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Review

An Integrated Approach for Electronic Waste Management—Overview of Sources of Generation, Toxicological Effects, Assessment, Governance, and Mitigation Approaches

Abhishek Nandan [1,*], Albin C. Suresh [1], Parth Saole [1], S. Amulya Jeevanasai [1], Ramprasad Chandrasekaran [2], Lucas Meili [3], Nur Izyan Wan Azelee [4,5] and Rangabhashiyam Selvasembian [6,*]

[1] Sustainability Cluster, School of Advanced Engineering, UPES, Dehradun 248007, India; anandan@ddn.upes.ac.in or albincsuresh@gmail.com (A.C.S.); parth.saole@gmail.com (P.S.); amulyajeevana024@gmail.com (S.A.J.)
[2] School of Civil Engineering, Centre for Advanced Research in Environment (CARE), SASTRA Deemed to be University, Thanjavur 613401, India; ramprasad@civil.sastra.edu
[3] Laboratory of Processes, Center of Technology, Federal University of Alagoas, Maceió 57072-900, AL, Brazil; lucas.meili@ctec.ufal.br
[4] Institute of Bioproduct Development (IBD), Universiti Teknologi Malaysia, Johor Bahru 81310, Johor, Malaysia; nur.izyan@utm.my
[5] Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Johor, Malaysia
[6] Department of Environmental Science and Engineering, School of Engineering and Sciences, SRM University—AP, Amaravati 522240, India
* Correspondence: abhisheknandanhseddn@gmail.com (A.N.); rambhashiyam@gmail.com (R.S.)

Abstract: Electronic waste (e-waste) management has become a significant challenge in recent years due to the increasing consumption of electronic devices and their improper disposal. Effective e-waste management requires a comprehensive approach that considers the environmental, economic, and social impacts of e-waste. This comprehensive review provides a critical assessment of e-waste management procedures, encompassing the stages of collection, transportation, treatment, and disposal. Emphasising the significance of embracing sustainable approaches like reusing, repairing, and recycling, the review underscores their pivotal role in mitigating the adverse environmental and human health effects of e-waste. This review provides an overview of e-waste management concerns specifically in India from its collection to the end cycle including toxicological, environmental, and human impacts and a graphical analysis of current and future e-waste trends. It emphasises the need to effectively enforce regulations and establish extended producer responsibility (EPR) to promote sustainable e-waste management practices. Additionally, the review delves into the complexities surrounding e-waste management, such as insufficient infrastructure, resource and funding constraints, and a dearth of awareness among stakeholders. It strongly underscores the necessity for a concerted endeavour involving governments, industries, and communities to tackle these obstacles and advance the cause of efficient e-waste management practices. This paper is valuable to the scientific community as it offers a thorough assessment of e-waste management, focusing on environmental, economic, and social impacts. It emphasises sustainable practices and regulatory measures, providing actionable insights to address e-waste challenges. Overall, this review provides a comprehensive overview of e-waste management and highlights the importance of adopting sustainable practices to address the negative impacts of e-waste on the environment, human health, and the economy.

Keywords: electronic waste; occupational safety; e-waste toxicity; e-waste management; extended producer responsibility (EPR); sustainable e-waste management practices

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Citation: Nandan, A.; Suresh, A.C.; Saole, P.; Jeevanasai, S.A.; Chandrasekaran, R.; Meili, L.; Wan Azelee, N.I.; Selvasembian, R. An Integrated Approach for Electronic Waste Management—Overview of Sources of Generation, Toxicological Effects, Assessment, Governance, and Mitigation Approaches. *Sustainability* **2023**, *15*, 16946. https://doi.org/10.3390/su152416946

Academic Editor: Silvia Fiore

Received: 31 October 2023
Revised: 11 December 2023
Accepted: 12 December 2023
Published: 18 December 2023

1. Introduction

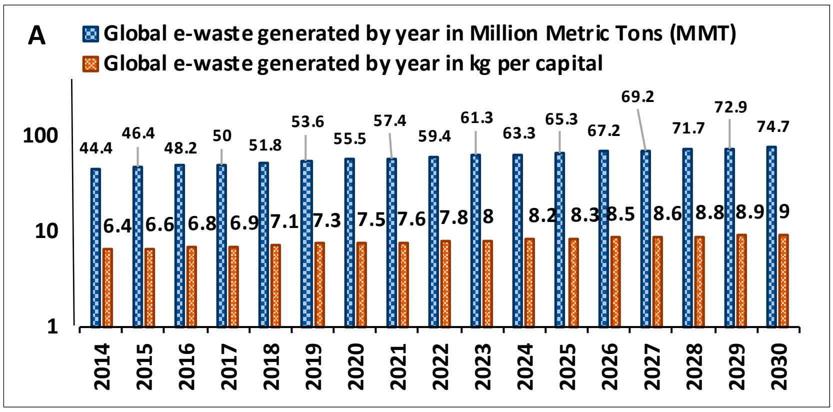
Electronic waste, often referred to as "e-waste", represents a substantial worldwide health and environmental peril. It encompasses electronic devices or equipment that have been discarded and are no longer needed or functional [1,2] or any electronic or electrical device that has reached its end of life, whether it is in good working order or not [3]. The generation of e-waste has increased due to the rapid growth of the electronics sector and ongoing technological advancements. Global e-waste production reached a surpassing record of 53.6 million metric tonnes in 2019, a 21% rise from 2014, and is expected to reach 74.6 million metric tonnes by 2030, according to a Global E-waste Monitor study in 2020 [4]. The improper handling and disposal of e-waste can lead to environmental pollution and serious health issues, including cancer, neurological disorders, and birth defects [5]. Therefore, the management of e-waste has become a crucial issue for governments, industries, and society. E-waste can originate from various sources, including households, businesses, and industries. Households are the primary source of e-waste, accounting for 53% of the total e-waste generated in the European Union (EU) [6]. The growing demand for electronic devices has led to an increase in e-waste generated by businesses and industries. A study by the United Nations University estimated that the generation of e-waste by businesses and industries worldwide reached 56.3 million metric tonnes in 2019, a 21% increase from 2014 [4]. The manufacturing industry is also a significant source of e-waste due to the frequent replacement of electronic equipment during upgrading of the production processes [7].

E-waste can be classified into several categories, including household appliances, IT and telecommunication equipment, and consumer electronics [8]. Household appliances, such as refrigerators, washing machines, and air conditioners, are the most significant contributors to e-waste in the EU, accounting for 49% of the total e-waste generated [6]. IT and telecommunication equipment, including computers, laptops, printers, and mobile phones, are also important contributors to e-waste. Misconduct of e-waste management can have serious negative effects on the environment and public health. Lead, cadmium, mercury, and bromine-containing flame retardants are just a few of the dangerous materials found in e-waste that can harm the environment and people's health [9,10]. These hazardous materials can pollute the air, water, and land when e-waste is improperly disposed of, causing ecological pollution and health risks like cancer, neurological illnesses, and issues related to human reproduction and growth [11]. Additionally, processing e-waste results in the production of greenhouse gases, which contribute to climate change. By 2025, it is anticipated that India, one of the nations in the world with the fastest economic growth, will produce more electronic trash than any other country [12]. India produced 3.2 million metric tonnes of e-waste in 2019, according to a report released by the Central Pollution Control Board (CPCB) of India with a growth rate of 21% each year [13]. However, according to the survey, only 10% of the entire amount of e-waste produced in the nation is recycled formally, with the remaining ninety percent ending up in incinerators, landfills, and unauthorised recycling centres. The inappropriate handling and disposal of e-waste can cause major health problems for neighbouring communities and workers as well as damage to the environment.

