A Review of the Indian Scenario of E-waste Management: Generation, Effect, and Material Recovery Method

Ujjaval P. Sarvaiya, Anuj D. Bhatt, and Kunwar D. Yadav

Abstract E-waste is the fastest growing type of waste on a global scale. E-waste refers to trash electrical and electronic equipment rejected or discarded in whole or in part during production, refurbishing, or repair processes. In 2019, 53.6 Mt (Million tonnes) of e-waste was generated globally and is expected to rise to 74.7 Mt by 2030, with a growing rate of 3–5% annually. An estimated amount of e-waste generated by India from 0.77 to 3.2 Mt and 1,64,663 tonnes have been dismantled and recycled, in 2019. Compared to many developed countries, the overall volume produced is higher while e-waste generation is 0.6–2.4 kg/capita in India due to its population and market size. This paper reviews the research on the current state of e-waste management, the quantification and qualification of e-waste, the potential for a circular economy, the impact of e-waste, and disposal. In India, there is still a widespread practice of landfilling and incinerating of e-waste, which is also ragged, unorganized, and crude. This paper reviews research on informal and poor handling of e-waste in India and discusses the negative impact of e-waste's effects due to its complex mixture of toxic compounds. According to the available research, sustainable e-waste management in India remains a major challenge due to more informal recycling practices, a lack of rules and regulations, e-waste importation from developed countries, and a lack of awareness and information. This paper also discusses the material recovery from e-waste with available methods (such as mechanical separation, pyro-metallurgy, and hydrometallurgy), along with the possibility for the circular economy to expand. As a result, the study covers the recovery options that are available, as well as the challenges and possibilities.

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Abbreviations

EEE	Electronic and electrical equipment
WEEE	Waste electrical and electronic equipment
E-waste	Electronic waste
Mt	Million metric tonnes
Kt	Kilometric ton
USD	United States dollar
PRO	Producer responsibility organization
EPR	Extended producer responsibility
CPCB	Central pollution control board
PCBs	Printed circuit boards

1 Introduction

The management of solid wastes, which are increasing in both amount and complexity, is still a serious environmental challenge on a global scale; this issue has been made worse by e-waste, which is frequently regarded as one of the most problematic types of solid waste [1]. E-waste is one of the fastest growing waste streams in the world because of rapid efficiency innovations, advancement in design, extensive rising demand, technological developments, upgradation, and rapid increase in obsolescence (either due to the reduced life span of the product or change in customers' requirement) of electrical and electronic equipment [2–4].

E-waste is generally defined as the waste generated by all parts and items of electronic and electrical equipment (EEE), or when EEE reaches the end of its lifecycle, or when EEE or its components are discarded without the intention of being reused, and is known as waste electrical and electronic equipment (WEEE), electronic waste (e-waste), or e-scrap (in a different part of the world). In this study, it is referred to by the term "E-waste" inclusively [5–7].

E-waste piles have raised concerns about their proper disposal. E-waste is disposed of through incineration, landfilling, blazing, and junking outdoors in many countries and that should be considered as the least preferred option for final disposal. To encourage the reuse of the entire product and remanufacturing, and then recycling, numerous academics have indicated that this alternative should be viewed as the least desirable one for the final disposal of e-waste [8, 9].

According to estimates by Islam et al. and Kaya [10, 11], e-waste probably accounts for between 5 and 8% of municipal solid waste globally. Sahin et al. [12]

mentioned that three times more e-waste was produced globally in 2019 than there were people on the planet [12]. As per the Global E-waste Monitor 2020 report, in 2019, 53.6 Mt of e-waste was generated globally (an average of 7.3 kg per capita). On average, the total weight of global EEE consumption increases annually by 0.4–2.5 Mt, at a rate of 3–5% per year. It is projected to grow E-waste generation to 74.7 Mt by 2030 and 110 Mt by 2050 [13].

A 9.3 Mt (17.4% of the e-waste generated) was formally collected and recycled in 2019, which is only marginally better than the rate anticipated in 2014 (17%) [7, 13]. Recycling helps keep non-biodegradable materials like glass, metals, and plastics out of landfills and reduces environmental pollution [14]. The destiny of 82.6% (44.3 Mt) of the e-waste produced in 2019 is unknown because it can be burned outdoors or discarded illegally, and its impact on the environment and human health. In 2019, 5.1 Mt of e-waste crossed international borders, of which 1.8 Mt was transported in a controlled manner. The remaining 3.3 Mt, however, was shipped in an uncontrolled manner as used-EEE or e-waste under the Basel Convention regime [13, 15]. It is recycled in informal contexts in developing nations, including Nigeria, Ghana, Brazil, Mexico, China, India, Vietnam, and the Philippines. For instance, between 25 and 75% of the used computers brought into Nigeria in 2005 were either non-operational or beyond repair, and were subsequently recycled discretely [16].

