Frontiers in Health Informatics
ISSN-Online: 2676-7104
www.healthinformaticsjournal.com
2023; Vol 12
Open Access

Composition of Heavy Metals in Electronic Waste and Their Impacts on Human Health and the Environment

Poonam Yadav[1], Savita Kalshan[2], Shivani Narwal[3], Amit Chhillar[4], Rajesh Dhankhar[5]
(e-mail: [1]poonam1987yadav@gmail.com; [2]savita.rs.evs@mdurohtak.ac.in; [3]Shivuunarwal7@gmail.com; [4]chhillar035@gmail.com; [5]rajeshdhankar.EVS@mdurohtak.ac.in)
Department of Environmental Science, Maharshi Dayanand University, Rohtak-124001, Haryana, India.

Cite this paper as: Poonam Yadav, Savita Kalshan, Shivani Narwal, Amit Chhillar, Rajesh Dhankhar (2023). Composition of Heavy Metals in Electronic Waste and Their Impacts on Human Health and the Environment. *Frontiers in Health Informatics*, *Vol.12(2023), 561-574*

Abstract
The rapid growth of electronic waste (e-waste) has now emerged as a major environmental and public health concern due to the presence of toxic heavy metals. This research paper examines the composition of various toxic heavy metals present in e-waste, their release pathways, and associated human health and environmental impacts. Results indicate that metals such as cadmium, lead, mercury, chromium, nickel, copper, arsenic, and antimony are prevalent in electronic components and are readily mobilized through informal recycling practices. Occupational exposure among informal recyclers and indirect exposure of surrounding communities through contaminated food and water are identified as major risk pathways. Exposure to these metals is linked to neurological, renal, respiratory, and carcinogenic effects, while environmental contamination leads to bioaccumulation and ecosystem degradation. The review highlights regulatory gaps in enforcement and implementation, particularly in developing countries and emphasizes the need for standardized assessment methods, sustainable recycling technologies, stronger regulatory enforcement, and integration of informal recycling sectors into formal systems.
Keywords: Electronic waste; Heavy metals; Human health; Environmental pollution; Informal recycling.

1. Introduction
The rapid advancement of science and technology over the past few decades has significantly increased the production, consumption, and disposal of electrical and electronic equipment (EEE). The advancements in technological innovation, while improving quality of life, has inadvertently created an unprecedented surge in electronic waste (e-waste), which is now among the fastest-growing solid waste streams worldwide (Forti et al., 2020; Kumar et al., 2017). E-waste comprises discarded electrical and electronic devices such as computers, mobile phones, televisions, refrigerators, and other consumer and industrial electronics that have reached the end of their useful life. According to recent global estimates, more than 60 million tonnes of e-waste are generated annually, with projections indicating a continuous increase due to rapid product obsolescence, urbanization, and digitalization (Baldé et al., 2024).
A major environmental and public health concern associated with e-waste arises from its complex chemical composition, particularly the toxic heavy metals. Electronic components such as printed circuit boards, cathode ray tubes, batteries, and semiconductors contain significant concentrations

of metals including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), nickel (Ni), copper (Cu), arsenic (As), antimony (Sb), and zinc (Zn) (Singh et al., 2018; Zhang et al., 2017). While some of these metals are valuable and recoverable, but their release into the environment during improper handling, informal recycling, and open dumping poses serious ecological and human health risks.

In many developing countries, e-waste management is largely dominated by informal recycling practices that involve manual dismantling, open burning, and chemical leaching, often without any environmental safeguards or personal protective equipment (Awasthi et al., 2019). These practices facilitate the discharge of heavy metals into soil, water bodies, and the atmosphere, leading to widespread contamination and exposure. Studies have reported elevated concentrations of cadmium, lead and mercury in the soil and groundwater near informal e-waste recycling sites, frequently exceeding permissible limits set by international regulatory agencies (Pradhan and Kumar, 2014; Abubakar et al., 2022). Such contamination not only degrades environmental quality but also enables the bioaccumulation of toxic metals into plants, animals, and ultimately in human beings through the food chain.