The E-waste (Management) Rules, 2016, which promote environmentally sound e-waste management and aim to increase the nation's recycling rate, have been implemented by the Indian government since 2016 as part of its efforts to address the e-waste issue. The lack of public awareness and insufficient infrastructure for proper handling and recycling of e-waste are just two of the many obstacles that still need to be overcome [12]. Recycling is becoming more and more recognised as a crucial strategy for managing e-waste. Recycling can lessen the negative environmental effects of electronic waste by recovering precious metals and components, such as copper, silver, and gold, which can be reused in the production of new electronic devices, according to a research study conducted by [14]. According to a study, recycling can greatly reduce energy use and emissions of greenhouse gases when compared to the manufacture of virgin materials. In 2018, approximately

50 million metric tonnes (Mt) of e-waste was accumulated all over the planet compared to 44.7 Mt in 2016, and the number is predicted to increase many folds in the coming years. In comparison with other continents, Asia ranked first in the generation of e-waste with an estimated amount of 18.2 Mt in 2016 [9].

In addition to recycling, refurbishing and repairing electronic devices can also play a significant role in reducing e-waste. The United Nations University (2017) estimated that extending the lifespan of mobile phones and laptops by one year could reduce the carbon footprint of the device by 30%. Moreover, refurbishing and repairing can provide economic benefits by creating job opportunities in the repair and refurbishment sector. Governments, industries, and society must work together to properly handle and manage e-waste. The implementation of proper regulations and policies can encourage the recycling and refurbishment of electronic devices and discourage the disposal of e-waste in landfills [15]. Education and awareness campaigns can also help to increase public awareness of the importance of proper e-waste management. Figure 1A provides data outlining the global e-waste generated annually in million metric tonnes (MMT) and the corresponding e-waste generated per capita in kilograms [16,17]. Figure 1B shows the statistical data on global e-waste generation by year and continent in 2022, with Asia being the largest generator by generating 25.2 MMT of e-waste



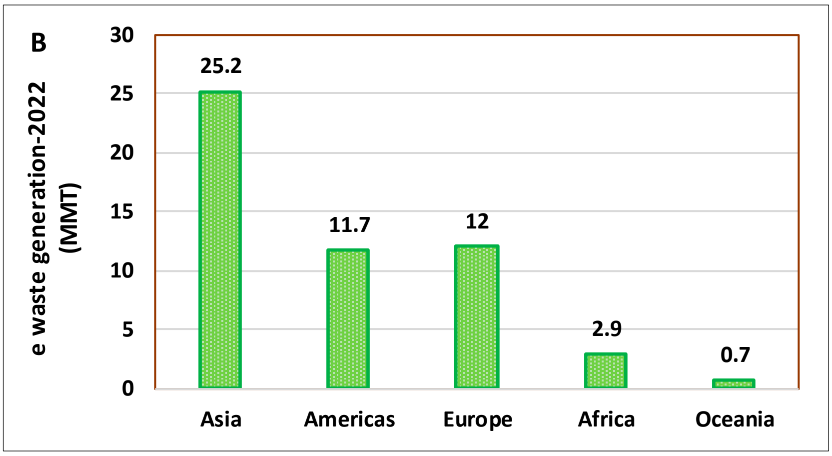


Figure 1. (**A**) Global e-waste generated by year in million metric tonnes and global e-waste generated by year in kg per capita. (**B**) Continent-wise e-waste generated—2019.

Figure 2 provides an overview of the significant e-waste generation in China (16.4 MMT), followed by the United States (12.9 MMT) and India (5.3 MMT), with other countries also contributing to the global e-waste volume.

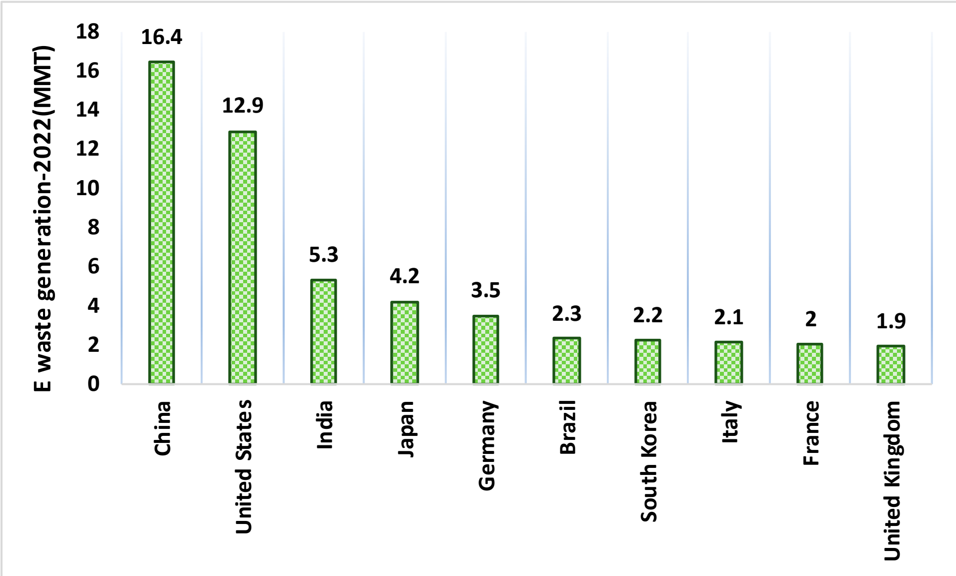


Figure 2. E-waste generation in 2022 by different countries.

1.1. Review Research Methodology

The research review methodology for "An Integrated Approach for Electronic Waste Management" involves a comprehensive and systematic exploration of the literature. The process begins with an extensive search across academic databases and journals, utilising keywords pertinent to electronic waste, toxicological effects, assessment, governance, and mitigation. Inclusion criteria are established to filter studies based on relevance, publication date, and the incorporation of key aspects. Subsequently, a meticulous data extraction process is undertaken, focusing on methodologies, key findings, and limitations. Quality assessment ensures the reliability of the selected studies. The synthesis of findings involves a comprehensive summary and the development of a conceptual framework that integrates components such as source generation, toxicological effects, assessment, governance, and mitigation approaches. The review concludes by identifying gaps in current knowledge, offering insights for future research directions and emphasising the significance of adopting an integrated perspective on electronic waste management.

1.2. Literature Review

Our planet is drowning in a sea of electronic waste, but a wave of innovative research is turning the tide. Table 1 shows use of e-waste, mentioning the field of their use and highlights. From efficient metal recovery methods [18] to creative e-waste art [19,20], scientists and artists are reimagining the lifecycle of discarded electronics. Studies are revealing the hidden treasures within e-waste, like valuable rare earth elements [21], while also cautioning about the environmental and health risks associated with improper recycling [17]. Could e-waste even become a source of energy? Research suggests it has the potential to fuel our future [22,23]. As we move towards a more sustainable future, e-waste is no longer just a problem; it's an opportunity. By embracing a circular economy approach [24] and developing effective management strategies, especially in developing nations [25,26], we can transform e-waste from a burden to a resource, ensuring a brighter future for both our planet and ourselves.

Table 1. Use of e-waste, mentioning the field of their use and highlights.