The collection, handling, recycling, and management of e-waste is a key challenge as for monitoring strategies it is quite unorganized and unofficial, which leads to the reuse and recycling of the whole product and remanufacturing, to conserve valuable materials and are designed to safeguard both the environment and public health [3, 17].

A major challenge faced today is the safe management of e-waste. To mitigate the global e-waste tsunami, current literature provides reviews on the existing state of e-waste management practice, the quantification and qualification of e-waste, the potential for a circular economy, the impact of e-waste disposal, and also discuss the e-waste generation in India, its challenges and opportunities, disposal of e-waste, and the impact on the environment.

2 Composition of E-waste

E-waste can be categorized as follows:

1. Large household equipment: Washing machines, televisions, air conditioners, refrigerator/freezer, and dishwashing machines.
2. Small household equipment: Vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, irons, coffee machines, electric shavers, calculators, radio sets, video cameras, small monitoring, stereo, and DVD/VCR player.
3. IT and Telecommunication equipment: Mobile phones, tablets, personal computers, laptops, printers, fax machines, routers, and telephones.

4. Lamp: Fluorescent lamps, high-intensity discharge lamps, and LED lamps.
5. Other electric and electronic equipment: Electrical and electronic toys, electrical and electronic tools, and medical devices.

Figure 1 illustrates the composition of e-waste, with analysis in Table 1.

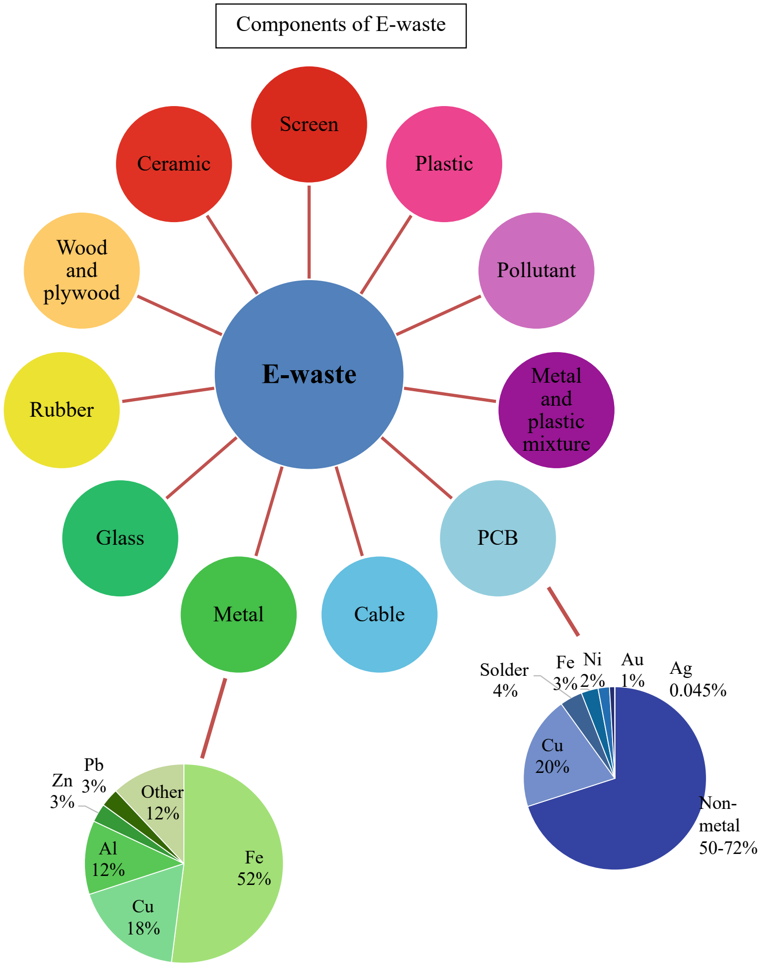

Fig. 1 E-waste composition Ref. [18–21]

Table 1 Composition of e-waste [18–20]