Heavy metal exposure originating from e-waste is strongly associated with adverse health outcomes. Chronic exposure to lead is known to cause neurological disorders, particularly in children, while cadmium exposure is linked to renal dysfunction and bone demineralization. Mercury is a potent neurotoxin, and hexavalent chromium is recognized for its carcinogenic potential (Jaishankar et al., 2014; Balali-Mood et al., 2021, WHO, 2023). Informal e-waste workers and nearby residents are among the most vulnerable populations, experiencing higher body burdens of toxic metals due to occupational exposure by contaminated food and water consumption, and inhalation of toxic metals polluted dust (Grant et al., 2013; Anselm et al., 2021).

Research into electronic waste is prolific, contributing to an ever-growing repository of literature, but existing studies are often fragmented, focusing either on metal recovery, environmental contamination, or isolated health impacts. A comprehensive synthesis that integrates the composition of heavy metals in electric waste along with their environmental pathways and health implications is still limited. Moreover, variations in reported metal concentrations across different types of electronic devices and geographical regions warrant a critical comparative analysis to identify the most hazardous components and exposure scenarios. Such an integrated understanding is crucial for developing effective regulatory frameworks, sustainable recycling strategies, and risk mitigation measures.

Therefore, the present study aims to provide a review-cum-analysis of the composition of heavy metals in electronic waste and critically examine their impacts on human health and the environment. Specifically, this paper seeks to: (i) systematically review the reported composition and concentration ranges of heavy metals in various e-waste components; (ii) analyze the major pathways through which these metals are released into the environment; (iii) critically assess the associated health and ecological risks; and (iv) identify research gaps and will have some suggested future directions for sustainable e-waste management and heavy metal mitigation.

By synthesizing recent research findings and providing analytical insights, this review is expected to serve as a valuable reference for researchers, policymakers, and environmental practitioners working toward safer and more sustainable management of electronic waste.

2. Composition of Heavy Metals in Electronic Waste

Electronic waste is composed of diverse components including printed circuit boards, batteries, displays, and cables. Thus, Electronic waste is a heterogeneous mixture of metals, polymers, ceramics, and glass, with heavy metals constituting a significant fraction of its hazardous components. The type and concentration of heavy metals in e-waste vary considerably depending on the category of electronic equipment, component type, manufacturing period, and geographic origin. Printed circuit boards (PCBs), cathode ray tubes (CRTs), batteries, switches, connectors, and solders are recognized as the most metal-rich fractions. PCBs, in particular, contain a complex mixture of base metals and toxic elements due to their multilayered structure and use of metal alloys (Onwasi et al., 2019).

Key Heavy Metals Present in Electronic Waste

2.1 Lead (Pb)

Lead is recognized as one of the most plentiful and hazardous heavy metals present in various electronic equipments and e-waste generated by these equipments. It is extensively used in solders, Cathode Ray Tube (CRT) glass, cables, and batteries. Studies report lead concentrations ranging from 1,000 to 25,000 mg/kg in printed circuit boards and CRT components, often exceeding permissible environmental limits (Pradhan and Kumar, 2014; Abubakar et al., 2022; WHO, 2023). Due to its high toxicity and persistence, lead remains a major concern in informal recycling and disposal sites.

2.2 Cadmium (Cd)

Cadmium is mainly present in rechargeable batteries, infrared(IR) detectors, semiconductors and chip resistors. Although present in relatively lower concentrations compared to lead, cadmium is highly toxic even at trace levels. Reported concentrations in e-waste components range from 5 to 300 mg/kg (Zhang et al., 2017). Improper handling of cadmium-containing components can lead to significant soil and groundwater contamination.

