. Both technological innovation and market expansion have played an important role in electronic waste (e-waste). Owing to hazardous material composition, electronic waste causes environmental problems during the waste management phase if not properly pre-treated. Growing attention is being given to the impacts of these

DOI: 10.4018/978-1-7998-4921-6.ch005

hazardous components from e-waste on the environment. Many countries have drafted legislation to improve the reuse, recycling, and other forms of recovery of such wastes so as to reduce disposal problems. The purpose of this chapter is to present an overview of electronic waste, the current status of management of electronic waste, and recycling technologies for the recovery of metals from end-of-life electronic equipment.

INTRODUCTION

The electronic industry has been raised as one of the world's leading and inventive sector as one of its kind. This is attributed to the profound privilege of the contemporary generation, which enjoys their entire social and economic life surrounded by electronics. This has led to an exceptional expansion of electronics, making them cheaper and more available. Unfortunately, the waste management system has not improved at a similar pace (Masud et al., 2019). All these reasons and others have contributed to the unprecedented accumulation of electronic waste. Other reasons for e-waste present the anthropocentric view of humans since most of the reasons do not have a requirement to dispose of e-waste, and some are merely for personal satisfaction. These include very less lifespan of electronic items since the consumer would like to upgrade technologically (even when the old or previous item is in good condition) and technological advancements that are being released into the market every day. For instance, in 2008, the users of computers are increased and surpassed 1 billion, and these goods are obsoleted in the next five years. For these and many other petty known reasons, e-waste ends up in dump yards resulting in environmental pollution. Components of e-waste yet times enter the food chain and affect humans also.

Pollution from e-waste is a global problem. According to the UN, global e-waste is projected to exceed 40 million tons per year. Recycling end of product life results in enhanced pollution, economically unviable, and is unregulated in most countries. Severe health concerns are caused by e-waste in millions of people, precisely in developing countries like Europe, Africa, and Asia. It is reported that more than 200 million people around the world are at threat from exposure to toxic waste. Recycling of valuable elements in e-waste like copper and gold has been a source of income typically in the informal sector from emerging industrialized countries. However, some of the recycling techniques employed like cable burning for retention of inherent copper leads to hazardous substances exposure to both adult and child workers and their families (Lakshmi and Raj, 2017; Li et al., 2020).

The objective of this chapter is to present an overview of electronic waste, the current status of electronic waste management, and recycling technologies for the recovery of metals from end-of-life electronic equipment.

Definition of E-Waste

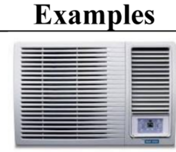
Some known definitions of E-waste are as follows:

- According to the Sinha-Khetriwal, 2002, the power-driven electronic appliances that have reached its End of life (EOL) is called E-Waste.
- Puckett et al., 2002, described that Electronic devices were ranging from individual household items to personal computers that have been discarded after EOL.
- The APME, 1995, defined as it is a combination of Ferrous, Non-ferrous, Ceramic, and Plastic Materials.

The term E-Waste and WEE (Waste Electronic Equipment's) is repeatedly used in the present scenario as the usage of electronic devices in our day to day life are increasing. Discarded electronic appliances belong to E-waste Category, whereas WEE additionally refers to EOL appliances. The European Commission Defined WEE as Wide-Ranging EOL is the raw material that can be utilized to produce, measure, and transfer electromagnetic current (EU RoHS Directive 2002/95/EC, 2003).

Classes of E-Waste Based on their Application and Size

Since much difference is not made between E-waste and WEEE, Indian legislation has considered e-waste for E-waste management (E-Waste Rules, 2011; Rodrigues et al., 2020). In this chapter, we use the term "E-waste" to refer to all the discarded/broken/surplus/obsolete electrical and electronic devices, as stated by Pathak et al., 2017. More specifically, E-waste can be divided into six categories Balde et al., 2015, as shown in **Table 1.**

Illustrations	Examples	Illustrations	Examples
Equipment's that Exchange heat and temperature comprises heat pumps, Air Conditioners, Refrigerators.		Large size equipment, Comprises Xerox machines, Washing Machines, Electronic Stoves.	
Computers, televisions, laptops, notebooks, and tablets		Electric lamps comprise Fluorescent lamps & LED Bulbs	
Small size equipment Comprises household items such as toasters, microwaves, electric kettles, vacuum cleaner, calculators, electrical toys, video cameras, and small medical devices		Small ICT equipment Comprises landline telephones, mobile phones, and routers, printers, GPS (global positioning systems)	

CHARACTERISTICS OF ELECTRONIC WASTE

Hazardous Components in e-Waste

E-waste consists of components like ferrous, non-ferrous, ceramic, and plastic in large quantities with different size and shapes; some of these materials contain hazardous components which need separate and precise treatment for their removal shown in Table 2 (Cooper, 2000).

Composition of E-Waste

Table 2. Hazardous components in WEE

Materials	Elucidation
Batteries	Batteries consist of heavy metals like Pb (Lead), Hg (Mercury), and Cd (Cadmium).
CRTs (Cathode ray tubes)	Lead is present in the cone glass and Fluorescent coatings inside the glass panel
Switches and its components containing mercury	Thermostats, sensors, and relay Switches generally consist of mercury. In addition, it is also used in mobile phones, data transmission devices, and medical equipment.
Asbestos left-over	Separate treatment is required for treating these left-overs
Cartridge tonners and colors	Toners and Colours consist of Toxic Chemical and Hazardous Substances, and these are abstemiously toxic if acute exposure occurs.
Printed Circuit Boards	In these boards, cadmium and lead are common and present in solder; SMD chip resistors, Semiconductors, and Infrared detectors contain cadmium.
Capacitors containing PCBs (Polychlorinated biphenyl)	Capacitors containing PCBs have to be removed for Safe Obliteration.
LCDs (Liquid Crystal Displays)	LCDs with older versions and Designs consist of Lead and Mercury in larger quantities, But the Surface area greater than 100 Cm^2 is removed from WEE.
Plastics with halogenated flame retardants.	Toxic substances will be released during the combustion and incineration of these types of plastics.
Equipment containing CFC HCFC or HFCs.	The CFC, HFC, or CFCs present in the foam and the refrigerating circuit must be properly extracted and destroyed or recycled.
Gas discharge lamps	Mercury has to be removed before discarding.

With reference to material composition, electronic waste can be defined as a mixture of various metals, particularly copper, aluminum, and steel, which are either attached to or covered with or mixed with various types of plastics and ceramics (Hoffmann, 1992). Precious metals have wide application in the manufacture of electronic appliances (Table 3), serving as contact materials due to their high chemical stability and their good conducting properties. Platinum group metals are used, among other things, in switching contacts (relays, switches) or as sensors to ascertain the electrical measure and as a function of the temperature (Teller, 2006).

