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Indian Electronic Waste Management and Policy Development: A Review

Aftab Khan[1] and Aruna Sudame[2]*

[1]Department of Biochemistry, Faculty of Biological and Health Sciences, Hazara University Mansehra, Dhodial, Mansehra, Khyber Pakhtunkhwa 21120, Pakistan.
[2]G H Raisoni University, Amravati, India and Assistant Professor, G H Raisoni College of Engineering, Nagpur, India.

ABSTRACT
Rapid technological advancement, rising consumer demand, an increased dependence on electrical and electronic equipment, and shorter product life cycles have resulted in electronic waste or e-waste being one of the fastest-growing waste streams globally. E-waste is a valuable source of secondary processed materials. These materials include copper, gold, palladium, silver, aluminum, and rare earth elements, which are contained in discarded devices such as televisions, computers, refrigerators, mobile phones, and other electrical devices. However, e-waste also includes toxic metals such as lead, mercury, cadmium, chromium, and beryllium, and organics such as brominated flame retardants, dioxins, and furans that could create serious hazards to the environment and the health of humans when not properly handled. In India, illegal and unmonitored recycling industries often use open burning, manual dismantling, and acid leaching methods. This has led to contamination of water, soil, and air, and exposes workers and adjoining communities to toxic pollutants. Managing e-waste effectively under these scenarios requires stronger collection systems, formal recycling infrastructure, and extended producer responsibility. In addition, public awareness, occupational safety measures, and circular economy approaches are also needed. It is essential to address e-waste for the sake of the environment, public health, and sustainable development using sustainable e-waste recycling with the target of reducing pollution, saving natural resources, recovering valuable metals, and providing safer livelihoods.

KEYWORDS: E-waste; informal recycling; occupational health; circular economy; environmental pollution
SDG Keywords: SDG 11: Sustainable Cities and Communities; SDG 12: Responsible Consumption and Production; SDG 13: Climate Action

INTRODUCTION

Electronic waste (e-waste) has become one of the fastest-growing waste streams across the world and is now considered a serious environmental issue in the twenty-first century. The rapid development of information technology (IT) has improved communication, education, healthcare services, business activities, as well as entertainment. IT uses in consumer electronics, telecommunication systems, and household electrical appliances have greatly changed modern lifestyles, and at the same time, IT also generates increasing amounts of waste electrical and electronic equipment (WEEE), which creates serious environmental and public health problems (Ravindra & Mor, 2019; Ren et al., 2009; Robinson, 2009; Santos et al., 2019; Wang et al., 2014; Widmer et al., 2005). Products such as mobile phones, laptop computers, televisions, refrigerators, air conditioners, and many other electronic devices are major outputs in the electronics manufacturing industry. These products are among the fastest-expanding industrial sectors globally because of continuous technological innovations and increasing consumer demands. They are often replaced regularly due to peer pressure or technological requirements even though they are still functioning properly. Other reasons include shorter technology cycles, aggressive advertising, and the declining habit of repairing electronic products. These phenomena have encouraged consumers to replace their devices more frequently, and repairing them is a thing of the past. These habits have resulted in millions of obsolete electronic products are being discarded every year. This has caused the amount of e-waste to increase rapidly (Bhagat-Ganguly, 2021), placing additional pressure on waste management systems. This issue is pressing especially in developing countries where recycling infrastructures are still limited.

E-waste contains a much more complicated mixture of useful and hazardous materials when compared with ordinary municipal solid waste. It is known that discarded electronic products are valuable due to the precious and base metal contents such as copper, gold, silver, palladium, and platinum. These metals can be recovered and reused. Unfortunately, these devices also contain toxic substances, including metals such as lead, mercury, cadmium, and chromium, and organics like brominated flame retardants and persistent organic pollutants. Indiscriminate dumping and illegal recycling methods of electronic waste result in toxic substances being released into the environment, causing the pollution of soil, surface water, groundwater, and even the atmosphere. This pollution eventually threatens the ecosystems and human health (Awasthi et al., 2016; Forti et al., 2020). The management of e-waste has therefore become more challenging over the past few decades. The amount of e-waste generated are increasing much faster than the available facilities for proper