No.	Equipment	Weight percentage (%)
1	Metal	33–60.6
2	Plastic	15.21–30
3	CRT, LCD	11.87
4	Metal plastic mixture	4.97
5	Pollutant	2.70
6	Cables	1.97
7	PCB	1.71–3.1
8	Other	1.38–16
9	Glass	5.4–37
10	Rubber	0.9
11	Wood and plywood	2.6
12	Ceramic	2.0

3 Indian Scenario of E-waste Management

Around the globe, India is one of the top five e-waste-generating countries. Compared to many developed countries, the overall volume produced is higher while e-waste generation is 0.6–2.4 kg/capita in India due to its population and market size. In India 7,71,215 to 32,30,000 tonnes of e-waste were generated in 2019. With a growth rate of 10% per annum, it is expected to achieve 8 Mt by 2025 [13, 22, 23].

Ten states in India make up roughly 60–70% of the nation's total production of e-waste, as shown in Fig. 3. Mumbai ranked first among the top 10 cities that produce e-waste. Delhi, Bangalore, Chennai, Calcutta, Ahmedabad, Hyderabad, Pune, Surat, and Nagpur are the following cities [24]. According to Parthasarathy et al. [25], an average middle-class family produces 18 kg of e-waste annually. Additionally, Mumbai, Delhi, Madras, Hyderabad, and Ahmedabad receive most of the e-waste as a charity [2]. According to Priya and Hait [23], India's imports of electronic goods for 2018–19 were about 55,475.52 million USD.

Domestic households, the public, and the private sectors, including business, mechanical, institutional, construction and demolition, foreign embassies, EEE manufacturers and retailers, emergency clinics, multinational corporations, other city administrations, and the secondary market for used gadgets, are potential sources for generating e-waste in India [5]. In India, desktops, smartphones, laptops, and televisions are the major electronic items that are contributing to an increase in e-waste. In terms of sales, use, and Internet usage, India is one of the top countries for smartphone users worldwide [23]. Figure 2 depicts the source of e-waste. E-waste management in India divided into formal and informal sectors is discussed further.

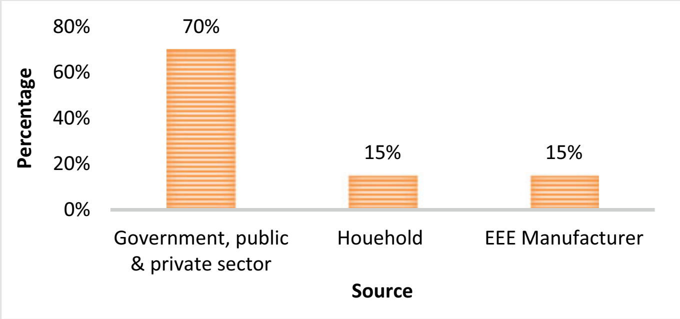

Fig. 2 Source of e-waste, Ref. [5]

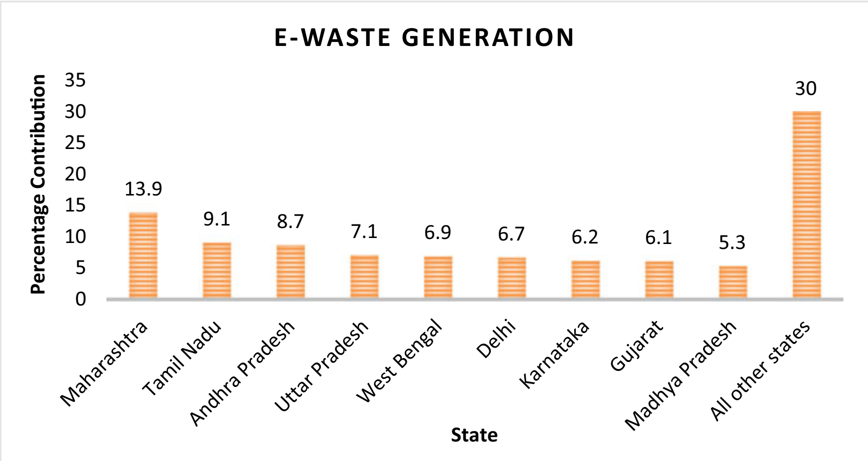

Fig. 3 State-wise generation of e-waste, Ref. [24]

3.1 Formal Sector

Formal e-waste treatment is a critical component of the sustainable management of solid waste in developing nations because it is closely related to environmental issues caused by a substantial informal industry. In Southern Asia, India is the only country with e-waste legislation. Since 2011, India has had e-waste management laws in place that require only authorized dismantlers and recyclers to collect e-waste. E-waste Management and Handling rules, 2011 strengthened the global best practice of EPR to take-back of end-of-life products. The E-Waste (Management) Rules 2016 included a manufacturer, dealer, refurbisher, and Producer Responsibility Organization (PRO) [3, 13].