Table 3. Composition of metals of different electronic scrap

E- Waste (Scrap)	Mass (%)					Mass (mg kg^{-1})			Reference
	Fe	Cu	Al	Pb	Ni	Ag	Au	Pd	Hageluken,2006
TV boards	28	10	10	1.0	0.3	280	20	10	Hageluken,2006
PC boards	7	20	5	1.5	1	1000	250	110	Hageluken,2006
Mobile phone	5	13	1	0.3	0.1	1380	350	210	Hageluken,2006
Portable audio	23	21	1	0.14	0.03	150	10	4	Hageluken,2006
DVD player	62	5	2	0.3	0.05	115	15	4	Hageluken,2006
Calculator	4	3	5	0.1	0.5	260	50	5	Hageluken,2006
PC mainboard	4.5	14.3	2.8	2.2	1.1	639	566	124	Legarth et al., 1995
Printed circuit boards	12	10	7	1.2	0.85	280	110	-	Zang and Forssberg, 1997
TV scrap (CRTs removed)	-	3.4	1.2	0.2	0.038	20	<10	<10	Cui & Forssberg, 2007
Electronic	8.3	8.5	0.71	3.15	2.0	29	12	-	Ilyas et al., 2007
PC	20	7	14	6	0.85	189	16	3	Patil and Sharma, 2017
Typical electronic	8	20	2	2	2	2000	1000	50	Sum, 1991
E-scrap sample 1	37.4	18.2	19	1.6	-	6	12	-	Busselle et al., 1991
E-scrap sample 2	27.3	16.4	11.0	1.4	-	210	150	20	Busselle et al., 1991
Printed circuit boards	5.3	26.8	1.9	-	0.47	3300	80	-	Theo, 1998
E-scrap (1972 sample)	26.2	18.6	-	-	-	1800	220	30	Bhuie et al., 2004
Nokia Cellular phones	8	19	9	0.9	1	9000	-	-	Bhuie et al., 2004

Note that "-" denotes not reported.

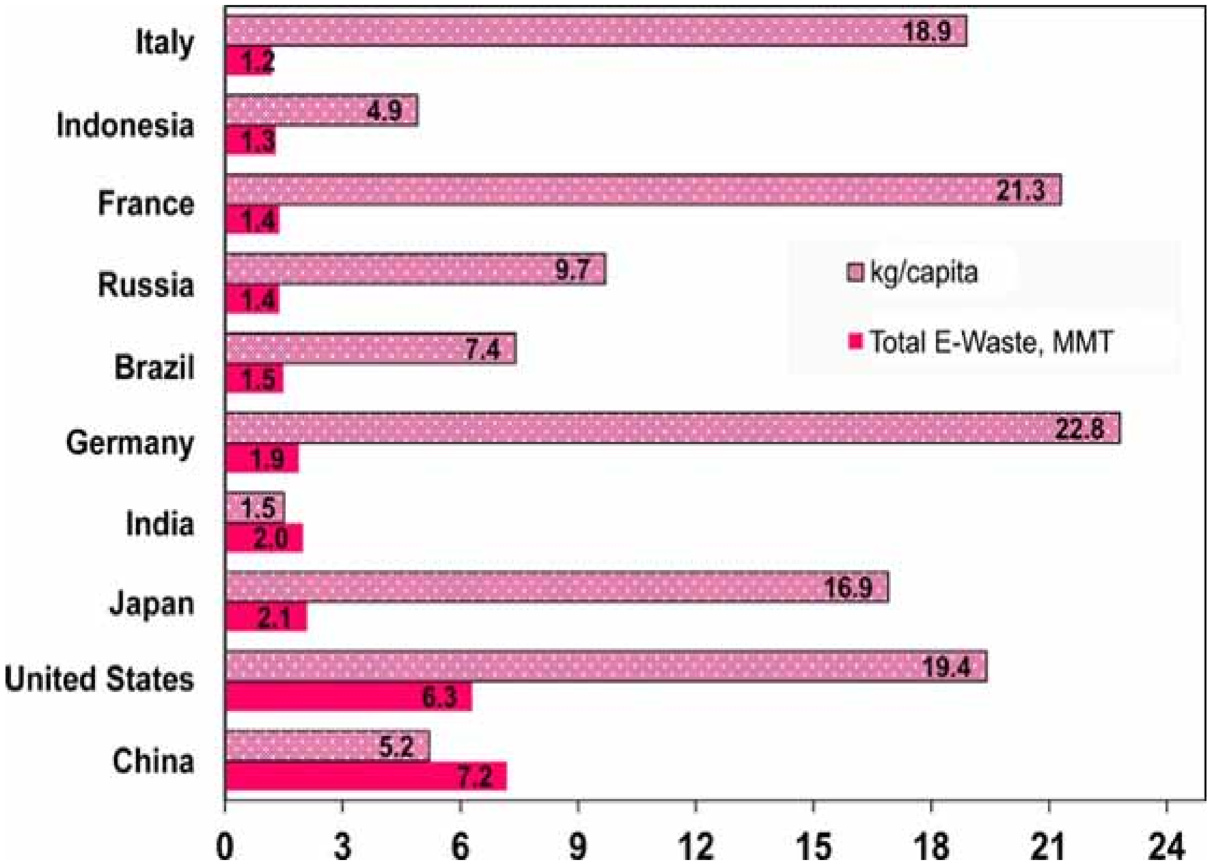
GLOBAL GENERATION OF E-WASTE

The Global development of electronic items has overstated modes of communication, transportation, entertainment, edification, and healthcare resulting in a mammoth amount of E-waste, which is discarded periodically and frequently. The global E-waste Monitor Report 2017 revealed that 44.7 Million Metric Tons of electronic waste had been produced in 2016 (Balde et al., 2017), which might surge beyond 50 MMT in the years to come. Fuelling is the major concern of sustainable management of E-waste, and it contributes a share of 5% of the entire solid waste generated in the world-wide (Kiddee et al., 2013). Developed countries like the United States and the leading countries of Europe are considered to be the main manufacturers and generators of the E-Waste (Robinson, 2009).

E-waste generation statistics change rapidly in the present scenario. Nations like China are leading in the generation of E-Waste (7.2 MMT/year), leaving the United States in second place. The share of another fast-developing country, India, is also increasing and expected to overtake the japan by 2020 for the third rank in global E-waste generation. The top 10 countries generating E-waste against total amount of generation and per capita consumption is as follows: (Figure 1)

During the year 2016, 44.7 MMT of E-waste was generated, out of which, small types of equipment has a major share with 16.8 MMT, large types of equipment with 9.1 MMT, temperature exchange equip-

Figure 1. The amount of E-waste generation: the top 10 countries in the year 2016

