



Research Paper

Electronic Waste Management: Challenges and Sustainable Solutions

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Received: 28/03/2026

Revised: 05/04/2026

Accepted: 13/04/2026

Abstract: Modernization has significantly improved human productivity and quality of life; however, it has concurrently generated profound environmental and public-health concerns. Rapid advancements in computer science, information technology, and automation have shortened the technological life cycle of electronic products, leading to accelerated obsolescence—often within a span of months. This phenomenon stimulates continuous consumer demand for upgraded devices while rendering older models redundant. Consequently, large volumes of end-of-life electrical and electronic equipment accumulate, comprising complex streams of hazardous and non-hazardous materials, including heavy metals, persistent plastics, flame retardants, and glass components. The escalating consumption of electronic goods—propelled by global digitalization, Industry 4.0, and innovations in microelectronics—has intensified the scale and complexity of the e-waste challenge. Empirical studies indicate that a substantial fraction of e-waste remains outside formal collection and recycling systems. Instead, it is frequently subjected to informal dumping, open burning, or crude dismantling practices, particularly in developing regions. Such

mismanagement not only undermines resource recovery but also poses severe ecological and health risks through soil contamination, groundwater pollution, and the release of toxic emissions.

Keywords: Incineration, hazardous, Dismantling, gold-plated components, reuse.

Introduction:

Digitalization, while transforming global systems, has also raised concerns about its unintended consequences. It is often argued that excessive dependence on digital technologies may reduce critical human engagement, while the rapid pace of technological innovation simultaneously generates vast quantities of obsolete electronic waste. Electronic waste—or e-waste—is broadly defined as discarded, end-of-life (EoL) or obsolete electrical and electronic equipment (EEE). It is commonly referred to as Waste Electrical and Electronic Equipment (WEEE) and includes a wide array of products such as cathode-ray tube devices; LCD and LED screens; computer monitors; ATMs; video cameras; printed circuit boards; semiconductor chips; gold-plated components; and various plastic parts

from printers, keyboards, mobile phones, and other gadgets. E-waste also comprises computer cables and wiring, as well as mixed metal fractions containing copper (Cu), aluminum (Al), iron (Fe), and other valuable or hazardous elements (cpcb.nic.in). Used electronics intended for refurbishment, reuse, resale, salvage, material recovery, recycling, or final disposal also fall under the category of e-waste (epa.gov). Current estimates suggest that approximately 100 million tonnes (Mt) of e-waste are generated globally each year. Studies further indicate that around 30% of household electronic items remain either non-functional or damaged. Additionally, consumers tend to stockpile 4–5 kg of unused electrical and electronic products per capita annually. Alarmingly, less than 20% of the total e-waste generated worldwide is formally collected and recycled, highlighting a substantial gap in sustainable resource management and environmental protection.

Materials & Methods:

This review paper is based on a systematic assessment of published literature, policy documents, and global reports related to electronic waste (e-waste). The methodology adopted includes:

Literature Search Strategy: A thorough literature survey was conducted using scientific databases such as Google Scholar, ScienceDirect, PubMed, ResearchGate, and SpringerLink. **Inclusion and Exclusion Criteria Including:** Peer-reviewed research articles (2010–2025), Government guidelines and e-waste management rules, international reports (UNEP, WHO, Global E-Waste Monitor, OECD), Technical documents from authorized recycling agencies.

Excluding: Non-scientific articles, Duplicate papers, Studies with incomplete data.

Data Extraction and Synthesis: Findings related to e-waste types, management technologies, environmental impacts, health implications, and global regulatory frameworks were extracted (tsocmms.nic.in).

Themes were synthesized to provide a coherent narrative for the review.

Management of E-waste:

The management of e-waste in India is governed by the E-Waste (Management) Rules, 2022, which have subsequently undergone three amendments to strengthen regulatory oversight and align with emerging technological and environmental challenges. E-waste represents a heterogeneous and highly complex waste stream, comprising plastics, metals, glass, gels, and numerous other components. As a result, hazardous and non-hazardous materials coexist within the same waste category, making handling, segregation, and processing particularly challenging.

Given this complexity, e-waste requires careful handling, specialized equipment, and trained personnel to prevent occupational hazards and environmental contamination. Accordingly, dedicated e-waste management facilities are established and operated in accordance with the provisions of the Rules, which outline guidelines for collection, storage, dismantling, recycling, and end-of-life disposal. Inefficient or improper management of e-waste can lead to severe adverse effects on human health—such as exposure to toxic metals and organic pollutants—and contribute significantly to soil, air, and water pollution. Therefore, scientifically designed and well-regulated e-waste management systems are essential for safeguarding both public health and the environment (eprewastecpcb.in).