collection, recycling, treatment, and final disposal. Although many countries have introduced regulations based on extended producer responsibility (EPR) together with circular economy principles, significant quantities of e-waste are still processed by informal recycling sectors where environmental protection and workers' safety are often inadequate (Chaudhary & Vrat, 2019; Dwivedy et al., 2015). Because of this, e-waste management is no longer regarded as only a local waste disposal problem. Instead, it has become an important global sustainability issue that requires cooperation among governments, industries, researchers, policy makers, and the general public.

Recent global reports further indicate that e-waste generation continues to rise at a faster rate than most other waste streams worldwide. The acceleration of this problem in the coming years is likely due to factors such as rapid digitalization and urbanization. Other reasons include the increase in living standards, population growth, and shorter product life cycles. Methods to mitigate this include improving collection systems, the development of sustainable recycling technologies, and the enhancement of resource recovery. Aside from this, an important mitigation factor is the implementation of environmentally responsible policies. These efforts are becoming increasingly important and will likely result in the reduction of the environmental impacts associated with e-waste. In addition, these efforts will maximize the recovery of valuable secondary raw materials, contributing towards a more sustainable and circular economy (Bhagat-Ganguly, 2021; Forti et al., 2020).

What Is E-Waste?

The term electronic waste (e-waste), sometimes called electronic scrap (e-scrap) or Waste Electrical and Electronic Equipment (WEEE), refers to electrical and electronic products that have reached the end of their useful life or have become obsolete. These include a wide variety of equipment such as computers, printers, televisions, mobile phones, refrigerators, washing machines, air conditioners, medical devices, lighting equipment, and many other consumer electronic products. In some cases, the term also covers used electronic equipment that is collected for reuse, refurbishment, resale, recycling, material recovery, or final disposal (Cui & Forssberg, 2003).

In many developing countries, including India, the simpler term "e-waste" is more commonly used, although within the European Union, this waste stream is officially known as Waste Electrical and Electronic Equipment (WEEE). However, WEEE is widely regarded as one of the most complicated waste streams. This is because electronic products are manufactured from hundreds of different materials and components using various production technologies. This diversity of product designs makes recycling and waste management much more difficult. Therefore, proper characterization of e-waste is important for developing efficient, environmentally sustainable, and economically feasible recycling systems (Cui & Forssberg, 2003).

E-waste is composed of a highly heterogeneous mixture of valuable resources together with hazardous materials. Generally, metals contribute about 60% of the total weight, while plastics account for nearly 30%, and the remaining fraction consists of glass, ceramics, and hazardous substances. Valuable metals recovered from electronic products include copper, aluminum, iron, nickel, tin, gold, silver, palladium, platinum, as well as rare earth elements. At the same time, electronic devices also contain toxic substances such as lead, mercury, cadmium, arsenic, chromium, brominated flame retardants, sulfur compounds, and phosphorus-containing materials. The hazardous chemicals can be released into the environment and may contaminate soil, water, and air, causing adverse effects on ecosystems and public health if these wastes are not managed properly (Awasthi et al., 2018; Forti et al., 2020).

Many researchers now consider e-waste as an important "urban mine because of its rich composition of valuable metals. In many cases, discarded electronic products contain higher concentrations of precious and strategic metals than natural mineral ores. Thus, the process of recovering these valuable materials through proper recycling not only reduces environmental pollution but also conserves natural resources. This process supports the development of a circular economy and decreases dependence on primary mining activities. These benefits make sustainable e-waste management increasingly important for both environmental protection and resource security (Chaudhary & Vrat, 2019).