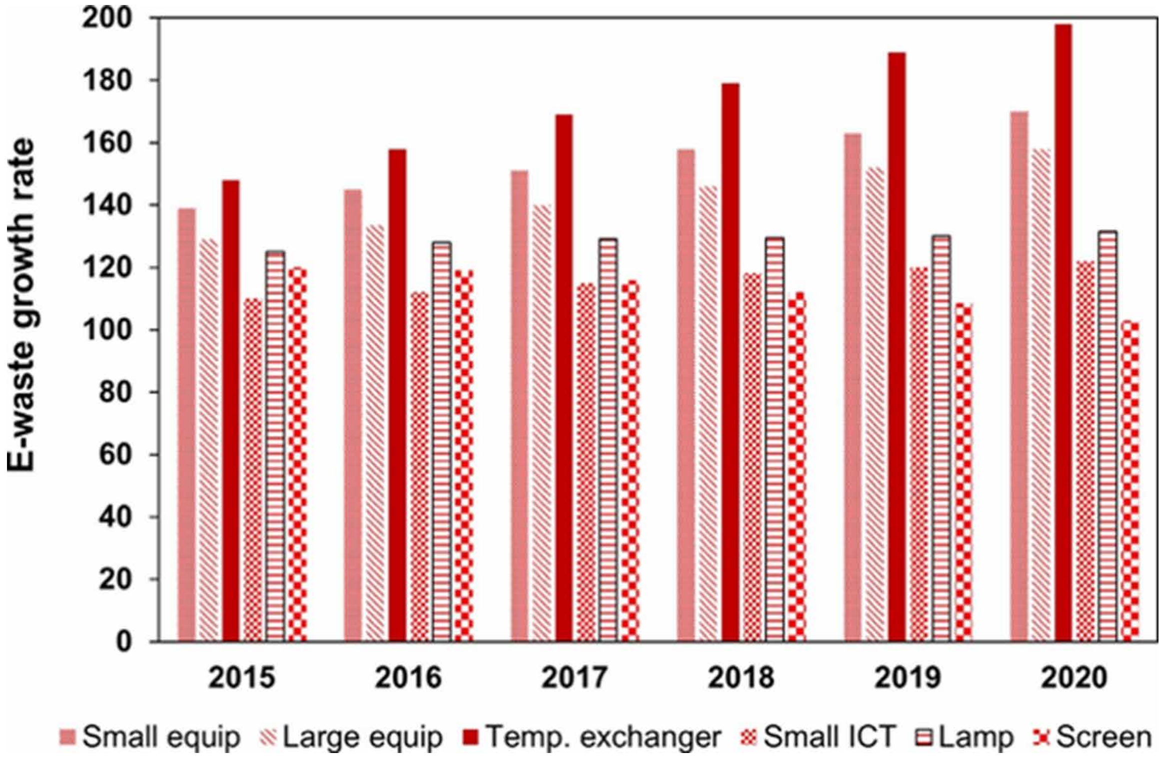


ment like freezing and cooling contributing 7.6 MMT, screens and monitors with 6.6 MMT, small ICT with 3.9 MMT and electric lamps with 0.7 MMT (E-Waste Recycling Facts and Figures, 2018). It was understood that the annual growth rate generated (E-waste) per category differs, but the overall amount will be increased in the coming years (Kumar et al., 2020).

CHALLENGES TO THE ENVIRONMENT

E-Waste is a protuberant environmental management problem that is alarmingly increasing with the pace of the global population and consumption. It has become an environmental curse to be battled. Owing to the stringent rules on the disposal of E-waste, the need for effective management has become mandatory, thus attracting researchers towards finding solutions. Apart from being the biggest contributors to E-waste, nations like China and India are also acting as dumping grounds for world-wide E-waste trade (Pathak et al., 2017; Zeng et al., 2017). Major reasons governing E-waste movement into these countries are deficiency of treatment facilities, valuable secondary materials recycling, and inexpensive operating costs for the transfer of waste (Figure 2 and 3).

Figure 2. Categorical growth rate of E-waste world-wide



Direct and Indirect Impacts on Environment and Human Health

Human health and the environment are adversely affected by the improper management of E-waste, either directly or indirectly. In order to reduce the cost of recycling, methods that are unsafe and informal are being used for recycling E-waste; these methods being unscientific, have a direct impact on humans and the environment. To illustrate these direct impacts, some cases in the different parts of India where the informal recycling taking place are accounted for here.

A study conducted by Pathak et al., 2017; Pradhan et al., 2017 reported severe environmental problems causing serious threats to human health at Mandoli industrial area in New Delhi. Kumar, 2014 analyzed soil and water around E-waste recycling areas revealed that heavy metal concentrations and hazardous materials are beyond the acceptable levels (Cadmium – 1.29mg/kg; Copper – 115.50mg/kg; Arsenic – 17.08mg/kg; Zinc – 776.84mg/kg; Selenium – 12.67mg/kg and Lead – 2,645.31mg/kg) which is attributed to the leaching of metals from E-waste into soil and groundwater. Additionally, Ha et al., 2009, found that the soils near the recycling areas consist of hazardous substances like organochlorine compounds (7mg/kg soil).

In Moradabad, Uttar Pradesh, severe pollution was observed due to the burning of PCBs (Printed Circuit Board) containing dioxins and furan and practicing improper disposable methods like dumping the burnt ashes in a subsidiary of Ganga, i.e., Ramganga river created severe acute water pollution as these ashes generally contain a high amount of heavy metals and poly-carbonaceous materials (Centre for Science and Environment, 2015).

Figure 3. The generation of (A) computers and (B) mobile phones in India as predicted by the mathematical modeling (with T5% extrapolation)