The E-Waste Management Rules 2016 required producers to establish a Producer Responsibility Organization (PRO) to support EPR and conduct their obligations;

currently, India has 51 PROs. The PROs are responsible for establishing a collection and recycling mechanism and running awareness campaigns. However, many government agencies do not consider a PRO to be an authorized entity eligible to bid on their e-waste [2, 22].

India has total 2,759 E-Waste collection centers of EPR-authorized producers for e-waste collection by Central Pollution Control Board (CPCB). There are 400 authorized dismantlers/recyclers with a total processing capacity of 10,68,542.72 tonnes. 1,64,663 tonnes of e-waste were dismantled and recycled in 2019 and 2,22,436 tonnes in 2020 [13, 22]. Formal sectors use metal recovery technologies such as bioleaching, bio-recovery, hydrometallurgy, pyro-metallurgy, and other sustainable technology [3].

3.2 Informal Sector

In India, environmental authorities are concentrating their efforts on developing a strategy for controlling the informal sector. However, the informal sector remains a problem. Due to the large informal sector's use of low-cost labor employees with useful skills, it is more cost-effective than the formal sector. The informal recycling sector handles 85–95% of e-waste, which is unacceptable despite the fact that it provides income to millions of people. Delhi has been identified as one of the largest informal recycling hotspots in India, with over 5000 informal recycling hotspots engaging over 50,000 people [5, 23]. Over 3000 units are involved in informal recycling activities throughout the country. However, informal recycling/backyard recycling has negative environmental and health consequences [3, 26].

According to the E-waste Management Rule 2016, a minimum of 300 m^2 area is required for dismantling 1 tonne of e-waste per day, but the informal sector only uses 20–40 m^2. According to government guidelines, the recycling facility should install a wastewater treatment plant, but the informal units lack such treatment plants. As a result, the informal sector creates a major impact on human health and the environment [23]. When compared to formal recyclers, informal recyclers offer higher prices when purchasing e-waste because the costs of legal, environmental, and social compliance are avoided in the informal economy [2].

Informal recycling includes different key players like kabadiwallas, rag-pickers, kabaddi shops, scape dealers, waste traders, dismantlers, refurbishers, and recyclers. The informal sector has a very well-connected structure, with a sizable base of last-mile collectors known as "kabadiwallas;" they offer convenient door-to-door service at a localized level. They purchase e-waste along with other recyclable waste like old newspapers, cardboard, books, plastics, glass, bottles, etc. from consumers and sell it to waste traders and then it goes to the wholesaler. After that, the wholesaler separates and sorts various waste materials with a considerable amount of specialization [2, 4].

These wholesalers provide materials for reprocessing to recyclers, dismantlers, and disposers. In India, e-waste is handled similar to other common recyclable trash like plastics, glass, cables, etc. and is typically disposed of informally. Once precious metals like copper, aluminum, gold, silver, etc. have been extracted from the leftover e-waste, it is either burned in an incinerator, disposed of in a landfill, or dumped outside [2, 4].

3.3 Material Recovery from E-waste

The conventional e-waste recycling process includes manual segregation, mechanical separation, plastic recycling, and transportation of nonferrous materials to metallurgical treatment plants for constituent metal separation [26].

The mechanical separation is the initial step in recovering material by employing hammers, screwdrivers, pincers, and other equipment to disassemble, dismantle, de-soldering, and crush e-waste. Manual dismantling often separates reusable e-waste components, directs material recovery, and separates hazardous material and valuable materials like PCBs, casing, monitors, and batteries [6, 26, 27].

Magnetic separation, eddy current separation, and electrostatic separation all separate metallic and non-metal components, as well as ferrous and nonferrous material, from crushed e-waste and PCBs. Other separation techniques that are often used include gravity separation, air separation, jigging, and froth floatation [7, 28, 29].