2.3 Mercury (Hg)

Mercury is commonly found in fluorescent lamps, LCD backlights, relays, and switches. Mercury concentrations in e-waste are generally lower than other metals; however, its volatility and neurotoxicity make it extremely hazardous. Concentrations between 0.1 and 50 mg/kg have been reported, with significant release occurring during dismantling and breakage of mercury-containing components (Anselm et al., 2021; Andeobu et al, 2023).

2.4 Chromium (Cr)

Chromium, particularly hexavalent chromium [Cr(VI)], is used for corrosion protection in metal housings and coatings. Chromium concentrations in e-waste typically range from 100 to 5,000 mg/kg, depending on the component type (Awasthi et al., 2019). The presence of Cr(VI), a known carcinogen, raises serious occupational and environmental health concerns.

2.5 Nickel (Ni) and Copper (Cu)

Nickel and copper are widely used in wiring, connectors, and printed circuit boards. Copper is often present in very high concentrations, mostly its range varying from 10,000 to 200,000 mg/kg, making e-waste a secondary resource for metal recovery (Kumar et al., 2017). Nickel concentrations generally range from 200 to 5,000 mg/kg. While copper is less toxic, excessive accumulation can still pose ecological risks.

2.6 Arsenic (As), Antimony (Sb), and Zinc (Zn)

Arsenic and antimony are used in semiconductors, flame retardants, and alloys. Their concentrations vary widely but are frequently reported range is of 10–1,000 mg/kg. Zinc is present in coatings and alloys and can even reach concentrations up to 20,000 mg/kg in certain components (Singh et al., 2018).

Table 1: Typical heavy metal composition in common e-waste components

E-waste component	Major heavy metals	Reported concentration range (mg/kg)	Key references
Printed circuit boards	Cu, Pb, Ni, Cr, Cd	500–200,000	Pradhan and Kumar, 2014; Onwasi et al., 2019
Cathode ray tubes	Pb, Ba, Sr	1,000–25,000	Abubakar et al., 2022
Batteries	Cd, Ni, Pb, Hg	50–30,000	Zhang et al., 2017
Cables & wires	Cu, Pb	5,000–150,000	Kumar et al., 2017
LCDs & lamps	Hg, Pb	0.1–5,000	Andeobu et al, 2023

A comparative analysis of reported data (Table 1) indicates that PCBs and CRTs are the most hazardous e-waste fractions in terms of heavy metal content. Copper dominates by mass, whereas lead, cadmium, mercury, and chromium pose the greatest toxicological risks (Anselm et al., 2021). Informal recycling activities significantly increase the mobilization of these metals, resulting in localized contamination hotspots. Notably, studies conducted in developing countries report substantially higher environmental concentrations of Pb, Cd, and Cr near e-waste processing sites compared to regulated recycling facilities in developed regions (Grant et al., 2013). This disparity highlights the influence of recycling practices on metal release rather than metal content alone.

Analytical Perspective

The heterogeneous composition of various heavy metals in the e-waste complicates risk assessment and management strategies. Metals like Pb, Cd, Hg, and Cr(VI) are consistently identified as priority pollutants due to their toxicity, persistence, and bioaccumulative nature. Understanding their distribution across the components of e-waste become essential for targeted interventions, safer recycling practices, and policy formulation.

3. Release Mechanisms and Environmental Pathways

The environmental and health risks associated with electronic waste are largely governed by the pathways through which heavy metals are released and subsequently exposed to living organisms. Although heavy metals are initially embedded within electronic components, improper handling, informal recycling techniques, specifically open incineration and acid washing, and uncontrolled disposal practices facilitate their mobilization into soil, water, and air. Understanding these pathways is essential for assessing contamination risks and designing effective mitigation strategies.

3.1 Release of Heavy Metals during E-Waste Processing

Heavy metals are being released from e-waste at various steps primarily during collection, dismantling, recycling and disposal stages. In informal recycling sectors, manual dismantling, open burning of cables, and acid leaching of printed circuit boards are commonly employed to recover valuable metals. These crude techniques significantly accelerate the release of metals like cadmium, lead, mercury and chromium into the environment (Awasthi et al., 2019; Grant et al., 2013; Anselm et al., 2021).