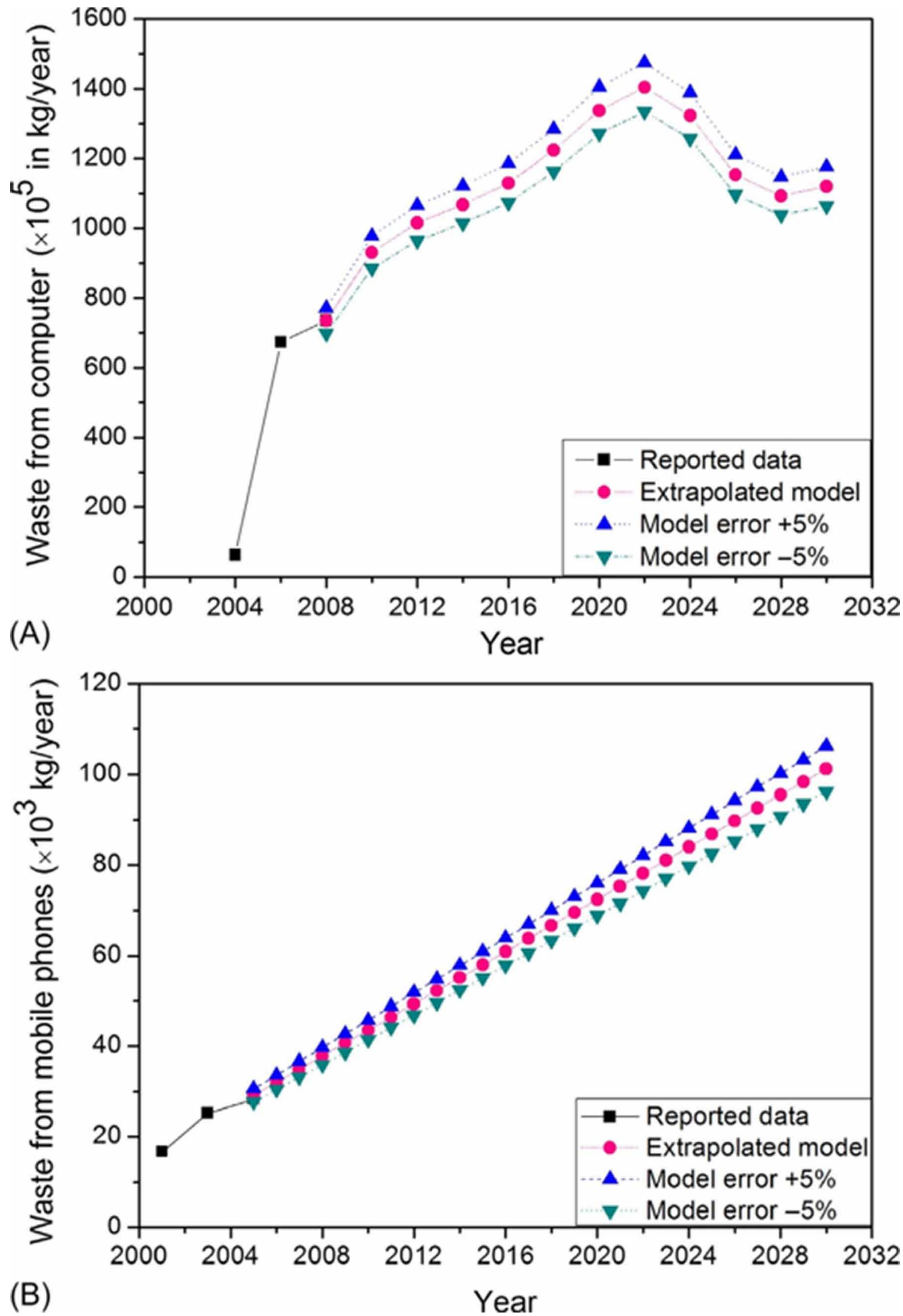


Table 4. Hazardous and radioactive waste category

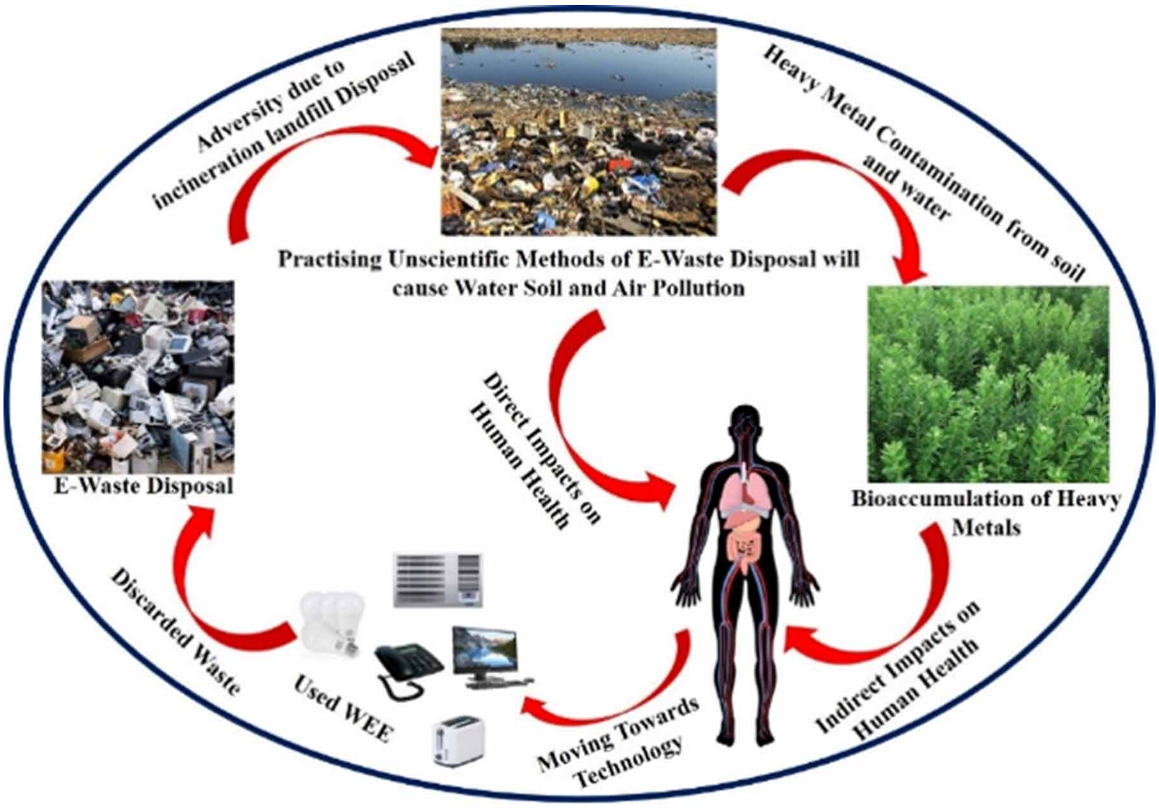
E-waste Components	Toxic Metals	Limit (ppm)	Disease Caused by the Exposure to Above Permissible Limit
Batteries and Capacitors made up of Ceramics	Ag[x]	5.0	It Causes blue pigmentation on the body, damages the liver, kidney, and brain.
Light-emitting devices	As[y]	5.0	Skin disease, cancer, and impaired nerve signaling
A fluorescent lamp, CRT gun	Ba[y]	<100	brain swelling, weakness in the muscle
Motherboards	Be[y]	0.75	Causes lung cancer, skin disease, berylliosis.
PVC Cables, PCB casings	Br[y]	0.1	hormonal issues, hearing loss, DNA damages.
Printer ink, toners	Cd[y]	1.0	Irreversible effects on the kidney.
Printed circuit boards	CN[y]	< 0.5	Cyanide poisoning, >2.5 ppm cause to coma
Computer hosing, cabling, hard discs.	Cr (VI)[y]	5.0	DNA damage and permanent eye impairment
LCD, switches, backlight bulbs	Hg[y]	0.2	Damages brain, kidney, and fetuses
Mobile batteries	Li[x]	< 10[a]	Diarrhea, vomiting, drowsiness,
CRT, PCB	Ni[x]	20.0	allergic reaction, bronchitis, lung cancers
LED lead-acid battery, solder, fluorescent tubes	Pb[z]	5.0	Damages the nervous system and reproductive system,
CRT glass and a solder alloy	Sb[y]	< 0.5	Carcinogen, diarrhea, and stomach ulcer
A fax machine, photoelectric cells	Se[y]	1.0	High concentration causes selenosis
CRT, batteries	Sr[y]	1.5	Somatic as well the genetic changes due to this cancer in the bone
Luminous substances	Zn[y]	250.0	Nausea, vomiting, pain, cramps, and diarrhea
Cooling units and insulation foam	CFCs[y]	<1.0	Depletes the ozone layer and leads to the incidence of skin cancer
Transformer, capacitor	PCBs[y]	5.0	PCB causes cancer in animals
Computer input units	PVC[y]	0.03	Hazardous and toxic air contaminants

[x]Critical,[y] hazardous and toxic, [z] radioactive waste, [a] limit in serum/blood.

Furthermore, during the attempts to recover valuable metals from the E-Waste, cyanide leaching into the soil and water was observed in the slum areas of Bangalore (Ha et al., 2009). In the process of extracting gold from the E-Waste, cyanidation is the most effective process for complete recovery; however, this cyanidation process should maintain alkaline conditions throughout the leaching as its pKa value is 9.5. Maintaining other than these conditions will form HCN gas, which is highly toxic in nature; if these exposures are greater than 500ppb, it causes severe impacts on human health. Discharging effluents generated from the cyanidation process will contaminate soil and groundwater. Sepulveda et al., 2010, observed from his study that nearly 247-fold higher content of lead leached into groundwater attributed to the burning of E-waste in the open. The presence of Higher concentrations of copper (Cu), Antimony (Sb), Bismuth (Bi), Cadmium (Cd), and Silver (Ag) in the blood and hair samples of workers is strong evidence of the adversity caused by improper recycling of E-waste.