Global Generation of E-Waste

During the last two decades, the rapid increase in technology has generated more waste yearly. Earlier global estimates reported that approximately 41.8 million metric tonnes (Mt) of e-waste were produced in 2014, with Asia contributing the largest share of nearly 16 Mt. Europe recorded the highest per-capita generation rate of around 15.6 kg per person, whereas Africa generated the lowest amount at approximately 1.7 kg per capita (Baldé et al., 2015). Since then, global e-waste generation is expected to continue to increase because of rapid technological advancement, population growth, rising incomes, shorter product life cycles, and increasing consumption of electronic devices. These trends place greater pressure on the collection, recycling, and disposal systems throughout both developed and developing countries (Matsukami et al., 2015; Ren et al., 2009; Widmer et al., 2005; Xue et al., 2026).

Recent global assessment exercises have shown that the e-waste problem has continued to become more serious over the years, with a worldwide generation of e-waste increasing from approximately 53.6 million metric tonnes (Mt) in 2019 to more than 62 Mt by 2022. This makes it the fastest-growing domestic waste stream globally. The global e-waste generation is projected to exceed 80 Mt by 2030 if the current patterns of electronic consumption and disposal continue (Forti et al., 2020). It has been documented that only a relatively small percentage are formally collected and recycled through regulated management systems, although the amount of discarded electronic products keeps increasing every year.

A considerable amount remains undocumented, enters informal recycling sectors, is transported across international borders, or is disposed of together with ordinary municipal solid waste. These practices reduce resource recovery while increasing the risk of environmental pollution and human exposure to hazardous substances. The diversity in the composition of e-waste generated worldwide exists and consists of large household appliances, cooling and freezing equipment, televisions, and computer monitors. Other devices include information technology devices, lighting equipment, and many categories of consumer electronics. Modern electronic products are becoming increasingly sophisticated, containing larger numbers of components and different materials than before. This increasing complexity makes collection, dismantling, separation, recycling, and pollution control much more difficult. In addition, insufficient information regarding illegal transboundary movement and informal recycling activities makes it difficult to

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accurately estimate global e-waste generation, material flows, and the associated environmental impacts (Forti et al., 2020).

Indian Scenario

India have emerged as one of the world's largest producers as well as consumers of electrical and electronic equipment. Rapid urbanization, expansion of the information technology sector, rising disposable incomes, and greater accessibility of electronic products have contributed significantly to the increasing amount of e-waste generated throughout the country. Since the economic liberalization policies introduced during the early 1990s, India's electronics manufacturing and software industries have expanded considerably. This growth has stimulated greater production, importation, and consumption of electrical and electronic equipment, resulting in a continuous increase in discarded electronic products (Dwivedy et al., 2015). Earlier reports illustrate the rapid expansion of the problem, with an estimate that India's e-waste generation increased from approximately 146,180 tonnes in 2005 to over 800,000 tonnes by 2012. A subsequent global study shows that India generated approximately 1.7 Mt of e-waste in 2014. This places India among the leading e-waste-producing nations in Asia (Baldé et al., 2015).

Based on more recent reports, India is also currently the third-largest generator of e-waste globally. The first and second are China and the United States, respectively (Bhagat-Ganguly, 2021; Forti et al., 2020). In India, the current recycling sector still processes only a relatively small proportion of the total e-waste generated. The remaining waste continues to be handled through informal recycling activities that often lack adequate environmental and occupational safety measures. In India, major metropolitan and industrial regions are the main contributors of E-waste since these areas are regions of economic development and electronic consumption is highest. More than 60% of the country's total e-waste generation is contributed by around 65 cities. In addition, nearly 70% of the national e-waste originates from only ten states such as Maharashtra, Tamil Nadu, Karnataka, Uttar Pradesh, Andhra Pradesh, West Bengal, Gujarat, Delhi, Madhya Pradesh, and Punjab.