Valuable metals can be recovered from e-waste as it is important for environmental and resource protection, specifically from PCBs via pyro-metallurgy, hydrometallurgy, and bio-metallurgy. Figure 4 shows a flow chart for material recovery from E-waste.

Pyro-metallurgy is a metal purification and extraction technology that uses high temperatures. The refining, smelting, combustion, roasting, sintering, combustion, and incineration are all examples of pyro-metallurgy. At higher temperatures, organic parts such as paper, wood, and rubber decompose; the volatile compounds generated can be used as chemical products. Poor operations can release hazardous substances into the environment, such as dioxin production from low-temperature incineration of brominated flame retardants [6, 26, 30].

Hydrometallurgy is the extraction of metals from concentrated mixtures or mixtures of PCBs using aqueous solutions such as inorganic acid, organic acid, cyanide, thiourea, thiosulfate, chelating agents, chlorinating agents, and so on. This is the method used by the vast majority of formal recycling operations in India. It is advantageous because there is a reduced risk of harmful and dust emissions, good metal separation, and minimal residue left over [26, 28, 31].

Another technology that has gained attention these days, is plasma technology, bio-metallurgical technology, supercritical fluid extraction technology, and vacuum metallurgical technology. These are environmentally friendly technologies shows promise, but much work is still required before they can be practical [29, 32, 33].

In India, the most common e-waste disposal methods are open dumping, landfilling, and burning. There is also some research available on emerging technology for converting waste to energy. For example, pyrolysis for energy generation, plasma

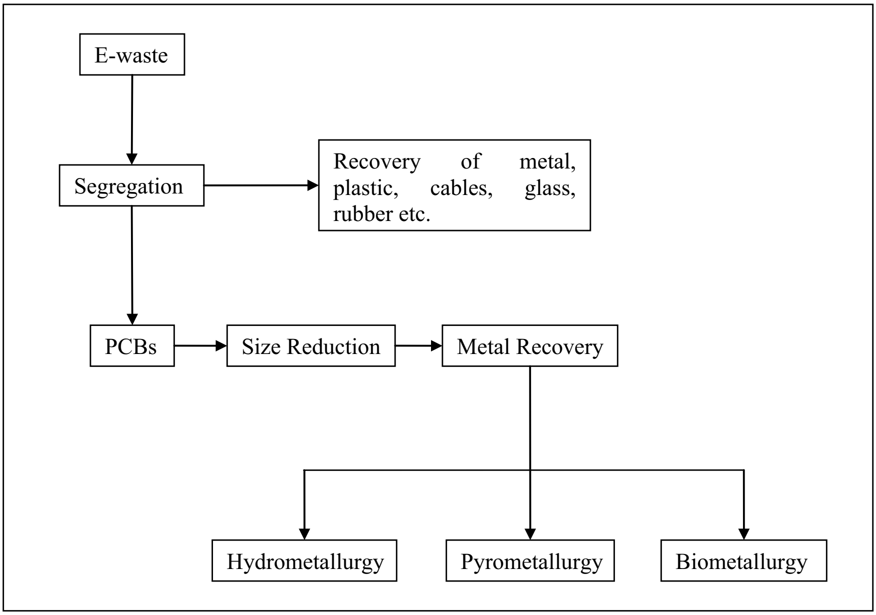

Fig. 4 Material recovery from e-waste

treatment for material recovery, hydrothermal treatment for the conversion of e-waste residual plastics into organic products, and so on [11, 28].

3.4 Challenges in India

- Informal hubs engagement and the collection and resale of e-waste informally.
- Mixing of e-waste with other solid waste at the household level.
- Dumping, landfilling, and incineration are the main methods for waste disposal.
- Lack of environmentally sound e-waste treatment (poor recycling and recovery process).
- Infrastructure for collection, transportation, treatment, recycling, and disposal is lacking, as well as formal treatment facilities.
- Unsafe treatment practices of e-waste.
- High cost for extraction of metals.
- There is a lack of coordination among various relevant authorities, stakeholders, formal channels, collectors, dismantlers, and recyclers.
- Lack of reliable parameters, non-identification of bulk consumers, unreliable data on e-waste, and inefficient audit procedures.

- Absence of strict government regulations and centralized administration with no integrated or coordinated efforts from municipal corporations and related departments.
- Lack of awareness and market information.
- Allowing import or export of hazardous waste for the purpose of recycling, recovery, and reuse process.
- Biased opinion toward selected and attractive item acceptance by recyclers.
- Poor reporting system and absence of financing for monitoring and control.