Additionally, the elements in E-waste may vary according to the produced goods/devices and contain more than 1000 diverse substances, many of which fall under the hazardous and radioactive waste category (see Table 4).

Figure 4. Impacts of E-Waste on human health and environment



The penalties due to these substances are primarily physical health outcomes, for example, dysfunction of lungs, thyroid, the nervous system, and fertility in mammals (Agrawal et al., 2012; Sepulveda et al., 2010). It has been observed that local refurbishes in India are not practicing eco-friendly disposable techniques as these methods are expensive, and locals follow the rudimentary techniques to reduce the cost of disposing of to gain more profits. The E-waste cycle (Negative Impacts of improper handling of E-waste) shown in Figure 4: highlights their sustainable management. Dumping of E-Waste in landfilling sites releases a huge amount of heavy metals and toxic substances that can eventually drain to pollute the groundwater (Kiddee et al., 2013).

Up to 600 m^3 of the water can be polluted by the cadmium content present in one mobile phone. Awasthi et al., 2017 and Wang et al., 2005 stated that electronic appliances containing PCB and other plastic components are highly inflammable in nature, releasing acute toxic gases like dioxins and furans on burning and these cause severe threat to the ecosystem. The Physico-chemical parameters of the soil are altered by the heavy metals after leaching of these substances from the landfill. During the process of dismantling and shredding, the suspended particles released into the atmosphere causes atmospheric pollution. The atmospheric pollution increases the particulate matter in the ambient air and causes severe adverse respiratory and non-respiratory problems like the enhanced concentration of particulate matter in the ambient air causing breathing difficulties, eye and respiratory irritation, coughing, choking, pneumonitis, tremors, and neuropsychiatric problems for humans.

Air pollution is caused by practicing unscientific incineration practices for E-waste, and this results in the release of hazardous substances and has indirect impacts on human health. For instance, the crops grown in contaminated soils with heavy metals can easily absorb the pollutants. Post-harvesting, the contaminants enter the human body through an indirect route, but they have the same effect as direct pollution (Vara et al., 2019, Varghese et al., 2016). The direct and direct impacts of the E-waste cycle are shown in Fig. 5.

Furthermore, valuable metals might be lost by improper management/recycling of E-waste, therein, and hence virgin materials are required from the primary source. Thus, the mining-to-metal retrieval process will be required again.

For instance, every year globally, 100% of In (indium), 72% of Ru (ruthenium), 50% of Sn (tin), 44% of Cu (Copper), 34% of Ag (Silver), and 22% of Hg (mercury) are mined resulting in severe environmental pollution (Zeng et al., 2017). The recovery of metals from primary sources during mining can approximately save 41% of the energy cost of mining and water consumption up to 391.5 m^3/kg in ore milling, and this process will help in reducing the environmental pollution generated by the energy-intensive process. Remarkably, on an average of 10 million cellular phones contain approximately 160 tons of Cu(copper), 3500 kg of Ag(silver), 340 kg Au(gold), and 150 kg of Pd (palladium).

DISASSEMBLY OF E-WASTE

Disassembly is a selective process, involves segregating valuable or singling of hazardous components, and it is a vital process in the recycling of E-Waste. Moreover, it is a systematic approach that allows the removal of components or sub-assembly from a product for a particular purpose. Researchers are focussed on innovation in disassembly facilities and the disassembly planning process (DPP). The main motto behind the DPP is to advance software and procedures in disassembly strategies.

Gupta et al., 1996 proposed the following phases for the DPP plan:

- In the phase of input and output product analysis, valuable, reusable, and hazardous components are defined after the identification of optimal disassembly and preliminary cost analysis.
- In the following phase (Assembly analysis), component hierarchy, joining elements, and former assembly sequences are analyzed.
- Uncertainty issues analysis: originates from defective parts or joints in the products while upgrading or downgrading the quality of the product for consumer satisfaction.
- Determination of dismantling strategy: this a final phase for deciding whether to use destructive or non-destructive disassembly. Highly flexible tools are required for a process plan and implementation of good disassembly. Even though the electronic equipment used for assembly is well advanced, the automation for disassembly of E-waste is too complicated and not developed.

The automated disassembly is being prevented from becoming commercially successful due to the following reasons:

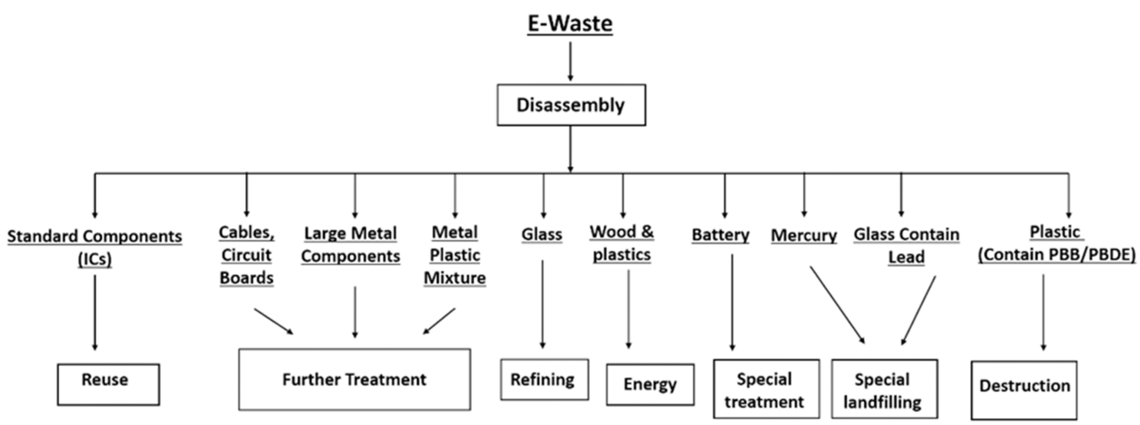
(1) Similar type of products; (2) the number of products that are similar is too small; (3) un-friendly product design for general disassembly; (4) problem in logistics during returns; and (5) dissimilarities in giving back products that to be disassembled.

Dismantling of electronic equipment in the recycling process in indispensable because; (1) the first priority is to reuse the components; (2) Hazardous components dismantling is essential; (3) High valuable and high-grade materials used in printed circuit boards, cables, and engineering plastics are common and simple to recover. In general, the manual dismantling process is practiced by recycling plants. Ragn-Sells Elektronika°tervinning AB in Sweden is a typical electronics-recycling corporation. Figure 5, present the contemporary disassembly process being used (Cui & Forssberg, 2003). Wide – a variety of tools are involved in the process of dismantling for the removal of hazardous components and for the recovery of valuable and reusable materials.