Study Title	Field of Use	Reference	Highlights
A novel hydrometallurgical-pyrometallurgical method for efficient recovery of valuable metals from electronic waste	Material Recycling	[18]	Introduces a novel method combining hydrometallurgical and pyrometallurgical approaches for efficient recovery of valuable metals from e-waste.
Rare earth elements in electronic waste: A global perspective and outlook	Electronics Manufacturing	[21]	Provides a comprehensive analysis of global rare earth elements in e-waste, discussing their distribution and recycling potential.
Life cycle assessment of e-waste reuse and recycling: A global analysis	Sustainability Assessment	[19]	Offers a comprehensive life cycle assessment comparing environmental impacts of e-waste reuse and recycling strategies.
E-waste art: Creative approaches for environmental sustainability	Art and Design	[20]	Explores creative use of e-waste in art, highlighting its potential for promoting environmental awareness through artistic expressions.
E-waste as a potential resource for electricity generation	Energy Generation	[22]	Investigates the feasibility of using e-waste as a fuel source for generating electricity.
A circular economy approach to e-waste management: A review	Material Recycling	[24]	Advocates for a circular economy approach in e-waste management, emphasising resource recovery and waste minimisation.
E-waste management in developing countries: Challenges and opportunities	Socioeconomic Impact	[25]	Analyses challenges and opportunities of e-waste management in developing nations, stressing the need for improved infrastructure and regulations.
Environmental impact of e-waste reuse and recycling	Sustainability Assessment	[26]	Conducts a global life cycle assessment comparing environmental impacts of e-waste reuse and recycling.
Health risks associated with exposure to toxic components in electronic waste	Environmental Health Assessment	[17]	Reviews health risks from exposure to toxic components in e-waste, advocating stricter regulations and awareness initiatives.
E-waste as a potential energy resource	Energy Generation	[23]	Assesses global potential of e-waste as an energy source for electricity generation.

2. Electronic Waste Toxicity

Electronic waste has become a global issue, with the amount of e-waste generation increasing exponentially due to rapidly advancing technology and inventions [27,28]. E-waste is composed of various materials, many of which contain toxic substances that can contaminate the environment and enter the food chain if not managed properly. E-waste recycling plants deal with numerous toxic chemicals, including heavy metals and persistent organic pollutants (POPs), which can contaminate the flora and fauna surrounding the plants and eventually reach the human body through the food cycle [28]. Table 2 summarizes the prime hazardous elements normally found in e-waste. Electronic waste (e-waste) includes its composition and components across various categories. The main components typically include ferrous and nonferrous metals, plastics, glass, pollutants, and other miscellaneous materials. Ferrous metals like iron and steel often constitute the largest fraction, followed by plastics and nonferrous metals like copper and aluminum [29]. Pollutants like lead, mercury, and brominated flame retardants are also present in varying amounts, requiring special handling and treatment. Additionally, e-waste can be categorized based on the type of product it originates from, such as large and small household appliances, information and communication technology equipment, consumer electronics, and electrical and electronic tools. This classification helps to determine appropriate recycling and processing methods for different e-waste streams [30].

It is crucial to implement and enforce proper electronic waste management. E-waste cannot be disposed of in landfills like other waste, as the toxicity present in the chemicals and heavy metals can accumulate in the ecosystem [29]. Incineration of e-waste can also generate hazardous fumes and gases which can damage the surrounding air [30]. Long-term metal leaching can occur when e-waste is disposed of in landfills, and the toxic chemicals from the e-waste can contaminate the surrounding soil and water bodies, causing damage to the flora and fauna of the ecosystem [29]. E-waste recycling plants also contribute to air pollution, as the process of refurbishing electronic equipment and recovering valuable materials through soldering and collective burning of plastic cable wires can create toxic chemicals such as dioxins emitted into the open air [31]. Open burning of plastics is a primitive method with zero safeguards to protect against toxic fumes. Acid baths of electronic equipment are another method used to recover valuable materials, and untreated acid waste is often dumped into rivers and land, resulting in high levels of pollution [32]. Figure 3A provides information about the components of e-waste [33]. Figure 3B outlines the quantities of various waste materials, including glass waste, metallic waste, specific metals like iron, copper, aluminium, zinc, and lead, as well as a category labeled as "Others". Together, they offer an understanding of the diverse components of electronic waste, including both non-metallic and metallic elements [34].

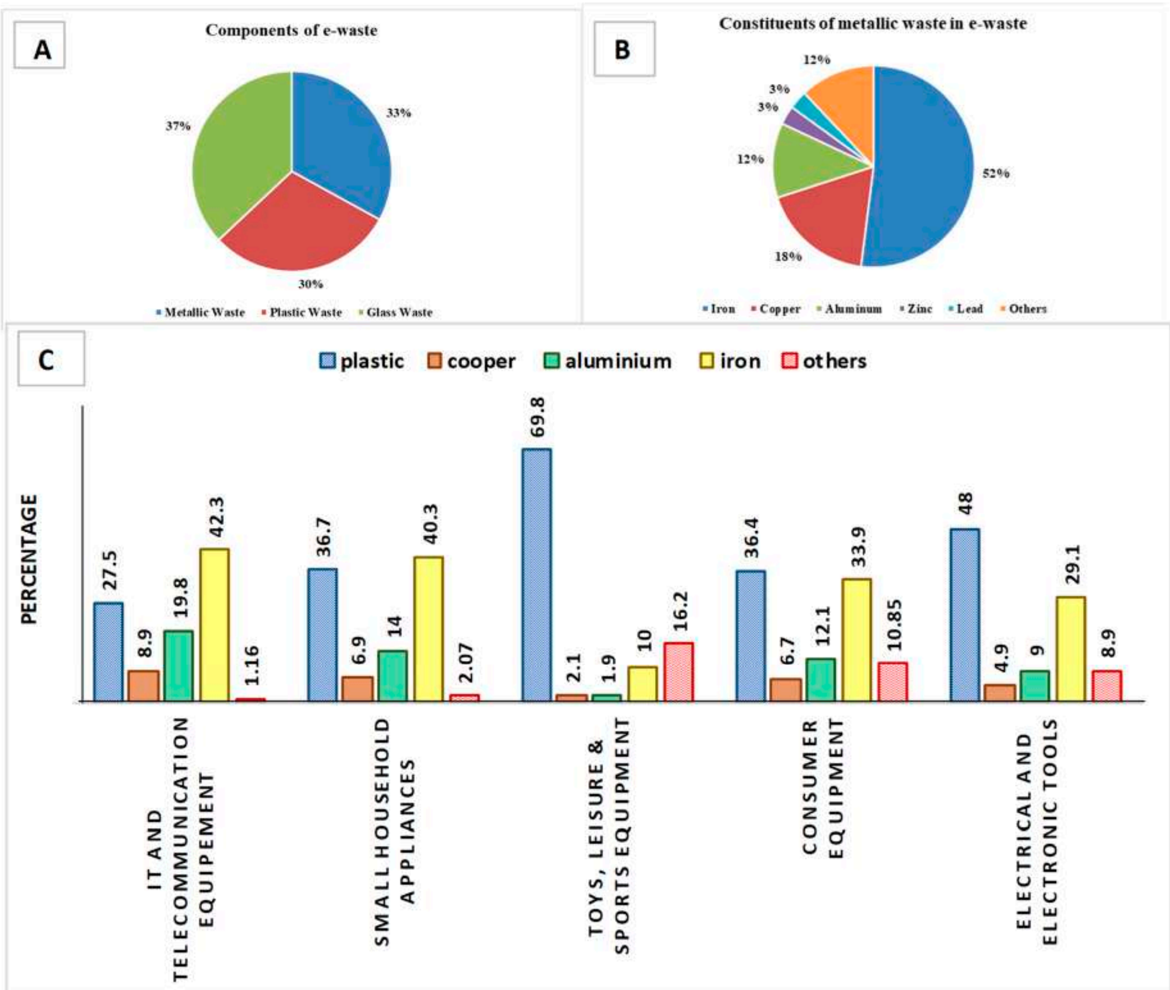


Figure 3. (**A**) Components of e-waste, (**B**) constituents of metallic waste in e-waste, and (**C**) average composition by mass percent of electrical and electronic equipment (EEE).