4 Potential for a Circular Economy

The circular economy is a concept that promotes the circulation of functional elements or components along with financial circuits to reduce the consumption of finite resources, optimization of resource usage, recover materials from products at the end of use, and provide closed-loop resource management by providing alternative resource raw materials in supply chains. It also enables cleaner production management, smaller material footprints, lessen the environmental burdens utilizing the 3R (reuse, recycle, and recover) concept, depending on the hierarchy level of the material in terms of economic value, thereby facilitating the circular economy [3, 34, 35].

Because of the high concentration of precious metals embedded within, printed circuit boards (PCBs) are the most valuable component of e-waste with more than 10 times the purity of mineral ores. They generate approximately 40% of the revenue generated by recycling metals in e-waste. That's why metal recovery from waste PCB is considered as "Urban Mining" [33, 35].

One tonne of e-waste has an economic potential of 500 USD to 92.9 thousand USD. The 44.7 Mt of e-waste generated in 2016 had a potential worth of 60 billion USD [35, 36]. As per the Global E-waste Monitor 2020 report, approximately $57 billion USD is the estimated value of raw materials in the global e-waste generated in 2019. With the current recycling rate of 17.4%, a raw material value of $10 billion USD is recovered in an environmentally sound way from e-waste globally, and 4 Mt of raw material could be made available for recycling [13].

The production of EEE requires various metals, including gold, silver, copper, iron, etc. For instance, it seems unclear that the mining of currently virgin minerals will be able to meet the 275–300% growth in copper demand predicted for 2050 [37]. There were 300 tonnes of gold in the global e-waste, in 2014 with a worth of 10.4 billion euro. As in the case of a million mobile phones, 9000 kg copper, 24 kg gold, 250 kg silver, and 9 kg palladium would be produced [36].

The recycling sector employs more than 1.5 million people, processes more than 500 Mt of waste annually, and generated 160 billion USD in revenue in 2019 [1]. Waste plastics are an unexploited resource for recovering valuable polymers, including polycarbonates (cost between 2.50 and 5.00 USD/kg) among many others.

In 2010, there was about 3.4 Mt of demand for waste plastics, with a 6% annual increasing rate [14].

The resale price of processed e-waste at the facility is 0.013–0.26 USD/kg for Cathode Ray Tube (CRT) glass, 0.18–0.29 USD/kg for metallic scrap components, 0.91–1.04 USD/kg for aluminum parts, and 0.100–0.13 USD/kg for shredded plastics. However, the business reports about 25–30% of the marginal profit [38].

5 Health Impact of E-waste

Although e-waste comprises over 60% useful resources; it also contains over 1000 different toxic and hazardous compounds [9]. These mixes of various substances, which include chemicals found in EEE components and chemicals produced during e-waste treatment and disposal, may constitute a substantial hazard to the environment. For example, in the United States, landfills were found to contain roughly 70% Hg and Cd and 40% Pb from consumer electronics [39]. Furthermore, because these compounds persist in the environment and have a high potential for accumulation in human and animal tissue, there may be damaging effects on human safety [16]. Table 2 shows the impact on human health and environmental damage caused by various components of e-waste.

5.1 Impact Due to Hazardous Components Generated from E-waste

5.2 Source of Toxins

These substances reach the environment through a variety of pathways. Uncontrolled e-waste disposal results in excessive metal concentrations being released into the surrounding air, dust, soils, sediments, and plants [41]. The source of these components is shown below in Table 3.

6 Conclusion

The purpose of this article was to alert people to the problem and raise their awareness about e-waste. Every year, thousands of tonnes of e-waste are dumped, and the problem worsens. E-waste is a relatively new and rapidly growing waste segment worldwide. In India, this growing problem is largely ignored or misunderstood. Since it covers all kinds of electrical and electronic devices, from smartphones to big-screen

Table 2 Impact of E-waste on the environment and human health, Ref. [11, 24, 36, 39, 40]