Open burning of plastic-coated wires releases metal-laden particulate matter and toxic fumes, while acid leaching mobilizes metals into liquid effluents that are often discharged untreated into nearby soils and water bodies. In contrast, controlled recycling facilities in developed regions employ enclosed systems and pollution control technologies, thereby reducing but not entirely eliminating metal emissions (Kumar et al., 2017).

3.2 Soil Contamination Pathway

Soil is one of the primary environmental sinks for heavy metals released from e-waste. Metals enter soil through direct dumping of e-waste residues, deposition of airborne particulates, and discharge of contaminated wastewater. Numerous studies have reported elevated concentrations of Pb, Cd, Cu, and Cr in soils surrounding informal recycling sites, often exceeding background levels and regulatory thresholds (Pradhan and Kumar, 2014; Abubakar et al., 2022).

Once after entering in the soil, heavy metals exhibit long-term persistence and can bind to organic matter or clay particles. Soil contamination poses direct risks to agricultural productivity and acts as a secondary source of contamination for groundwater and crops, thereby amplifying human exposure risks.

3.3 Water Contamination Pathway

Heavy metals released from e-waste can infiltrate surface water and groundwater systems through leaching and runoff. Acidic conditions generated during informal recycling enhance the solubility and mobility of metals like Cd, Pb, and Ni, increasing their transport into water bodies (Zhang et al., 2017). Contaminated groundwater near e-waste processing sites has been reported to contain metal concentrations significantly above WHO drinking water limits.

Aquatic contamination not only affects water quality but also leads to the accumulation of metals in sediments and aquatic organisms. Fish and other aquatic species exposed to metal-contaminated water may accumulate toxic metals in their tissues, posing dietary risks to humans.

3.4 Airborne Release and Atmospheric Exposure

Airborne pathway plays a very critical role in the dispersion of various heavy metals present in the e-waste during waste recycling activities. Open burning and mechanical processing generate fine particulate matter enriched with metals such as Pb, Cd, and Cr. These particles can be transported over long distances, leading to regional contamination (Andeobu et al, 2023).

Inhalation of contaminated dust is a major exposure route for informal recyclers and nearby residents. Studies have reported higher concentrations of heavy metals in airborne dust and in blood and urine samples of the workers involved in informal e-waste recycling compared to non-exposed populations (Grant et al., 2013).

3.5 Human Exposure Pathways

Human beings exposure to heavy metals originating from e-waste occurs through many pathways, including inhalation, ingestion, and dermal contact. Occupational exposure is particularly significant among informal recyclers who handle e-waste without protective equipment. Chronic exposure through inhalation of metal-laden dust and fumes is associated with neurological, respiratory, and carcinogenic effects.

Non-occupational exposure affects surrounding communities through consumption of contaminated food and water. Children are more vulnerable due to their hand-to-mouth behavior and thier higher absorption rates of metals such as lead and cadmium (Balali-Mood et al., 2021; WHO, 2023). The cumulative nature of heavy metal exposure further exacerbates long-term health risks.

3.6 Bioaccumulation and Food Chain Transfer

Heavy metals that are released from e-waste bioaccumulates in the plants and animals, leading to biomagnification along the food chain. Crops grown on contaminated soils may accumulate metals in edible tissues, while livestock exposed to contaminated feed and water can act as secondary exposure sources for humans. Metals such as Hg, Cd, and As are particularly known for their bioaccumulative properties (Jaishankar et al., 2014).

This indirect exposure pathway underscores the far-reaching impacts of improper e-waste management, extending beyond recycling sites to broader ecosystems and food systems.