Figure 3C reveals varying material compositions across electronic categories. Iron dominates in IT and Telecommunication Equipment (42.3%) and Small Household Appliances (40.3%), while plastic is prevalent in Toys, Leisure & Sports Equipment (69.8%) and Electrical and Electronic Tools (48%). 'Others' signify diverse materials, notably in Toys, Leisure & Sports Equipment (16.2%) and Consumer Equipment (10.85%). This breakdown underscores the prominence of iron and plastic, aiding in targeted recycling strategies for sustainable e-waste management [35].

Table 2. The prime hazardous elements in e-waste.

No	Hazardous Elements	Detrimental Effects of the Hazardous Elements from E-Waste
1	Arsenic (As)	Impacts on the skin and slows down nerve conduction. Chronic contact with arsenic can occasionally be lethal and cause lung cancer [36].
2	Lead (Pb)	Kidneys, reproductive systems, and neurological connections could all be affected. May lead to brain and blood issues and may be fatal [37].
3	Barium (Ba)	Affects the cardiac muscle [38].
4	Chromium (Cr)	Liver and kidney damage from chromium can lead to lung cancer and asthmatic bronchitis [39].
5	Beryllium (Be)	May cause lung diseases [40].
6	Mercury (Hg)	Growth of the foetus is hampered by its effects on the immune system, kidneys, and the brain. Injury to the liver or brain [41].
7	Cadmium (Cd)	May lead to excruciating joint and back discomfort. It weakens bones and affects the kidneys [42].
8	BFR (Brominated flame retardants)	Damage to the immunological and reproductive systems and possibly leading to hormonal imbalances such as thyroid disorders [43].
9	Chlorofluorocarbon (CCl_2F_2)	Harm to the ozone layer. Both human skin cancer and organisms' genetic harm could result from it [44].
10	Polychlorinated Biphenyl ($C_{12}H_{10}$-nCln)	Animals' immune systems, reproductive systems, neurological systems, and endocrine systems may be affected. May cause cancer. PCBs continuously poison the environment and harm it severely [45].
11	Polyvinyl Chloride (C_2H_3Cl)	PVC burns with a hydrogen chloride gas that contains up to 56% chlorine and creates hydrochloric acid, which is harmful to the respiratory system [46,47].
12	Dioxin	Extremely hazardous to mammals and can cause foetal abnormalities, slowed growth and reproduction, and immune system effects [48].

3. Health, Safety, and Environmental Impacts of E-Waste during Treatment Processes

The recognition of e-waste toxicity emerged relatively recently, prompting limited consideration for global laws and policies addressing its management. With rapid technological advancements worldwide, safeguarding both the environment and human health has become increasingly crucial. Occupational safety and health of the workers involved in e-waste treatment and disposal may be exposed to a range of hazardous materials, including lead, mercury, and cadmium. This exposure can lead to a range of serious health problems, including respiratory issues, skin disorders, and neurological damage [37] which can be either acute or chronic. Improper e-waste disposal can result in the release of hazardous chemicals into the air and water. This can cause respiratory problems, cancer, and other health issues in nearby populations, as well as damage to local ecosystems [48].

In many cases, workers in e-waste treatment facilities may not have access to proper protective equipment or training, which can increase their risk of injury or illness [49]. E-waste contains a range of heavy metals and other hazardous materials that can contaminate soil and groundwater if not properly managed. This contamination can persist for years and pose a risk to both human health and the environment [50]. E-waste treatment and disposal facilities may pose a risk of fire and explosion due to the presence of flammable materials and chemicals. These hazards can cause injury or even death to workers and nearby populations [51]. Improper handling and disposal practices, such as burning or dumping e-waste in landfills, can exacerbate the health, safety, and environmental impacts of e-waste treatment. Proper management practices, such as recycling and safe disposal, are essential to minimise these impacts [52].

In addition, e-waste treatment can also cause environmental pollution. For example, improper handling of e-waste can result in the release of toxic chemicals into the air, soil, and water, which can affect the health of local communities and ecosystems [53]. To mitigate these impacts, it is important to ensure that e-waste treatment facilities adhere to proper safety and environmental standards, including the use of proper protective equipment and waste management practices [31]. It is also important to provide training and support for workers to ensure their safety and well-being during the e-waste treatment process. Effective management of e-waste in disposal sites is important to reduce the significant risks to the health and safety of people by implementing adequate legislation and management strategies [10,54,55]. Additionally, hazardous waste transportation to developing countries such as India is a serious concern that occurs because of low-cost labour and the less strict environmental laws in India [32].

Occupational Safety and Environmental Hazards Due to E-Waste

Occupational safety and environmental hazards due to electronic waste (e-waste) have emerged as significant concerns in recent years. Workers engaged in the handling, dismantling, and recycling of e-waste face various occupational risks, primarily stemming from exposure to hazardous chemicals [56]. E-waste contains substances like lead, mercury, cadmium, and brominated flame retardants, which can result in skin irritations, respiratory issues, and, in severe cases, chronic illnesses among workers. Moreover, the physical nature of the work puts employees at risk of injuries from sharp objects, leading to cuts, bruises, and fractures. Additionally, repetitive tasks and poor ergonomics in e-waste management processes contribute to musculoskeletal disorders among workers, creating long-term health challenges [57].

Technologies primarily pertain to electrical and electronic equipment (EEE), consisting of various materials, some valuable and others hazardous in nature. In several developing countries, particularly in India, proper management of such waste is lacking, and there is minimal oversight by authorities [32]. This disposal challenge has emerged as a significant issue in numerous regions globally. Inadequate handling results in the creation of contaminated leachates, leading to groundwater pollution, and the disposal of computer and mobile chips produces acids and sludges, ultimately contaminating the soil. Addressing this situation is crucial, requiring immediate attention, improvement, and action.

In an incident at a flourishing area in Guangdong China, Guiyu, water contamination had occurred due to improper e-waste disposal methods causing acids and sludges to reach the nearby river [18]. When some electronic devices, such as circuit breakers and condensers are broken, hazardous elements such as mercury and polychlorinated biphenyls (PCBs) may leak out. Both polybrominated diphenyl ethers (PBDE) and cadmium may leak through into water and soil when brominated flame retardant (BFR) plastics or cadmium-containing polymers are landfilled. Significant amounts of lead ions are dissolved from shattered lead-containing glass, such as the cone glass of cathode ray tubes, when it encounters acidic waters, which is frequent in dumps [55]. Many improper disposals and recycling methods are being practiced in dismantling industries. The most dangerous one is burning e-waste in open land to recover valuable materials like copper from coated plastic cables. This leads to air pollution resulting in highly toxic fumes containing dioxins and furans being spread around the space [21].

4. Current E-Waste Management in India

India produced 3.2 million metric tonnes of e-waste in 2019, and it is anticipated that this number will increase to 5.2 million metric tonnes by 2025, according to research by the Central Pollution Control Board (CPCB) of India. To handle this enormous volume of rubbish, the existing e-waste management system in India is insufficient. The majority of e-waste in India is managed by an uncontrolled industry that is typified by the use of outmoded methods of disassembly and disposal and poses a substantial risk to both human well-being and the environment [41,49]. There are only a few authorised e-waste recycling facilities in India, and they are unable to meet the demand for recycling due to the lack of investment, infrastructure, and incentives by the government [46].