The e-waste management process involves the following steps:

Collection of waste from the user: E-waste is collected from homes, business centres and other organizations through entitled collection points, municipal corporation e-waste collection services, or through take-back programs by e-waste producers in a formal process of collection. Informally: E-waste can also be collected by kabarias; the waste dealers or companies with less focus on the safe disposal of EOL. The collection

centre which stores waste refrigerator and air conditioners should have suitable facilities for handling leakage of coolant/refrigerant gases CFCs/HFCs, compressor oils and mercury from discarded fluorescent and other mercury lamps. Spills of the broken fluorescent lamps and Oils should be prevented from spreading of the stuff to other areas. Spills can be managed by the use of dry sand, exclusive booms / absorbent swobs, stabilizing chemicals.

Sorting and Segregation: Every collector will store the e-waste for a period not exceeding one hundred and eighty days and shall maintain a record of storage of e-wastes. The storage of the e-waste is done according to the guidelines of E-waste management rules. E-waste is separated based on the type of device (e.g., computers, phones, appliances) and its condition. Hazardous materials like lead and mercury are separated for safe disposal, while valuable materials like copper, aluminium, and gold are extracted.

Dismantling and Material Recovery: The centre for the dismantling the e-waste is pre-approved by the pollution control boards. They are properly designed to handle the waste that are hazardous/Toxic in nature. Polychlorinated biphenyls, tetra Bromo-bisphenol-A, polybrominated biphenyls, polybrominated diphenyl ethers, Chlorofluorocarbon, polyvinyl chloride, Heavy metals and other metals: Arsenic, Barium, Beryllium, Cadmium from rechargeable computer batteries, printer inks and toners, Chromium VI, Lead, Lithium Li-batteries, Mercury, Nickel, Rare Earth elements like Yttrium, Europium, Selenium, Zinc sulphide are some of the examples of the toxic materials present in E-waste. PBTs are toxic to human health and the environment. They have been reported to cause cancer, nerve impairment and reproductive disorders in humans.

Any person or organisation can engage in dismantling of e-waste by obtaining authorisation from the respective State

Pollution Control Boards/Pollution Control Committees. Dismantlers can also set up their collection centre, details of which shall be inserted in their authorisation. No separate authorisation is needed for these collection centres. This approval from SPCBs/PCCs will cover authorizations under the Water (Prevention and Control of Pollution) Act, 1974 and the Air (Prevention and Control of Pollution) Act, 1981, E-Waste (Management) Rules, 2016, the Hazardous Wastes (Management, Handling and Transboundary Movements) Rules, 2008, the E-waste (Management & Handling) Rules, 2011 (www.who.int.)

A dismantling facility should have appropriate weighing facility for all types E-wastes. There should no damage to health, environment and to the product itself while dropping of e-waste. While unloading Cathode Ray Tubes, E-waste containing compressors, Plasma TVs, fluorescent mercury containing lamps special supervision is necessary. For permanently deleting data saved in the memory of EOL products (Hard Disk, Telephones, Mobile phones) experts should be employed by the dismantler. Treasured metals like copper, aluminium and gold are extracted for recycling, while hazardous materials are handled separately. Devices are stripped either by hand or with dedicated equipment, to extract valuable components and materials. may use. Dismantling by the dismantler can be carried out by hand tools like screwdrivers, wrenches, pliers, wire cutters, tongs and hammers etc. The dismantled material should be referred to authorised e-waste recyclers or recyclers having legal consent to operate (CTO). Manual dismantling operations should be carried out over the dismantling table with space de-dusting system so as to preserve desirable work zone air quality as per the factories Act (amended). The de dusting system should consist of suction hoods placed over dismantling table linked with a storm bag filter and expelling through a

chimney of three-meter height above roof level. Collection boxes should be placed near dismantling table for keeping the dismantled components. During dismantling operations, the workers should use proper personal protective equipment such as goggles, masks, gloves, helmet and gumboot etc. Dismantlers are not permitted to carry out chemical leaching or heating process or melting the E-waste components. E-waste management facilities should have proper arrangement for the collection of coolant/refrigerant gases and compressor oil, mercury from end of life fluorescent before starting the dismantling. Dismantled batteries, circuit boards, capacitors and capacitors containing Polychlorinated biphenyls /Polychlorinated terphenyls should be warehoused in closed space. Tools used for the collection of spills should be exclusive booms or absorbent pads, dry sand, stabilizing substances in the form of chemical compounds. The premise for dismantling operation must have Water proof roofing and surfaces.