Analytical Perspective

An integrated analysis of exposure pathways reveals that informal recycling practices are dominant drivers of heavy metal release and exposure. While the composition of e-waste determines the types of metals present, the intensity of environmental and health impacts is largely influenced by processing methods. This distinction highlights the importance of policy enforcement, technological intervention, and community awareness in reducing exposure risks.

4. Human Exposure Pathways and Health Impacts

The composition of heavy metals in electronic waste poses a significant risk to human health due to their toxicity, persistence, and bioaccumulative nature. Exposure to these heavy metals occurs through occupational activities, environmental contamination, and food chain transfer, as discussed in the previous section. Unlike organic pollutants, heavy metals are non-biodegradable and accumulate in human tissues over the time and thus leading to chronic and often irreversible health effects. Chronic exposure is associated with neurological disorders, kidney damage, respiratory diseases, and cancer.

Populations residing near informal e-waste recycling sites and workers involved in dismantling and metal recovery are exposed to complex mixtures of toxic metals through inhalation of these metals contaminated dust, ingestion of polluted food and water, and dermal contact. Biomonitoring studies have consistently reported elevated concentrations of Cd, Pb, Hg, and Cr in blood, urine, and hair samples of exposed individuals compared to control populations (Grant et al., 2013; Abubakar et al., 2022). Such exposure is associated with neurological disorders, respiratory diseases, renal impairment, and increased cancer risk.

4.1 Metal-Specific Health Impacts

Lead (Pb)

Lead is considered as one of the most extensively studied toxic metals associated with electronic equipments and e-waste. Chronic exposure to lead affects the central nervous system(CNS), hematopoietic system and kidneys. In children, even low-level exposure has potential to reduce intelligence quotient (IQ) and learning disabilities and even lead to many behavioral problems. In adults, exposure to lead has been linked to hypertension, anemia, and reproductive toxicity (Balali-Mood et al., 2021; WHO, 2023). Informal e-waste recyclers often exhibit blood lead levels exceeding recommended safety thresholds due to prolonged occupational exposure.

Cadmium (Cd)

Cadmium exposure primarily affects the renal and skeletal systems. Long-term accumulation in the kidneys can lead to renal dysfunction, proteinuria, and eventual kidney failure. Cadmium is also associated with bone demineralization and osteoporosis, particularly in chronically exposed populations. Additionally, cadmium is classified a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) (Jaishankar et al., 2014).

Mercury (Hg)

Mercury, especially in its organic forms, is a potent neurotoxin. Exposure can impair cognitive function, memory, and motor coordination. Prenatal and early childhood exposure to mercury is particularly harmful, as it interferes with brain development. Workers handling mercury-containing components such as fluorescent lamps and switches are at increased risk of neurological disorders (Anselm et al., 2021; Andeobu et al., 2023).

Chromium (Cr)

Chromium exists in many oxidation states, with hexavalent chromium [Cr (VI)] being the most toxic. Cr (VI) exposure is associated with respiratory problems, skin ulceration, allergic reactions, and lung cancer. In e-waste recycling settings, chromium exposure occurs through inhalation of contaminated dust and fumes, which are released during dismantling, and metal treatment processes (Awasthi et al., 2019).

Nickel (Ni) and Copper (Cu)

Nickel exposure can cause allergic dermatitis, respiratory issues, and carcinogenic effects upon long-term inhalation. Copper, while an essential trace element, can cause gastrointestinal distress and liver damage when present in excessive concentrations. Elevated levels of nickel and copper have been detected in biological samples of e-waste workers, indicating occupational exposure risks (Kumar et al., 2017).

Arsenic (As) and Antimony (Sb)

Arsenic exposure is may cause skin lesions, cardiovascular diseases, and various cancers, including skin and lung cancer. Antimony exposure can cause respiratory irritation, cardiovascular effects, and gastrointestinal disorders. Although typically present in lower concentrations, their chronic exposure through e-waste cannot be overlooked (Singh et al., 2018).