The E-waste (Management) Rules, 2016, aimed to govern e-waste management and encourage sustainable recycling of e-waste, were put into effect by the Government of India to address this issue. Producers, importers, and owners of brands are required by the regulations to collect consumers' e-wastes and ensure their disposal in an environmentally sound manner [58]. Along with the government's efforts, many private businesses and non-governmental organizations (NGOs) have also taken steps to invest in improving e-waste management in India. For instance, organisations like Toxics Link have launched awareness campaigns and constructed e-waste collection centres across numerous cities, while manufacturers like Dell, HP, and Nokia have set up take-back programs for their products [47]. Even though the present e-waste management system in India is insufficient, the government and other stakeholders are working hard to find the best solution. To improve environmentally friendly e-waste management in India, more money, infrastructure, and incentives are required. Figure 4A provides data outlining the projected e-waste generation in million metric tonnes (MMT) for several years from 2015 to 2050 [36]. Figure 4B shows the import profile of EEE in India from year 2014 to 2022 [36]. Figure 5A presents state-wise data on e-waste generators, revealing regional disparities in electronic waste production [35]. Additionally, Figure 5B pinpoints key cities in India that significantly contribute to the e-waste generation in the nation, highlighting specific urban areas where focused waste management strategies are essential [24].

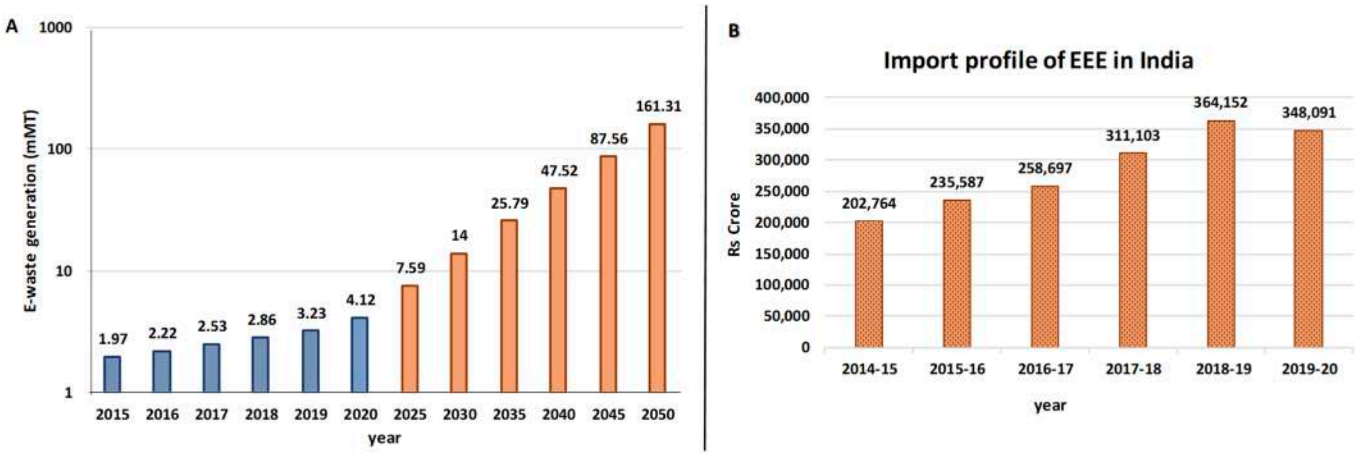


Figure 4. (**A**) Year-wise e-waste generation and projected e-waste generation in India. (**B**) Import profile of EEE in India.

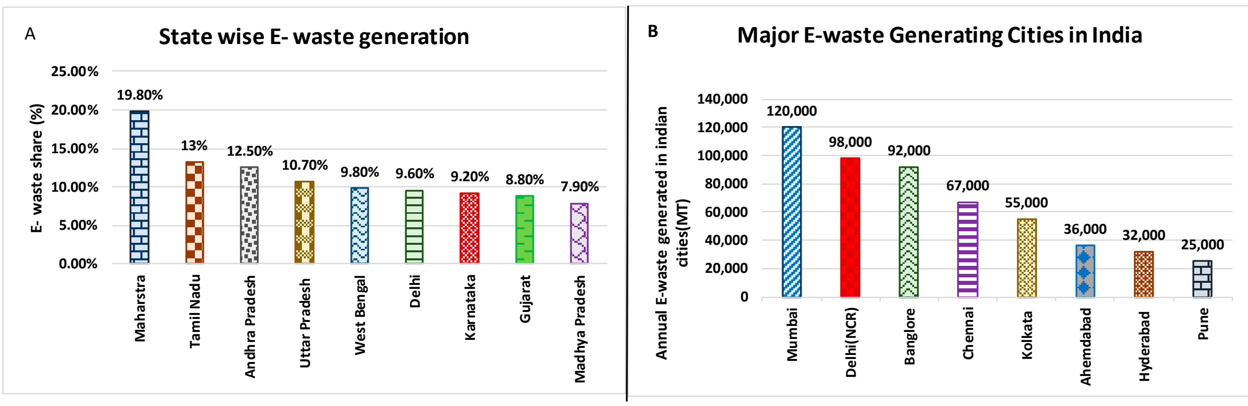


Figure 5. (**A**). State-wise e-waste generators—2021. (**B**) Major e-waste generating cities, India 2021.

4.1. E-waste Management Approaches and Initiatives

There are several e-waste management approaches and initiatives in India aimed at addressing the growing problem of e-waste. In terms of e-waste management, the EPR approach is based on the principle that manufacturers handle the entire lifecycle of their products, including disposal. The E-waste (Management) Rules, 2016 has made it mandatory for producers, importers, and brand owners to take back the e-waste from consumers and ensure its environmentally safe disposal [50].

The informal sector, which includes waste pickers and recyclers, plays a significant role in the management of e-waste in India. Several initiatives aim to integrate the informal sector into the formal waste management system by providing them with training, equipment, and support services [49]. Public-Private Partnerships (PPPs) involve collaboration between the government and private companies to promote e-waste management. For example, the government of Maharashtra has partnered with e-waste recycling companies to establish e-waste collection centres in several cities in India [46]. Several NGOs, such as Toxics Link, have conducted awareness campaigns to educate consumers about the importance of e-waste management and provide them with information on how to dispose of their e-waste safely [47].

Various technological solutions have been developed to improve e-waste management in India. For example, a mobile app called 'Eco E-Waste' enables consumers to request doorstep e-waste pickup services [47]. The e-waste management approaches and initiatives in India include EPR, informal sector integration, PPPs, awareness campaigns, and technological solutions. These efforts aim to promote environmentally sound recycling of e-waste and mitigate the negative impacts of e-waste on human health and the environment.

In India, two disposal methods are carried out, which are landfilling and incineration. Unfortunately, both methods are not an effective way of treating e-waste and are dangerously hazardous to nature. Effective management of e-waste recycling and recovery is needed, including dismantling and segregating materials including metals and non-metals (like plastics). Dismantling includes removing all the removable parts of valuable materials like gold, copper, silver, iron, and steel and non-valuable parts of electronic equipment. Refurbishment is one good method to repair the electrical parts and return them to their previous stage [43]. According to a study of the e-waste recycling industry in India, e-waste recycling begins with the informal dismantling sector and progresses to the informal recycling sector. The whole e-waste processing process takes place in an uncontrolled atmosphere with no emissions regulations [45].

4.2. E-Waste Management Agency

There are several agencies involved in e-waste management in India. The Ministry of Environment, Forest and Climate Change (MoEFCC) is the primary agency responsible for e-waste management in India [50]. The Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) are also involved in regulating and monitoring e-waste management practices in the country [46]. In addition, several authorised e-waste management companies in India are licensed by the CPCB and SPCBs to collect, transport, and dispose of e-waste in an environmentally sound manner. Some examples of authorised e-waste management companies in India include Attero Recycling, Ecoreco, Sims Recycling Solutions, and TES-AMM India [46].