RECYCLING TECHNOLOGY OF ELECTRONIC WASTE

Magnetic Separation

Figure 5. The recycling process developed by RagneSells Elektronika°tervinning AB in Sweden

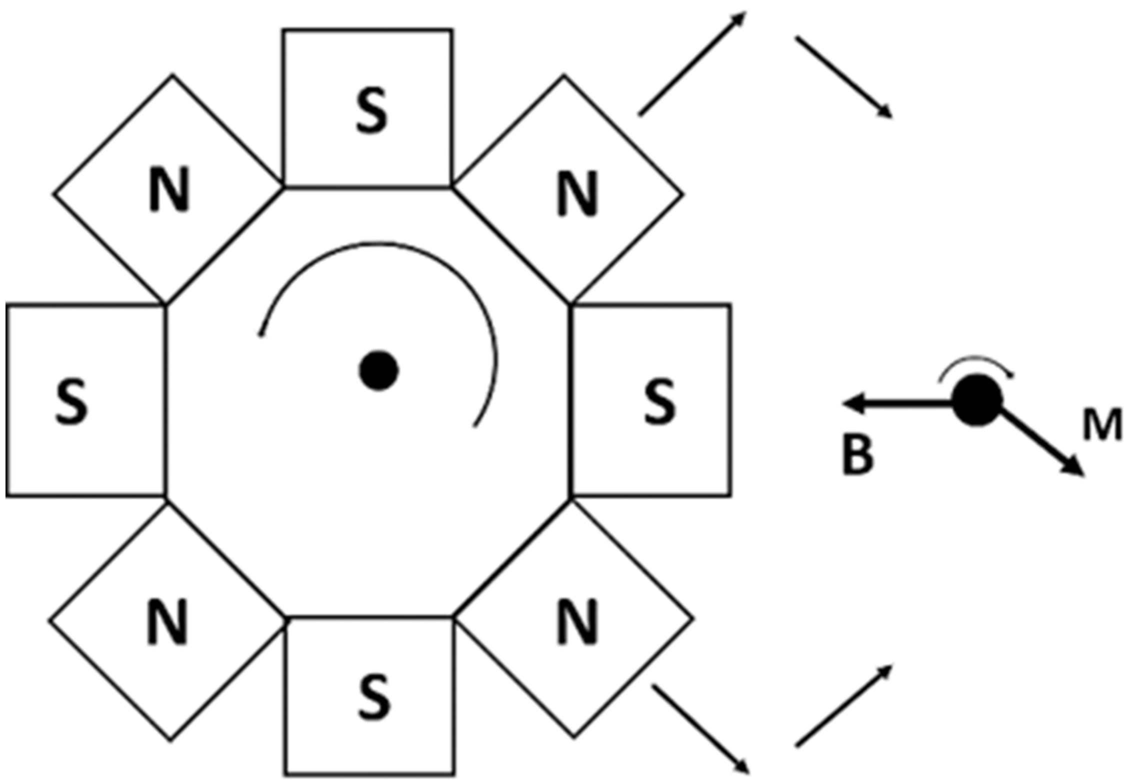


Magnetic separators, i.e., low-intensity drum separators, are mostly used for separating the ferromagnetic metals from non-ferrous metals. The high-intensity magnetic separators design has been modified after the introduction of rare earth alloy permanent magnets capable of providing very high-field strengths and gradients.

Eddy Current Separation

Introducing eddy current separators in recycling industries is one of the most significant development. Figure 6 illustrates the principle of eddy current. Eddy currents can be actuated in an electrically conductive particle by a time-dependent attractive magnetic field (magnet rotor in the figure). Further, the eddy currents will, in return, result in magnetic fields that oppose the inducing fields, giving rise to a so-called Lorentz force, a repulsive force.

Figure 6. Illustration of Eddy current separation: magnet rotor (left) produces a time-dependent magnetic field B, including Eddy currents in a particle (right) resulting in a particle magnetic moment M



Density-Based Separation

Gravity concentration separates materials of different specific gravity by their relative movement in response to the force of gravity and one or more other forces, the latter often being the resistance to motion offered by a fluid, such as water or air (Wills & Finch, 2015). The motion of a particle in a fluid is dependent not only on the density of the particle but also on its size and shape; large particles will be affected more than smaller ones. In practice, close size control of feeds to gravity processes is required to reduce the effect on the size and make the relative motion of the particle specific gravity-dependent.

Optical Sorting

With the fast development of the Charge- Coupled Device (CCD) sensor, computing, and software technology, optical sorting processes have been developed in both the recycling and mineral processing industry. In addition, recording more and better data with sensors improves the separation performance of automated sorting equipment. The measuring of particle properties such as color, texture, morphology, conductivity, and others allows high-quality sorting of mixed materials into almost pure fractions. Hence, multisensory systems involving the use of two or more different sensors have been developed over the past few years.

Table 5. Metals recovery from various process

Techniques	Metals recovered	Main process features	Main results	References
Noranda process	Cu, Au, Ag, Pt, Pd, Se, Te, Ni	Copper smelter is feeding with 14% of copper for total throughput; Converter upgrading; Metal recovery by electrorefining	Copper and precious metals are recovered in huge amounts	Veldhuizen & Sippel, 1994
Boliden Ronnskar Smelter	Cu, Ag, Au, Pd, Ni, Se, Zn, Pb	Kaldo reactor is feeding with high concentrations of lead; Coper converter up-gradation and refining process	Copper and precious metals are recovered in huge amounts	Theo, 1998; Lehner,2003
Test at Ronnskar Smelter	Copper and precious metals	Computer component scrap feeding to Zinc fuming process in 1:1 ratio with revert slag; Plastics were used as fuel and reducing agents; Copper smelter recovers the precious metals and Copper that are following the copper collector	Complete recovery of precious metals and copper in the Zinc fuming process	Mark & Lehner, 1999
Umicore's Precious metal refining process	Base metals, Precious metals, Platinum group metals and Selenium, Tellurium, Indium	Electrowinning, IsaSmelt copper leaching and precious metal recovery for precious metal operation; E-waste cover up to 10% of the feed; Plastics substitute coke, which acts a reducing and fuel to the IsaSmelt; Off gas emission control system is installed at the IsaSmelt furnace	Special metals like Sb, Bi, Sn, Se, Te, In are recovered along with base metals and precious metals.	Hagelüken, 2006; Hageluken & Art, 2007
Full-scale trial at Umicore's smelter	Metals in electronic scrap	Coke is replaced by plastic rich materials from WEEE, and these substances act as a reducing agent as well as an energy source for the IsaSmelt	Using WEEE (6%) and coke (1%) doesn't negatively affect the metal recovery process (instead of using only coke (4.5%))	Brusselaers et al., 2005
Dunn's patent for gold refining	Gold	Gold scrap subjected to chlorine at 300^0C to 700^0C; Impurity-Metal chlorides are washed with Hydrochloric acid; Silver chloride is dissolved by ammonium hydroxide and nitric acid washing; Samples should contain more than 80% of gold	Gold with 99.9% purity was recovered from gold scraps	Dunn et al., 1991
Day's patent for refractory ceramic precious metals scraps	platinum and palladium	In the plasma arc furnace, scrap was subjected to heat (at least 1400 C); Precious metals in molten metallic phase and collector metals were produced; Ceramic residues went into a slag phase;	Recoveries of 80.3% and 94.2% were obtained for platinum and palladium, respectively	Day, 1984
Aleksandrovich's Patent for recovery of platinum group metal and gold from electronic scraps	Platinum group metal and gold	Fusing together scraps based on chalcogenides of base metals with carbon reducer; After the settling and cooling of melted materials, solidification and separation of solidified products are facilitated by formed phase boundaries	Platinum group metal and gold was recovered	Aleksandrovich et al., 1998

Pyrometallurgical Process

Pyrometallurgical processing is a traditional method for recovering precious and non-ferrous materials from electronic waste. The pyrometallurgical process includes incineration, smelting in the blast furnace, sintering, melting, dross formation, and reactions in a gas phase at high temperatures. In this process, the scrap that is crushed was subjected to heating in a furnace or in a molten bath to remove plastics and the refractory oxides from the slag phase together with some metals.