Recycling and Refurbishment: Most of the e-waste is discarded because of minor defects, reduced performance, or software/hardware modernization. These can be refurbished and put on for resale at a low price. During refurbishment of e-waste, the parts are segregated, improved and can be reused. The refurbishing process involves; Initial analysis of the product, followed by Sanitisation and Wiping of data. This is then Repaired for software enhancement. After which it is tested. Further some cosmetic changes are made to make it compatible with the market demand. It is essential that refurbished EEE gadget should feel like 'new' along with performance like a 'new' one (who.int.)

Fridge, washing machines, TVs, Monitors & CRT, keyboards, laptops, modems, telephones, hard drives, floppy drives, Compact disks, mobiles, fax machines, printers, CPUs, memory chips, connecting wires & cables can be recycled. Recycling

involves dismantling (Krishnamoorthy et al). This involves removal of different parts of e-waste that contains risky materials like printed circuit boards, Polychlorinated biphenyls, mercury and its salts, separation of plastic, removal of CRT, separation of ferrous and nonferrous metals. Precious metals copper, gold, palladium are dissolved in strong acids before they are precipitated. Recyclable material like plastic and glass etc. is converted into new products.

Safe Disposal of Hazardous Materials (Wath et al.): Hazardous materials are handled according to specific regulations to prevent environmental contamination. Chemical treatment, incineration or high-temperature treatment, safe storage are the disposal options. Hazardous waste is recovered from E-waste and recycled. Most hazardous waste cause irrevocable loss to humans (Krishnamoorthy et al).

Barium; Barium metal is oxidised to a poisonous oxide which is very injurious for the functioning of the heart muscles, spleen and liver. It also causes brain oedema.

Arsenic; It mainly causes skin diseases, reduced neural conduction, causes lung cancer and can be fatal.

Beryllium; it is carcinogenic; causes lung cancer (dtsc.ca.gov).

Cadmium; Cadmium exposure is coupled with lung cancer, prostate and renal cancer.

Chromium; Hexavalent chromium compounds are man-made toxic and carcinogen form which is widely used in different electronic products. It can cause lung cancer, irritation or damage to the nose, throat, and lung (respiratory tract), irritation or damage to the eyes and skin etc.

Mercury; Elemental and methyl mercury are toxic to the central and peripheral nervous systems, digestive and immune systems, lungs and kidneys, and may be fatal. The inorganic salts of mercury are eroding to the skin, eyes and gastrointestinal tract, and may induce kidney toxicity if ingested. Neurological and behavioural disorders,

tremors, insomnia, memory loss may also be observed (Needhidasan et al.).

Lead; Exposure to lead can cause serious health issues like neurological damage and developmental delays in children.

Nickel, Yttrium, Europium, Selenium, Zinc Sulphide, Americium are some of the other metals present in e-waste which cause similar health issues.

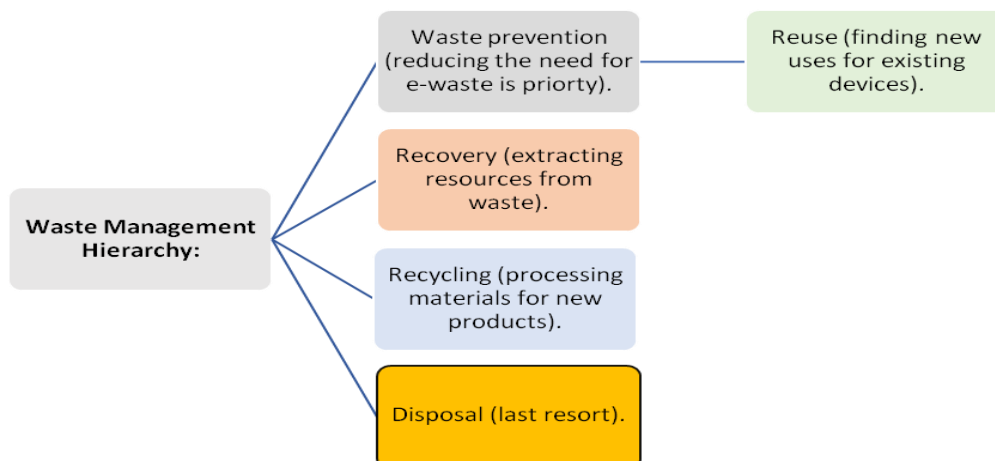


Figure: 1. E-Waste Management Process:

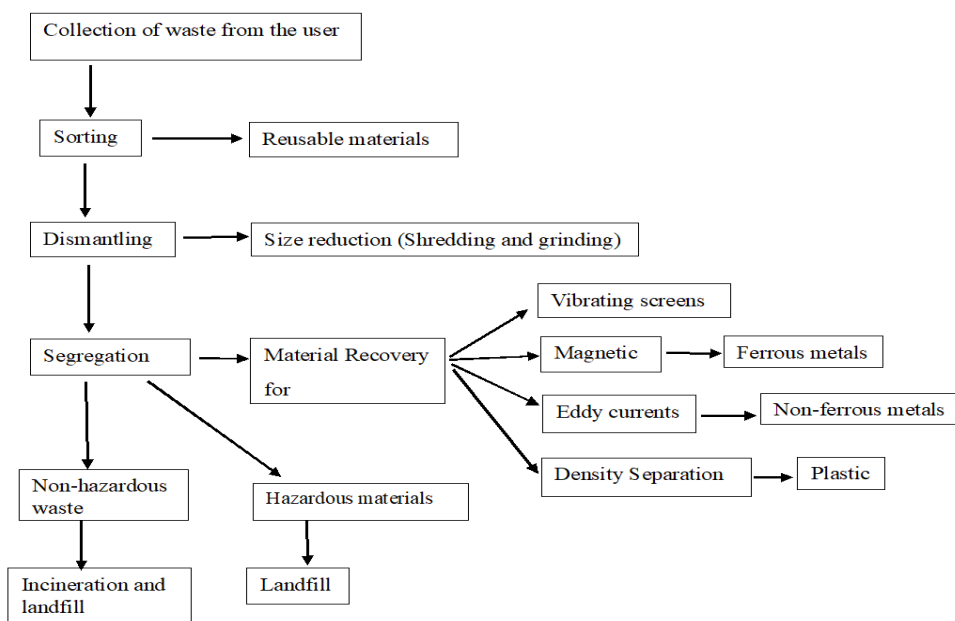


Figure: 2. E-Waste Management Process

Result and Discussion:

E-waste management and Challenges in India

On the Environmental Performance Index India lie far behind the list. Our country generates beyond two million tonnes of e-waste per year. Electronic dumps contain significant amounts of toxic metals that leach

into the ground, water bodies and air. This causes harmful impacts on the environment and human health too. For this proper scientific management of the e-Waste is required. There are proper e-waste management rules in India but waste management is mostly limited to the

metropolitan cities that too partially (Annamalai, J).

Poor infrastructure to recycle e-waste, A serious lack of awareness, Mismanagement of products and Unsustainable and ecologically degradation are the main challenges in E-waste management. Dismantlers are not permitted to carry out chemical leaching or heating process or melting the E-waste components (Joon et al.). E-waste management facilities should have proper arrangement for the collection of coolant/refrigerant gases and compressor oil, mercury from end of life fluorescent before starting the dismantling. Dismantled circuit boards, capacitors, batteries, capacitors containing polychlorinated biphenyls or polychlorinated terphenyls ought to be stored in closed space. Dry sand, exclusive booms and absorptive pads, stabilizing chemicals should be used to prevent spills of broken fluorescent lamps and Oils. The premise for dismantling operation must have Water proof roofing and surfaces.

Karo Sambhav, a certified PRO in India, endeavours to improvise and maximise the efficiency and scope of formal E-waste management. The organisation uses cutting-edge technology and an upgraded EPR framework to educate and incentivize electronic waste recycling.

Conclusion:

If e-waste is managed properly, it becomes a powerful tool for environmental conservation and sustainable development. Scientific segregation, safe collection, and environmentally sound recycling prevent the release of hazardous substances into soil, water, and air. The recovery of valuable materials like copper, aluminium, gold, and rare earth elements reduces dependence on virgin mining and conserves natural resources. Effective implementation of e-waste management rules will promote a circular economy. This will also creates green employment opportunities, will

improve occupational safety. In the long term, responsible e-waste management minimizes health risks, supports technological sustainability, and ensures that rapid modernization does not compromise environmental and human well-being.

Acknowledgment:

Thanks to the management of LPU Phagwara who has always supported the researchers to pursue their research fruitfully.

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