Furthermore, under the E-waste (Management) Rules, 2016, producers of EEE are required to obtain EPR authorisation from the CPCB and ensure that their e-waste is collected and properly disposed of through authorised e-waste management companies [51]. Overall, the e-waste management system in India involves a multi-agency approach with the involvement of both government agencies and private sector companies to ensure that e-waste is properly managed and disposed of. Figure 6A provides an overview of the recycling capacities across different states in India, ranging from large capacities in states like Uttar Pradesh and Maharashtra to smaller capacities in states like Goa and Jammu and Kashmir [36]. Figure 6B provides an overview of Informal recycling—sources of e-waste [52].

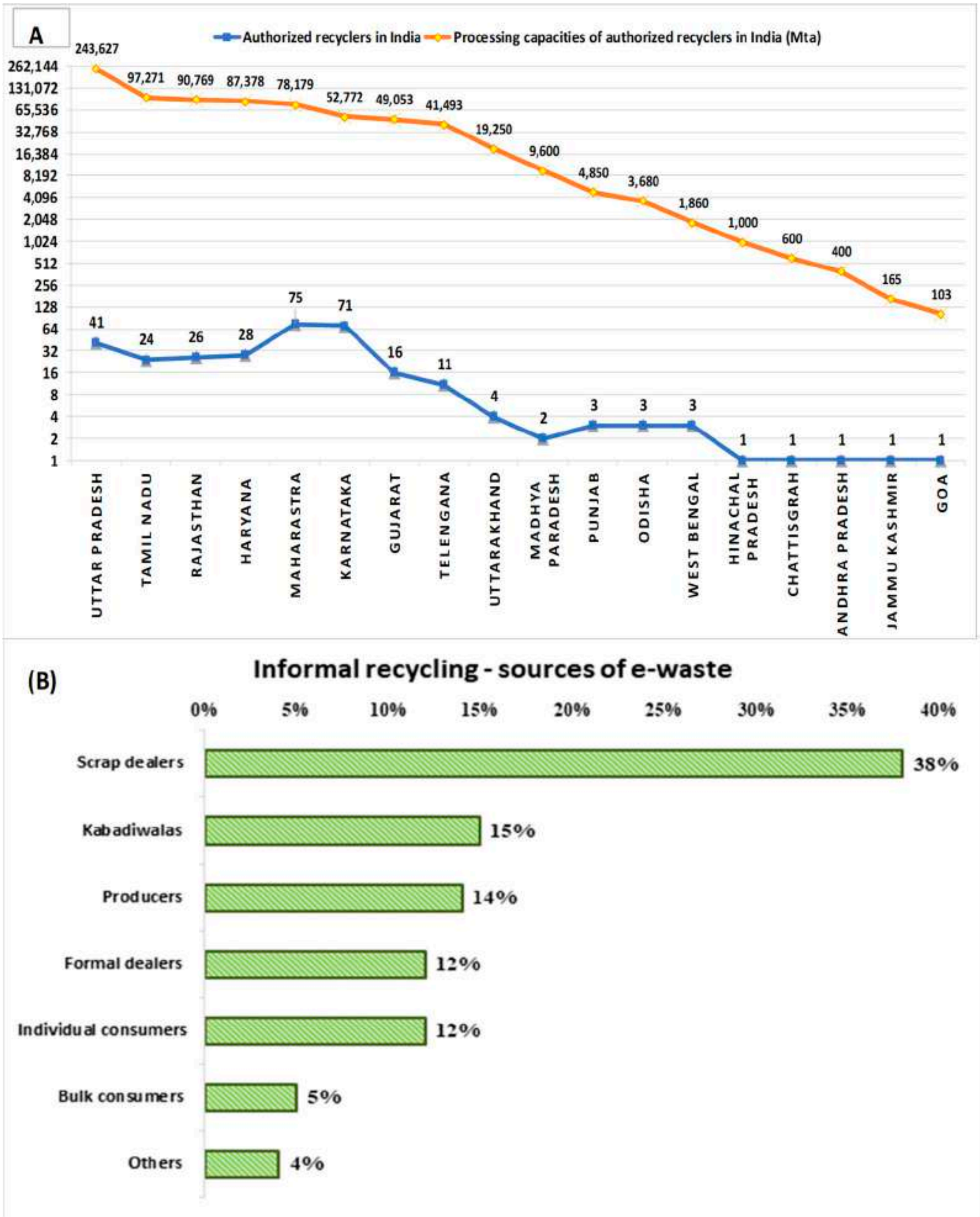


Figure 6. (**A**) Authorised recyclers in India and processing capacities of authorised recyclers in India. (**B**) Informal recycling—sources of e-waste.

4.3. E-Waste Issues in the Electrical and Electronic Industry

Electronic waste (e-waste) includes consumer electronics like computers and smartphones that contain hazardous materials. Managing it involves recycling and safe disposal. Electrical waste encompasses items related to electrical power, like wiring and transformers, with concerns about insulation materials. Both require separation and recycling. Legal compliance, especially with "e-waste management amendment rules", is crucial for responsible disposal, contributing to sustainable practices [53].

Improper administrative actions toward the customer and public awareness about e-waste management resulted in inadequate disposal methods [53]. The people need to be educated about the e-waste recycling and return policies of companies [54]. The policies and standards of developing nations like India still need to be improved. The Indian government has initiated new guidelines named "e-waste management amendment rules 2018" to increase public awareness about e-waste management [55].

However, there is a huge question about how these new recommendations will be implemented; regulations are available, but the implementation and enforcement are still inefficient. Another policy is that the Indian government prohibited the import of e-waste from outside. However, these guidelines and polices are only documented but not strictly followed. Many concerns must be addressed in this sector, as new corporations such as Volvo, Kodak, Electrolux, and Xerox have embraced new green production practices. Hence, these practices along with return policies and recycling treatments are needed for effective management of e-waste altogether [55,56].

4.4. Global Collection and Management Issues in Developing Countries

In 2019, the world generated 53.6 million metric tonnes of e-waste, and only 17.4% of it was collected and recycled properly [4]. Developing countries are disproportionately affected by the e-waste problem, as they receive the majority of the world's e-waste imports for recycling [57]. A significant amount of e-waste in developing countries is informally recycled, often using unsafe methods that expose workers and the environment to hazardous chemicals and toxins [57]. The management of e-waste is a global issue that affects both developed and developing countries. Developing countries, however, face challenges in managing e-waste due to their limited resources and infrastructure. One of the key issues is the lack of adequate collection systems and formal e-waste management facilities [59]. In many developing countries, e-waste is often collected and processed by the informal sector, which consists of small-scale enterprises and individual workers who collect and dismantle e-waste in their homes or small workshops. This informal sector often lacks proper equipment, training, and protective measures, leading to serious health and environmental risks for workers and communities [60]. E-waste recycling in developing countries is often conducted by marginalised groups, including women and children [61].

The informal e-waste recycling sector in developing countries is estimated to employ 15 million people worldwide [58]. Another issue is the transboundary movement of e-waste, where developed countries export their e-waste to developing countries for disposal or recycling. This practice often leads to the dumping of e-waste in these countries, causing environmental pollution and health hazards [62]. To address these issues, there is a need for global collaboration and the establishment of effective e-waste management systems. This includes the development of appropriate policies, regulations, and standards, as well as the promotion of environmentally sound and socially responsible e-waste management practices [59]. Figure 7 highlights the top five e-waste-generating countries in 2019. These significant data offer valuable insights into the nations contributing most significantly to the global electronic waste stream [63].