The above table gives a summary of typical pyrometallurgical methods for the recovery of metals from electronic waste. The traditional technology of pyrometallurgy has been used for the recovery of copper and precious metals from electronic waste equipment for years. However, most methods involving the pyrometallurgical processing of electronic waste has the following limitations (Hageluken, 2006; Sum, 1991):

- Integrated smelters cannot recover aluminum and iron as metals; they are transferred into the slag component. Unfortunately, aluminum has an influence on the slag properties that are undesirable in most cases.
- The presence of halogenated flame retardants in the smelter feed can lead to the formation of dioxins unless special installations and measures are present. Traditional smelters designed for the treatment of mining concentrates or simple copper scrap encounter some challenges for electronic waste treatment. However, state-of-the-art smelters are highly dependent on investments.
- Ceramic components and glass in the e-waste increase the amount of slag from blast furnaces, which results in a loss of precious metals and base metals from the scrap.
- Energy recovery and the use of organic constituents as reducing agents are beginning to be used only now.
- Only partial separation of metals can be achieved using pyrometallurgy, resulting in a limited upgrading of the metal value. Subsequent hydrometallurgical techniques and/or electrochemical processing are therefore necessary.
- Precious metals take a long time to separate in pyrometallurgical processes and are thus only obtained at the very end of the process.

Hydrometallurgical Process

Precious metals contribute the highest value to electronic scrap. From an economic point of view, the recovery of precious metals from e-waste is most attractive. In the past two decades, the most active research area on the recovery of metals from electronic scraps is recovering precious metals by hydrometallurgical techniques (Quinet et al., 2005; Macaskie et al., 2007; Ogata & Nakano, 2005). Compared with pyrometallurgical processing, the hydrometallurgical method is more exact, more predictable, and more easily controlled. The main steps in hydrometallurgical processing consist of a series of acid or caustic leaches of solid material. The solutions are then subjected to separation and purification procedures such as precipitation of impurities, solvent extraction, adsorption, and ion-exchange to isolate and concentrate the metals of interest. Consequently, the solutions are treated by electrorefining process, chemical reduction, or crystallization for metal recovery (Safarzadeh et al., 2007; Ritcey, 2006; Tavlarides et al., 1987).

A summary of new developments in the recovery of metals from electronic waste by hydrometallurgical techniques is listed in Table 6. It can be seen that most of the hydrometallurgical techniques for the

Table 6. Recovery of Metals from Electronic Waste by Hydrometallurgical Techniques (most practiced)

Metals recovered	Main process features	Main product	References
Au	Computer chips were treated in nitric acid to dissolve base metals; the residue was leached with aqua regia; ferrous sulfate precipitation was used for gold recovery	Gold flakes	Sheng & Etsell, 2007
Au and Ag	E-waste with size - 0.5 mm was treated with a combination of KI and I2 or NaCl and bleaching powder; solvent extraction was used for gold and silver recovery	Au and Ag	Shibata & Matsumoto, 1999
Ni	Leaching of nickel from waste multi-layer ceramic capacitors was performed by using 1M HNO3 at 90_C, 90-min reaction time, and 5 g/l pulp density	Ni in solution	Kim et al., 2007
Au (98%), Pd (96%), Pt (92%), Ag (84%)	H2SO4 and MgCl2 for dissolution of base metals; HCl and bromide ions were used to dissolve precious metals; cementation of gold by zinc powder	Au and platinum group metals powders	Kogan, 2006
Cu (98%)	Copper was dissolved by sulphuric acid or aqua regia; electrowinning was performed for copper recovery	Cu	Veit et al., 2006
Cu, Ag (93%), Pd (99%), Au (95%)	Sulphuric acid leaching of copper, chloride leaching of palladium, thiourea or cyanide leaching of gold and silver, activated carbon adsorption of gold, silver, and palladium	AgCl, Cu, Pd, Au	Quinet et al., 2005
92% for Au, Ag, Pd	HCl or H2SO4 for dissolution of base metals, leaching of silver by HNO3, leaching of gold and palladium by HCl and NaClO3; precipitation of Au by FeCl2	Gold sponge	Zhou et al., 2005
Au	E-scrap was treated with a leaching solution based on NaCl, CuCO3, and HCl	Gold residue	Olper et al., 2004
Sn, Pb	The solder was dissolved with a solution comprising Ti(IV) and an acid. Tin and lead were recovered by electrowinning	Sn and Pb	Gibson et al., 2004
Cu, Pb, and Sn	HNO3 leaching of PCBs, electrodeposition recovery of base metals	Cu, Pb, and Sn	Mecucci & Scott, 2002
Au	Thermal treatment, HNO3 leaching, and aqua regia leaching for gold dissolution, solvent extraction of gold by diethyl malonate, ferrous sulfate solution was used for gold precipitation	Metallic gold	Chmielewski et al., 1997
Au and Ni	Leaching of base metals by sulphuric acid and oxidant (ferric sulfate) and aqua regia leaching of precious metals	Ni and Au in solution	Zakrewski et al., 1992

recovery of metals are involved in acid leaching and/or halide leaching. This is because acid leaching is the most feasible approach for the removal of base metals resulting in the exposure of precious metals surfaces. However, to develop an environment-friendly technique for the recovery of precious metals from e-waste, more attention should be paid to evaluate the environmental impact of the various techniques.

REGULATIONS DEALING WITH ELECTRONIC WASTE

It is a well-known fact that the environmental quality is dwindling at a very fast pace due to such informal, unplanned, and untrained treatment of E-wastes. But one significant cause for such environmental degradation due to E-wastes is the inability of the law to deter violators. In many countries, there are now legislations and statutes in place specifically to deter such crimes.[37] In India also many environmental legislations and the rules are there, which are dealing with E-waste either directly or indirectly. Such legislations have, inopportunely, not resulted in preventing environmental dilapidation as penal provisions in environmental laws dealing with electronic wastes are weak, lenient, hard to impose, and unlikely to affect 'business as usual.' The situation is aggravated by other problems like slow justice delivery system, poor monitoring and enforcement capacity of regulators, and lack of comprehensive databases to evidence violations, among others.

There are various legislations/rules dealing with E-wastes in environmental laws either directly and indirectly, to name a few are:

1. Electronic waste (management) Amendment rules, 2018.
2. Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016.
3. The Environment (Protection) Act, 1986
4. The Air (Prevention and Control of Pollution) Act, 1981
5. The Water (Prevention and Control of Pollution) Act, 1974

Out of these legislations and legal provisions, only a few legislations provide for penal provisions to deal with the menace produced by improper disposal of electronic waste. Improper disposal like burning and segregating electronic waste in open areas and not in a manner in which environmentally sound causes leakage in the environment, which results in pollution to the air, water, and soil.