The dense population, expanding industries, increasing purchasing power, and widespread use of electrical and electronic products of large cities have become important e-waste hotspots. These cities include Mumbai, Delhi, Bengaluru, Chennai, Kolkata, Hyderabad, Ahmedabad, Pune, Surat, and Nagpur (Chaudhary & Vrat, 2019; Dwivedy et al., 2015; Dwivedy & Mittal, 2012). As urbanization continues to increase, the quantity of obsolete electronic equipment generated in these cities is also expected to rise further.

In India, a large proportion of the country's e-waste continues to be managed by the informal recycling sector, although India has introduced the E-Waste Management Rules together with the Extended Producer Responsibility (EPR) framework. Artisanal recyclers use simple and inexpensive methods such as manual dismantling, open burning of cables and plastics, and acid leaching to recover valuable metals. These techniques are often performed without proper pollution control equipment or adequate protection for workers, and consequently, hazardous substances and persistent organic pollutants are released into the surrounding environment. This has led to the contamination of soil, water, and air. In addition, workers and nearby communities are exposed to serious health risks (Awasthi et al., 2016; Bhagat-Ganguly, 2021; Borthakur, 2023; Borthakur & Govind, 2017; Chaudhary & Vrat, 2019; Dwivedy et al., 2015; Dwivedy & Mittal, 2012). The economic benefits obtained from informal recycling therefore come at considerable environmental and social costs. Another big challenge India faces is the lack of comprehensive and reliable information on e-waste generation, collection rates, recycling efficiency, and activities of the informal sector. Inaccurate reporting and insufficient monitoring have made effective planning and policy implementation more difficult. National-level mitigation processes include strengthening the formal recycling infrastructure, expanding collection facilities, improving public awareness regarding proper disposal, and finally, integrating informal recyclers into regulated recycling systems. It is anticipated that such efforts would reduce environmental pollution and improve the recovery of valuable metals. In addition, this will accelerate the country's transition towards a more sustainable circular economy and create safer employment opportunities.

E-Waste Issues

E-waste was once mainly a local waste management concern. However, the remarkable growth in the production and consumption of electronic products has transformed E-waste into a complex global environmental, economic, and public health issue. Studies have revealed many weaknesses within existing waste management systems around the world, including poor collection systems, insufficient recycling capacities, and unavailability of environmentally sound disposal methods. These have resulted in large quantities of e-waste not being properly handled every year, which reduces resource recovery while increasing environmental contamination.

Local and international assessments have identified several major challenges associated with e-waste generation, collection, transportation, recycling, treatment, and final disposal. These problems are especially severe in developing countries, where formal recycling facilities are limited and much of the e-waste is processed by informal recyclers using low-cost but environmentally unsafe methods. Weak regulatory enforcement, limited public awareness, insufficient investment, and inadequate monitoring have further complicated the management of this rapidly growing waste stream. Hence, addressing e-waste issues involves not only technological improvements but also effective legislation, stronger policies, greater industry responsibility, increased public participation, and close cooperation among governments, industries, researchers, and local communities (Grant et al., 2013; Heacock et al., 2016; Parvez et al., 2021; Perkins et al., 2014).

Increasing Amount of E-Waste

The amount of e-waste generated around the world has increased very rapidly over the last two decades, and this growth is mainly driven by continuous technological developments, shorter product life spans, frequent software updates, and changing consumer preferences. The number of electronic products entering the market is ever increasing due to the usage of smart devices, artificial intelligence (AI), and the Internet of Things (IoT). Consequently, if the present consumption patterns continue globally, e-waste generation is expected to increase from approximately 44.4 million tonnes in 2016 to more than 62 million tonnes in 2022, and it is expected to exceed 80 million tonnes by 2030 (Baldé et al., 2024; Forti et al., 2020).

Toxic Components

Common toxic materials found in electronic products include lead, mercury, cadmium, chromium, arsenic, and brominated flame retardants, making electronic waste not only a valuable source of recyclable materials but also containing many

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hazardous substances. In the event e-waste is inappropriately recycled using theough methods such as open burning, acid leaching, or manual dismantling, these harmful substances can be released into the environment and can threaten both the environment and human health. Studies have shown that long-term exposure, especially among workers involved in informal recycling activities, has been linked with respiratory diseases, neurological disorders, kidney damage, reproductive problems, and even cancer (Awasthi et al., 2018; Grant et al., 2013).