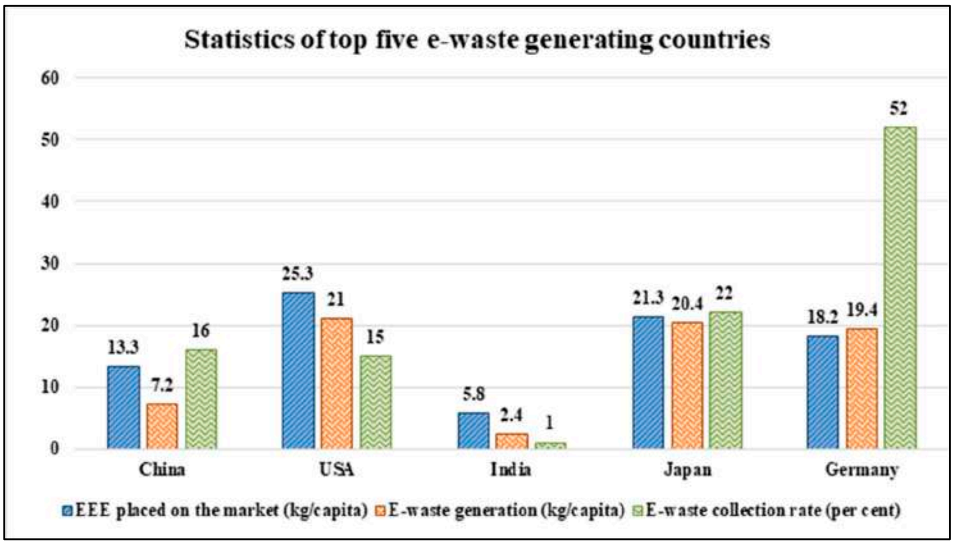


Figure 7. Statistics of the top five e-waste generating countries in 2019.

4.5. Benefits of E-Waste Management

E-waste management plays a crucial role in protecting the environment and public health. Proper e-waste management practices have several benefits, including reducing pollution, conserving resources, and promoting sustainability [64]. One of the primary benefits of e-waste management is the reduction of pollution. E-waste that is not managed properly can release hazardous substances into the environment, contaminating soil, water, and air. This pollution can harm human health and the ecosystem. Proper e-waste management practices, such as recycling and incineration, can help to reduce pollution levels and mitigate the negative impacts of e-waste [65]. E-waste management also plays a crucial role in conserving resources. Recycling and reusing e-waste materials can help to conserve natural resources such as timber, minerals, and water. Additionally, waste-to-energy technologies can help to reduce the need for fossil fuels by generating energy from waste [32].

Furthermore, proper e-waste management practices can promote sustainability by reducing e-waste generation and increasing the use of renewable resources. This can help to reduce greenhouse gas emissions and mitigate the impacts of climate change [66]. In conclusion, e-waste management is critical for protecting the environment and public health. The benefits of proper e-waste management practices include reducing pollution, conserving resources, and promoting sustainability. Individuals and governments need to take action to ensure that e-waste is managed properly to reap these benefits. Additionally, if the e-waste is properly separated and recycled, valuable elements such as gold, silver, palladium, copper, plastic, rare earth elements, and many others can be extracted from µg to ng levels [67]. There are many proven technologies like hydrometallurgical, pyrometallurgical, and bioprocessing available to recover the valuables from e-waste and prove that "waste is a wealth, but in the wrong place" [67].

5. Economic, Social, Environmental, and Human Health Implications of E-Waste in India

Numerous negative effects on the economy, society, ecology, and health have resulted from India's rapid e-waste growth. India's e-waste management industry has the ability to boost the nation's economy and offer job opportunities. However, the unofficial industry predominates in the management of e-waste, and the development of the official sector is hampered by the absence of adequate policies and regulations [68]. The e-waste management business in India is predicted to reach Rs 30 billion by 2025 and generate over 120,000 employees, according to a report by the Association of Indian Chamber of Commerce and Industry (ASSOCHAM). E-waste management may have social repercussions, particularly for the unregulated market. E-waste recycling is under the purview of the informal sector, where workers may be exposed to harmful compounds, endangering their health [69]. A study by the United Nations University found that informal recycling of e-waste in India exposes employees and communities to dangerous substances, which has a negative impact on their health [70,71].

Improper disposal of e-waste in landfills results in water and soil contamination as well as climate change. E-waste management in India needs a comprehensive policy framework, according to a report by the Centre for Science and the Environment. Health dangers from incorrect disposal of electronic waste and illegal recycling methods are particularly high for those who work and live near these facilities. The World Health Organisation (WHO) reports that exposure to potentially harmful compounds during the reuse and recycling of e-waste might result in neurological problems, respiratory and skin ailments, and even cancer development [72].

6. Recycling and Disposal Processes of E-Waste

Figure 8 provides the view on general movement of e-waste throughout several sectors [36]. In India, recycling of discarded technology products is being carried out in both the formal and informal sectors. The fundamental distinction between formal and informal recyclers is that official recyclers adhere to environmental safety and health standards because they are inspected and licensed by government regulators frequently [73]. Recycling is the best practice to be followed in terms of managing e-waste. However, landfilling practices in India are mainly carried out, resulting in the leaching behaviour of metals into the surrounding soil and making it contaminated. Adding to the leaching issue, mercury and cadmium contamination happens in these landfill areas. E-waste consists of different characteristics of metals and non-metals, and efficient recycling methods need to be followed [36,41]. Figure 8 shows the flowchart of the lifecycle of electronic devices, from production and consumption to disposal and recycling. This study may be used to analyse the e-waste pathway through industries.

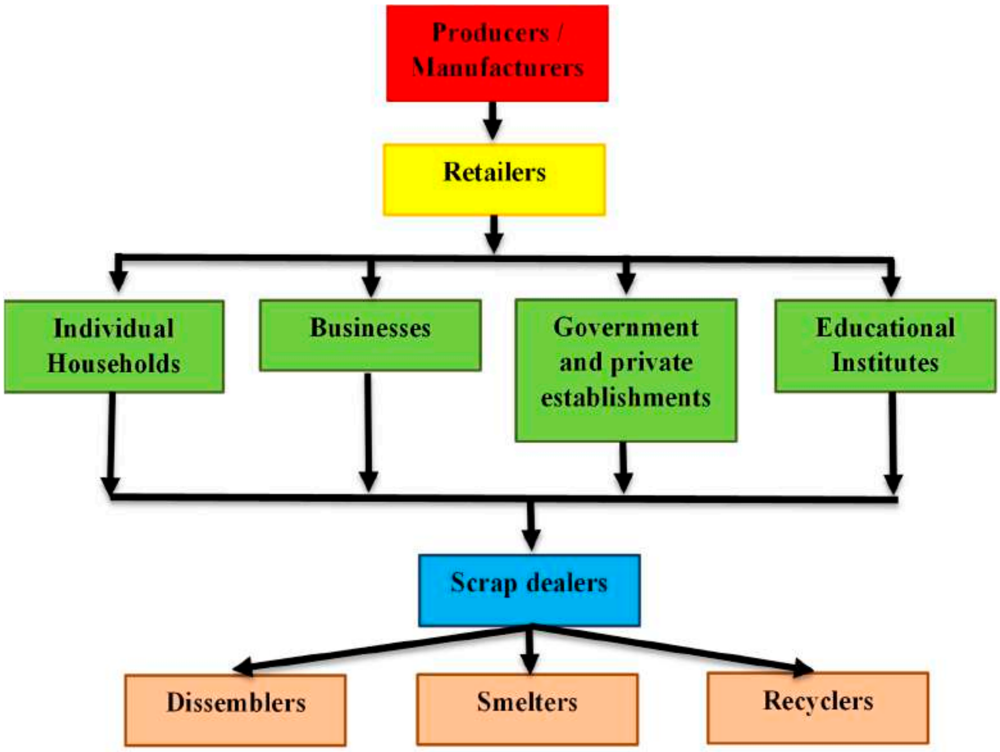


Figure 8. General movement of e-waste throughout several sectors.