No.	Component	Human health impacts	Environment damage
1	Lead	Can damage children's brain development, neurobehavioral development and cause intellectual impairment, can damage the central and peripheral nervous systems, kidney, blood, and reproductive systems, chronic neurotoxicity, appetite loss, abdominal pain, constipation, fatigue, sleeplessness, irritability, and headache, leads to death	Cause air and water pollution with the release crushing of powder and fumes and toxic leachates
2	Mercury	Can damage the brain, central nervous system, neurobehavioral development of children (methylmercury), anemia, kidney damage, cause muscle tumors, mental retardation, and skin diseases	Cause air and water pollution
3	Cadmium	Highly toxic, neurotoxin, carcinogenic, and affecting the kidneys, respiratory systems, possibly reproductive damage and lung emphysema, itai-itai syndrome and severe pain in joints and spine, can be DNA damage	Cause surface and ground water, bioaccumulation in the environment, air pollution
4	Chromium or hexavalent chromium compounds	Damage to DNA, Carcinogenic, impacts neonates, reproductive and endocrine functions, liver, kidney, including asthma, bronchitis, and lung cancer, leads to death, irritating to eyes, skin, and mucous membranes	Cause groundwater pollution and higher levels of concentration deteriorate the soil quality
5	Nickel	Increased risk of lung cancer, nose cancer, cardiovascular disease, neurological deficits, developmental deficits in childhood, and high blood pressure	–
6	PVC	Incineration of PVC produces chlorinated dioxins and furans, which are highly persistent in the environment and toxic even in very low concentrations. It is carcinogenic and can damage the immune system, hormone system, and reproductive system, cause pulmonary dysfunction	Leach into landfills cause water and land pollution, pollute water bodies form methylated mercury and lead to bio-magnification
7	POPs including brominated flame retardants (penta-, octa-, deca-BDE)	Neurotoxicity, long-term exposure can lead to impaired learning and memory functions, interfere with thyroid and estrogen hormone systems, exposure in the womb has been linked to behavioral problems	Bioaccumulation in the environment (very resistant to breakdown)

(continued)

Table 2 (continued)

No.	Component	Human health impacts	Environment damage
8	Beryllium	Affect organs such as the liver, kidneys, heart, nervous system, and lymphatic system, may develop beryllium sensitization or chronic beryllium disease and skin disease, allergic reactions	–
9	Zinc	Increased risk of copper deficiency (anemia, neurological abnormalities)	–
10	Lithium	Can cause nausea, diarrhea, dizziness, muscle weakness, fatigue, and a dazed feeling	–
11	Antimony	Carcinogenic potential, irritation of eye, skin and lungs, stomach pain, diarrhea	Cause air and water pollution with the release crushing of powder and fumes and toxic leachates
12	Arsenic	Affects digestive tract, lung cancer, skin cancer, suppressed immune system, liver, nervous and reproductive system damage, allergic reaction	Toxic chemical exposures lead to air pollution and hazards from fire
13	Barium	Can cause liver, cardiac, or spleen damage, low or elevated blood potassium, cardiac arrhythmias, respiratory failure, gastrointestinal dysfunction, paralysis, muscle twitching and weakness, stomach irritation	Cause potential damage to aquatic animals and plants also high levels cause soil pollution
14	Gallium	Throat irritation, breathing problems, pain on chest	Clear evidence of carcinogenesis in experimental animals
15	Flame retardant	Retarded mental growth in children, anemia, renal toxicity and insomnia, chronic brain damage, respiratory and skin diseases	Cause air and water pollution with the release crushing of powder and fumes and toxic leachates
16	Chlorofluoro carbon (CFC)	Increased incidence of skin cancer and/or genetic damages	Deleterious effect on the ozone layer
17	Polychlorinated biphenyls	Cancer, effects on the immune systems, reproductive system, nervous system, endocrine system, and other health effect	–

Table 3 Source of hazardous component from e-waste [17, 24, 36, 40]