STRATEGIES TOOK FOR THE MANAGEMENT OF E-WASTE

Inventory Management: Proper control over the materials used in the manufacturing process is an important way to reduce waste generation. By reducing both the number of hazardous materials used in the process, and the amount of excess raw materials in stock, the quantity of waste generated can be reduced. This can be done in two ways, i.e., establishing material-purchase review and control procedures and inventory tracking system. Developing review procedures for all material purchased is the first step in establishing an inventory management program. Procedures should require that all materials be approved prior to purchase. In the approval process, all production materials are evaluated to examine if they contain hazardous constituents and whether alternative

Non-hazardous materials are available. Another inventory management procedure for waste reduction is to ensure that only the needed quantity of material is ordered. This will require the establishment of a strict inventory tracking system. Purchase procedures must be implemented which ensure that materials are ordered only on an as-needed basis and that only the amount needed for a specific period of time is ordered (Zhang et al., 2020).

Production-Process Modification: Changes can be made in the production process, which will reduce waste generation. This reduction can be accomplished by changing the materials used to make the product or by the more efficient use of input materials in the production process or both.

Waste reduction can be accomplished by the more efficient use of input 0020wq

1. Material change and

2. Process-equipment modification.
    a. **Material Change:** Hazardous material used in the production process may be replaced by the less hazardous material. For example, a circuit board manufacturer can replace the solvent-based product with water-based flux and simultaneously replace the solvent vapor degreaser with the detergent part washer.
    b. **Process Equipment Modification:** Modifying existing equipment to take advantage of better production techniques can significantly reduce waste generation. For example, in many electronic manufacturing operations, which involve porting a product, such as electroplating or painting, the chemical is used to strip off coating from rejected products so that they can be recoated.

Improvements in the operation and maintenance of process equipment can result in significant waste reduction. This can be accomplished by reviewing current operational procedures and examination of the production process for ways to improve its efficiency. Instituting standard operation procedures can optimize the use of raw materials in the production process and reduce the potential for materials to be lost through leaks and spills. A strict maintenance program, which stresses corrective maintenance, can reduce waste generation caused by equipment failure. An employee-training program is a key element of any waste reduction program. Training should include correct operating and handling procedures, proper equipment uses, recommended maintenance and inspection schedules, correct process control specifications, and proper management of waste materials (Esenduran et al., 2019).

Hazardous materials used in either a product formulation or a production process may be replaced with less hazardous or non-hazardous material. Implementation of this waste reduction technique may require only some minor process adjustments, or it may require extensive new process equipment (Esenduran et al., 2019).

For example, a circuit board manufacturer can replace the solvent-based product with water-based flux and simultaneously replace the solvent vapor degreaser with a detergent parts washer. Installing more efficient process equipment or modifying existing equipment to take advantage of better production techniques can significantly reduce waste generation. New or updated equipment can use process materials more efficiently, producing less waste.

Modifying existing process equipment can be a very cost-effective method of reducing waste generation. In many cases, the modification can just be relatively simple changes in the way the materials are handled within the process to ensure that they are not wasted. For example, in many electronic manufacturing operations, which involve coating a product, such as electroplating or painting, chemicals are used to strip off coating from rejected products so that they can be recoated. These chemicals, which can include acids, caustics, cyanides, etc., are often hazardous waste and must be properly managed. By reducing the number of parts that have to be reworked, the quantity of waste can be significantly reduced.

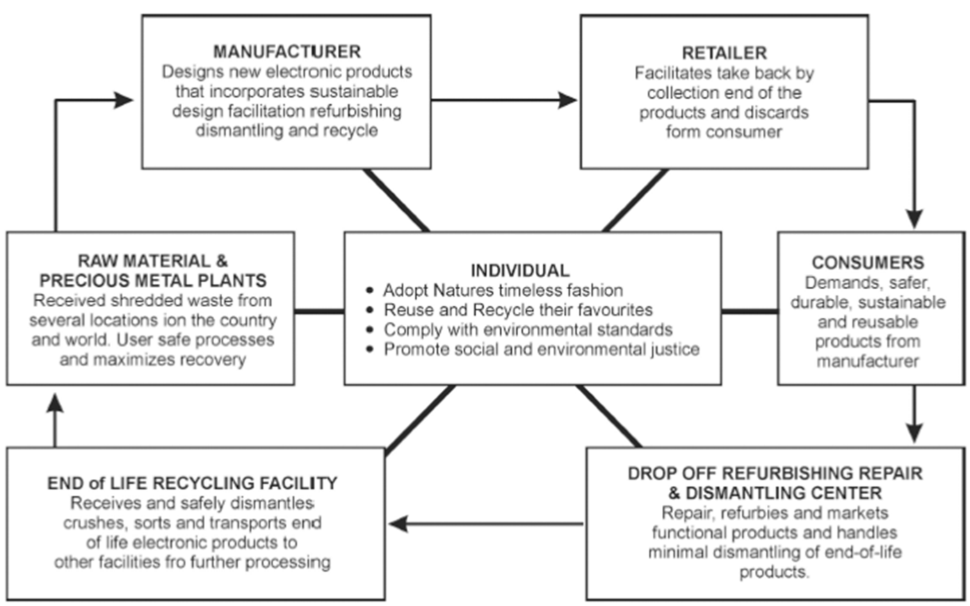
- **Volume Reduction:** Volume reduction includes those techniques that remove the hazardous portion of waste from a non-hazardous portion. These techniques are used to reduce the volume, and thus the cost of disposing of waste material. The techniques that can be used to reduce waste-stream volume can be divided into two general categories:

Source segregation and Waste concentration.

- **Segregation of waste** is, in many cases, a simple and economical technique for waste reduction. Wastes containing different types of metals can be treated separately so that the metal value in the sludge can be recovered.
- **The concentration of a waste** stream may increase the likelihood that the material can be recycled or reused. Methods include gravity and filtration, ultra-filtration, reverse osmosis, freeze vaporization, etc.
- **Recovery and Reuse:** The technique could eliminate waste disposal costs, reduce raw material costs, and provide income from a saleable waste. Waste can be recovered on-site, or at an off-site recovery facility, or through the inter-industry exchange. Several physical and chemical techniques are available to reclaim a waste material such as reverse osmosis, electrolysis, condensation, electrolytic recovery, filtration, centrifugation, etc. for example, a printed circuit board manufacturer can use electrolytic recovery to reclaim metals from copper and tin-lead plating bath (Islam & Huda, 2020; Song et al., 2019).

However, recycling of hazardous products has little environmental benefit if it simply moves the hazards into secondary products that eventually have to be disposed of. Unless the goal is to redesign the product to use non-hazardous materials, such recycling is a false solution (Figure 7).

Figure 7. Sustainable life cycle of E-waste



CONCLUSION

It is evident from the above discussion, pollution from improper handling of E-waste cannot be ignored owing to the magnitude of health and environmental impacts. To escape from hazardous effects, it is vital to appropriately manage E-waste. Inadequate infrastructure and insufficient budget are two issues that restrict E-waste management. This is high time to follow scientific and safe methods for recycling E-waste. Sustainable E-waste management methods discussed in the article, along with their challenges, might prove to be useful in implementing strategies. Integrating these solutions with existing waste management systems might be a possible way to solve problems related to E-waste management.

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