Electronic garbage or e-waste recycling and disposal are critical for environmental sustainability and human health. E-waste is made up of abandoned electronic devices and components such as cellphones, computers, and circuit boards that may include dangerous elements such as lead, mercury, and cadmium [74]. The recycling process begins with collection and sorting, which involves gathering and categorising e-waste to ensure that valuable elements can be recovered [75].The devices are then disassembled and shredded into smaller components. Valuable materials such as precious metals and polymers are removed for reuse at this step. To prevent environmental pollution, dangerous substances must be properly disposed of. Furthermore, some e-waste components can be reconditioned, resold, or donated to extend their useful life [76]. All these encompassing approaches to e-waste treatment not only decrease environmental effects but also save vital resources.

To summarise, e-waste recycling and disposal entails gathering, sorting, disassembling, and shredding to recover valuable materials while ensuring the safe disposal of hazardous components. This procedure is critical for minimising the environmental impact of electronic trash and conserving important resources.

6.1. Reuse and Recycling Techniques of E-Waste

In the recycling process, the valuable and non-valuable materials and metals are taken without damaging their properties or else converted into useful products by reducing the impact that they may create, and if they are non-recyclable, they will be thrown out into the environment [34]. Many materials can be recovered from these kinds of e-waste including precious metals, iron, glass, steel, plastics, etc. Recycling also reduces the burden of the producers by giving them back the resources needed to reproduce the products [77]. When compared with other developed nations like Switzerland, where consumers pay a recycling fee for the recycling process, in India it is the opposite as scrap collectors pay consumers a certain amount for recycling. But rather than other industries, e-waste recycling is an upcoming profitable industrial area [78,79]. E-waste recycling industries are new as these technological boosts are recent and have created a new set of recycling methods [80].

Being a large consumer of second-hand goods, there is an emerging market for this area in India. Many scrap recyclers available in India have the potential to create their e-waste recycling centers and sell valuable metals along with the previous sections. These recycled metals are then used as feedstocks for automotive industries and manufacturing industries [78]. For the recycling processes, the most developed separation processes may effectively recycle different combinations of e-wastes including conductors, semiconductors, and non-conductors [81].

In terms of the volume of e-waste recycling, only a small percentage from the total e-waste is recycled in India. Therefore, all parties in this e-waste lifecycle need to be involved to mitigate this problem, including electronic manufacturers, government agencies, end users, and authorised recyclers, and their involvement must begin from the generation to disposal stage. In India, an integrated approach to e-waste management is still absent, and dealing with it is a monumental task; there are no authorised connections between scrap collectors and recyclers or dismantlers [82].

6.2. Technological Methods for E-Waste Recycling

E-waste recycling encompasses diverse technological methods crucial for resource recovery and environmental conservation. Mechanical recycling techniques involve shredding or crushing e-waste materials to facilitate separation, employing screening methods based on size and shape, air classification for lighter materials, and electromagnetic separation for magnetic components [83]. Chemical recycling, encompassing leaching, precipitation, and purification processes, utilises chemical solutions to dissolve and recover valuable metals from e-waste [84]. Pyrometallurgical methods like smelting and refining involve high-temperature processes to melt and purify metals from e-waste. Biometallurgical approaches leverage microorganisms for metal extraction, including bioleaching, biosorption, and bioprecipitation methods. Electrochemical processes like electrolysis and electrowinning use electrical currents for metal dissolution and recovery in an eco-friendly manner [85,86].

These recycling methods vary in their applicability, efficiency, and environmental impact. The choice of method often depends on the type of e-waste, the targeted materials for recovery, economic feasibility, and environmental considerations. Integrating multiple recycling approaches offers a more comprehensive strategy for managing the diverse components within electronic devices, contributing significantly to sustainable e-waste management efforts globally [87].

7. E-waste Management and SDGs

E-waste management can play a crucial role in achieving several Sustainable Development Goals (SDGs), particularly those related to environmental protection, health, and sustainable consumption and production. Improper e-waste disposal can cause major health risks to both humans and the environment [88]. We can safeguard human health and welfare by treating e-waste safely and responsibly to align with SDG#3: Good health and well-being. According to a World Health Organisation (WHO) study, toxic compounds found in e-waste can have negative health impacts on the body, including cancer, reproduction and developmental issues, and nervous system harm. These health concerns can be avoided with proper e-waste disposal, according to the World Health Organisation [89].

By encouraging the reuse, restoration, repair, and recycling of electronic items (to adhere to SDG#12: Responsible consumption and production), e-waste management can help promote responsible consumption and production. We can lessen the need for new items and save natural resources by increasing the lifespan of technological devices. The recycling and reuse of e-waste can save many resources and assist the environment, according to a United Nations University report [90,91]. By lowering the greenhouse gas emissions linked to the manufacture and disposal of technological items, e-waste management may additionally achieve SDG#13 on climate action [92]. E-waste contains large amounts of valuable materials, such as precious metals like gold, silver, copper, and aluminium, that can be recovered and repurposed, reducing the need for new production and decreasing carbon emissions, according to a research study conducted by the United Nations Environment Programme (UNEP). In general, managing e-waste can be crucial to attaining several SDGs, especially those concerned with the environment, human health, and sustainable production and consumption [93].

8. Concluding Remarks

The exponential growth of e-waste is becoming a threat to the environment in the Indian as well as the global context. Globally generated e-waste is around 53.6 million metric tonnes (Mt) in 2019, and out of this only 17.4% is recycled effectively, which means a huge proportion of e-waste generated is still untouched and is increasing every year. The Asian continent is the top ranked globally in e-waste generation with 24.9 million metric tonnes in 2019. The forecasting graph of e-waste generation in India indicates that by the year 2050 around 161.32 million metric tons of e-waste will be accumulated in India alone. The cities that generate the most e-waste are the more developed ones like Mumbai and Delhi, and state-wise the top is Maharashtra with 19.80% of overall e-waste. Scrap dealers are found to be far more efficient than other informal recyclers, with 38% of the overall collection.

E-waste management poses challenges due to its rapid growth, complex composition, informal recycling, and inadequate infrastructure. However, it also presents opportunities through resource recovery, circular economy adoption, technological innovations, extended producer responsibility (EPR), and job creation in a green economy. Addressing these challenges unlocks potential for sustainable solutions and responsible resource usage.

In India, the main issue is regarding the ineffective management and knowledge about the nature of e-waste. Many electronic junks are unattended in regular households, warehouses, and office wastes and finally end up in regular landfills rather than separate sections. To mitigate this main issue, more stringent regulations and management practices are needed to secure good health and a safe society. The main drawback is the application of these e-waste management policies at the root levels, as these laws are present only on papers and not well-translated in reality. Because there are no authorised linkages between scrap collectors and recyclers or dismantlers, an integrated solution is required. For effective management of e-waste in India, more focus needs to be put on effective implementation of e-waste policies and regulations at all levels, increasing producer responsibilities, effective collection methods and management, proper recycling practices, and innovative methods for environmentally friendly disposal methods. By spotlighting the severity of e-waste concerns and proposing solutions, this review holds significant relevance to the scientific community globally engaged in addressing the escalating challenges posed by e-waste.

Funding: This research received no external funding.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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