Inadequate Recycling Infrastructure

Many developing countries have inadequate facilities for the appropriate collection and recycling of E-waste, and due to this, a large proportion of discarded electronics are handled by artisanal recycling sectors. The methods used to recycle often lack legal and proper approaches, such as the lack of safety requirements, and often there is a lack of pollution control. This inadequacy often leads to a reduction in recycling efficiency and an increase in environmental pollution. Ways to mitigate these inadequacies include upgrading the formal recycling facilities and improving the collection systems. The gradual integration of the informal recyclers into one that is regulated is an important step for achieving sustainable E-waste management (Chaudhary & Vrat, 2019; Forti et al., 2020).

Environmental and Human Health Impacts

The improper handling and disposal of e-waste have led to environmental pollution globally. Improper disposal of e-waste in landfills, open burning, and acid processing are the major sources of contamination of soil, water, and air, leading to accumulation in the food chains over time. Workers and people, including children and older people living close to informal recycling sites, are particularly more vulnerable. This is because they may be exposed through breathing contaminated air, consuming contaminated food or water, and direct skin contact. Therefore, to reduce these impacts, we need better recycling technologies, stronger environmental regulations and policies, and greater public awareness (Grant et al., 2013; Robinson, 2009).

Occupational Health Impacts

Health risks of exposure to dioxins and furans

Polyvinyl chloride (PVC), chlorinated plastics, and brominated flame-retardant-containing materials in e-waste can contribute to the formation of persistent organic pollutants during uncontrolled burning, including polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). These pollutants may enter the body through inhalation, ingestion, and dermal absorption. Exposure to high levels of PCDD/PCDFs has been associated with chloracne, skin pigmentation changes, altered liver function, and long-term effects on the immune, nervous, endocrine, and reproductive systems (Grant et al., 2013; Perkins et al., 2014; Tsydenova & Bengtsson, 2011).

Dangers of lead exposure to health

Lead (Pb) is commonly found in cathode-ray tube glass, solder, printed circuit boards, and other electronic components. Acute high-level exposure may cause gastrointestinal distress, neurological symptoms, coma, and death, while chronic exposure can affect the blood, kidneys, brain, and nervous system. Children are especially vulnerable because lead exposure can impair intellectual development, behaviour, growth, and hearing. In pregnant women, lead can cross the placenta and may adversely affect fetal development; studies of e-waste-exposed populations have also reported associations with adverse birth outcomes such as miscarriage, stillbirth, premature birth, and reduced birth weight (Grant et al., 2013; Heacock et al., 2016; Perkins et al., 2014).

Health hazards of beryllium exposure

Beryllium is used in some electrical connectors, springs, contacts, and electronic components because of its strength, conductivity, and heat resistance. During dismantling, shredding, or other recycling operations, beryllium-containing dust may be released. Occupational exposure to beryllium dust is associated with chronic beryllium disease, a serious lung condition, and beryllium is also classified as a human carcinogen (International Agency for Research on Cancer, 2012; National Institute for Occupational Safety and Health, 2011; Tsydenova & Bengtsson, 2011).

Cadmium exposure health risks

Cadmium is present in some rechargeable batteries, semiconductors, chip resistors, plastics, solders, and older television components. Exposure may occur through inhalation of contaminated dust or fumes, ingestion of contaminated particles, or dermal contact. Cadmium exposure is associated with kidney damage, bone effects, respiratory toxicity, and cancer risk, making it an important occupational hazard in unsafe e-waste recycling environments (Grant et al., 2013; Perkins et al., 2014; Tsydenova & Bengtsson, 2011).