No.	Component	Source
1	Lead	CRTs (4–22% of Pb), television sets, batteries, PCBs, lamps, computer monitors, PCBs, batteries
2	Mercury	Lighting devices for flat screen displays (LCD), PCBs, thermostats, sensors, cathode fluorescent lamps (1–2 g per device), relays, alkaline batteries
3	Cadmium	Rechargeable and Ni–Cd batteries, switches, older CRTs, PCBs, infrared detectors, semi-conductor chips, ink or toner of photocopying machines, mobile phones, toys, and plastics
4	Chromium or hexavalent chromium compounds	Production of metal housings as corrosion-resistant coatings used for coating electro-galvanized steels and individual components (screws, rivets, switches, plugs, antenna, and other accessories), data tapes, floppy disks
5	Nickel	Ni–Cd batteries, electron guns in CRTs
6	PVC	For insulation on wires and cables, computer housings, switches, relays, older transformers, capacitors, fluorescent lighting fixtures, electrical devices
7	POPs include brominated flame retardants (penta-, octa-, deca-BDE)	Used in circuit boards (fire retardants for electronic equipment), plastic casings of computers, cables, as dielectric fluids in capacitors and transformers, lubricants and coolants in generators, fluorescent lighting, ceiling fans, dishwashers, electric motors, components such as connectors and mobile phones
8	Beryllium	Used with copper and nickel to produce electrical contacts, gyroscopes, spot-welding electrodes, springs, non-sparking tools, gears and cogs in aviation industry, power supply boxes, computers, X-ray machines, ceramic components of electronics, PCBs
9	Zinc	CRTs, metal coatings, batteries
10	Lithium	Li-batteries
11	Antimony	Batteries, semiconductors, PCB’s and CRT, flame retardants in plastics
12	Arsenic	Integrated circuit, semi-conductors, gallium arsenide in light emitting diodes (LED), microwaves, solar cells, doping agent in transistors, PCBs
13	Barium	CRTs (2–9% Ba), fluorescent lamps, ceramics, automobile, electronic tubes and glass, plastics fillers, lubricant additives
14	Gallium	Semiconductors, PCBs
15	Flame retardant	Fluorescent lamp, PCBs, and CRT LCDs
16	Chlorofluoro carbon (CFC)	Cooling units, insulation foams
17	Polychlorinated biphenyls	Condensers, transformers

televisions, the rapid growth of e-waste is having a negative impact on both the environment and humanity. The formal sector in India faces several challenges when it comes to managing e-waste. Most states currently lack regular mechanisms for monitoring e-waste generation and subsequent activities because it varies due to its availability in various forms, making it difficult to plan and implement management strategies. Electronic and electrical equipment are made up of over 1000 different components. If heavy metals from e-waste are exposed, they can cause significant harm to the environment and human health. Antimony, arsenic, barium, cadmium, chromium, lead, mercury, nickel, and other heavy metals cause significant and life-threatening diseases in humans and pollute water and air. Only 17% of global e-waste is formally collected and recycled, indicating insufficient e-waste management, rules, and regulations. In India, the informal sector is particularly powerful in terms of e-waste collection and recycling. Because informal recycling does not include any health or environmental precautions, it is less expensive than formal recycling. Additionally, the informal sector promises more labor and skilled jobs for poor and middle-class families. Based on the critical review in various aspects, future suggestions for India are that without disrupting the powerful informal cycle, new regulations and policies should be enacted in India, with various schemes providing opportunities to safeguard the environment and human health, improve the formal sector of e-waste disposal, and raise awareness among consumers of electronic appliances about e-waste disposal. The concept of "urban mining" is gaining popularity since e-waste contains precious and valuable materials worth millions of dollars. However, there is no research on the entire circular economic chain of formal recycling and the recovery of precious and valuable materials. Today, eco-friendly and sustainable material recovery technologies must be implemented.

7 Research Gap

Traditional methods for recycling e-waste, like pyro-metallurgical and hydrometallurgical processes, have undergone significant advancements; nevertheless, more work needs to be done to make it practical to use these processes on an industrial scale while minimizing environmental impact. A deeper understanding is required to understand the mechanism of e-waste metal recovery and the viability of engineering applications within the context of the circular economy. Focus should be placed on electrochemical, bio-metallurgical, and supercritical fluid extraction techniques due to their superior environmental performances compared to the current industrial recycling approaches.

The majority of research on a greener and more sustainable metal recovery technique is done in laboratories. In addition, studies are needed to develop a full, closed-loop, scientific metal recovery system that should be used to increase the yield and rate of metal recovery from mixed metal solutions that contain even low concentrations. To investigate the potential for industrial implementation of these techniques, particularly in developing countries, more research is needed.

Economic concerns are the main reason that the extraction of precious metals from particular and individual electronic components like capacitors, integrated circuits, and central processing units is becoming more and more important. However, it is necessary to determine the project's overall economic viability. Therefore, researching the cost-effective sequential recycling of all components on an industrial scale is crucial, aiming to minimize the environmental impact.

The utilization of non-metallic fractions as a reinforcement in composites eliminates the need for coke, a potential fuel source or chemical feedstock. However, more research on characterization of non-metal values for determining toxic content is required in order to selectively and directly convert PCB resources into value-added products in metals, composites, carbon-based products, and catalysts.

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