Mercury exposure health concerns

Mercury is used in some switches, relays, fluorescent lamps, flat-panel displays, batteries, and other electrical and electronic equipment. Mercury has no known beneficial biological function, and exposure may damage the nervous system, kidneys, liver, and developing fetus. Mercury exposure is of particular concern in informal recycling because breakage, burning, and unsafe handling of mercury-containing components can release toxic vapors and residues (Grant et al., 2013; Tsydenova & Bengtsson, 2011; World Health Organization, 2021).

Exposure to flame retardants and health risks

Polybrominated diphenyl ethers (PBDEs) are synthetic brominated flame retardants used in plastics, circuit boards, casings, wires, and electronic products such as televisions, computers, and mobile phones. PBDEs can be released during dismantling, heating, burning, and shredding of e-waste. Exposure to PBDEs has been associated with endocrine disruption, altered thyroid function, developmental effects, and increased cancer and non-cancer health risks among informal e-waste workers (Grant et al., 2013; Heacock et al., 2016; Ohajinwa et al., 2019).

The occupational health risks of informal e-waste recycling are not only theoretical but have significant real-world consequences. Improper e-waste disposal can cause accidental releases, chemical spills, toxic dust exposure, and emissions of harmful gases. Crude recovery methods, including open burning, manual dismantling, and acid leaching, are major contributors to e-waste pollution and occupational exposure. These practices remain common in informal recycling sectors despite repeated warnings about their health risks (Annamalai, 2015; Grant et al., 2013; Perkins et al., 2014; Tsydenova & Bengtsson, 2011). The consequences include environmental degradation, toxic exposure among workers and nearby communities, and possible release of genotoxic substances that may affect both current and future generations. Therefore, safe, regulated, and environmentally sound e-waste collection, disposal, and recycling systems are urgently needed (Baldé et al., 2017; Heacock et al., 2016; World Health Organization, 2021).

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CONCLUSION

This review paper discusses the generation and management of electronic waste in India. The paper also makes a comparison with trends observed in other countries. It covers the meaning of e-waste, its material composition, existing disposal methods, and hazardous substances that are normally found in end-of-life electronic goods, such as heavy metals and halogenated compounds. The improper handling, recycling and end-of-life treatment of e-waste can pose serious risks to the environment and human health. Mitigation challenges in India are caused by low public awareness about the safe disposal of electronic goods, weak regulations and enforcement, and poor policy implementation. There are no large-scale and well-organized e-waste recycling facilities, so the informal sector has become the main recycling channel, which recycles with unsafe and poorly controlled methods. These practices cause pollution of the environment and health hazards for the workers, and therefore an urgent need for a comprehensive assessment of current and future situations of e-waste is required. This includes waste characteristics, predicting future disposal practices, predicting the fate of environmental impacts, and future occupational hazards from emerging E-waste pollutants. There is a need to establish effective systems for collection, transportation, treatment, storage, recovery, recycling and final disposal of e-waste at national and regional levels to achieve environmentally sound and sustainable e-waste management.

CONFLICT OF INTERESTS

The authors have no competing financial interests or personal relationships to disclose.

ETHICS STATEMENT

Not applicable

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AUTHORS' CONTRIBUTIONS

Both A.K. and A.S. contributed to conceptualization, methodology, analysis, and writing of the original draft.

DATA AND MATERIALS AVAILABILITY

Data available upon request

AI STATEMENT

In preparing this work, the authors used generative AI technologies solely for language editing and refinement. All authors reviewed and revised the manuscript and accept full responsibility for the content of this publication.

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Abbreviations:

WEEE	Waste electrical and electronic equipment
PCDDs	Polychlorinated dibenzo-*p*-dioxins
PCDFs	Polychlorinated dibenzofurans
PVC	Polyvinyl chloride
PBDES	Polybrominated diphenyl ethers

**** Corresponding author.***

Assoc. Prof Dr Aruna Sudame
G H Raisoni University, Amravati, India and Assistant Professor, G H Raisoni College of Engineering, Nagpur, India
Email: aruna.sudame@raisoni.net

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