4.2 Vulnerable Populations

Certain population groups are disproportionately affected by heavy metal exposure from e-waste. Informal recyclers, often working without protective equipment, experience high occupational exposure. Children living near recycling sites are particularly vulnerable due to their developing physiological systems, higher absorption rates, and hand-to-mouth behavior. Pregnant women exposed to heavy metals face increased risks of adverse birth outcomes of the developing fetus, including low birth weight of the baby and various developmental disorders in infants (Balali-Mood et al., 2021).

4.3 Cumulative and Synergistic Effects

An important analytical aspect of e-waste exposure is the combined effect of multiple metals. Humans are rarely exposed to a single metal; instead, they encounter complex mixtures that may produce additive or synergistic toxic effects. This cumulative exposure complicates risk assessment and may intensify health outcomes beyond what is predicted for individual metals alone (Grant et al., 2013).

Analytical Perspective

The analysis of existing studies indicates that the severity of health impacts is not solely dependent on concentration of the particular metal in e-waste but is strongly influenced by exposure duration, recycling practices, and socio-economic conditions. Informal recycling environments consistently show higher health risks compared to regulated facilities, underscoring the need for improved occupational safety, policy enforcement, and community-level interventions.

5. Environmental Impacts

The improper management of electronic waste has now emerged as a major source of environmental pollution due to the discharge of many toxic heavy metals into various environmental compartments. Once released, these metals persist in the environment, undergo complex transformations, and exert long-term ecological effects. The environmental impacts of heavy metals released from electronic devices and e-waste are evident across soil, water, air, and biological systems, posing serious threats to ecosystem integrity and sustainability.

5.1 Soil Contamination and Degradation

Soil is the primary receptor of heavy metals released from e-waste through open dumping, informal recycling, and atmospheric deposition. Numerous studies have documented elevated concentrations of Pb, Cd, Cu, Ni, and Cr in soils surrounding e-waste dismantling and recycling sites, often exceeding background levels by several orders of magnitude Pradhan and Kumar, 2014; Abubakar et al., 2022). These heavy metals exhibit strong affinity for soil particles and organic matter, resulting in long-term persistence.

Heavy metal accumulation adversely affects soil physicochemical properties, microbial activity, and nutrient cycling. Elevated metal concentrations can inhibit soil enzymes, reduce microbial diversity, and impair plant growth, thereby diminishing soil fertility and agricultural productivity. Contaminated soils also act as secondary sources of pollution, releasing metals into groundwater and crops over time.

5.2 Water Pollution and Aquatic Ecosystems

Heavy metals from e-waste often enter into surface water and groundwater systems by leaching, runoff, and discharge of untreated recycling effluents. Acidic conditions commonly associated with informal recycling enhance mobility and solubility of metals like Cd, Pb, and Ni, facilitating their transport into various water bodies (Zhang et al., 2017). Elevated metal concentrations in rivers, ponds, and groundwater near e-waste processing sites have been reported to exceed international drinking water standards.

Aquatic ecosystems are particularly vulnerable to heavy metal contamination. Metals accumulate in sediments, where they can be remobilized under changing environmental conditions. Aquatic organisms, including fish, mollusks, and plankton, readily bioaccumulate metals, leading to impaired growth, reproductive failure, and increased mortality. Such contamination disrupts aquatic food webs and poses significant risks to human populations dependent on these water resources.

5.3 Air Pollution and Atmospheric Deposition

Airborne emissions represent a critical pathway for dispersion of many heavy metals during various e-waste recycling activities. Activities like open burning of cables, plastic components, and circuit boards releases metal-laden particulate matter and toxic fumes into the atmosphere. Metals such as Pb, Cd, and Cr are commonly detected in airborne dust near informal recycling sites (Andeobu et al., 2023).

These fine particles can be transported over long distances before settling on soil and water surfaces, contributing to regional-scale contamination. Atmospheric deposition not only degrades air quality but also serves as an indirect source of soil and water pollution, extending the e-waste environmental footprint beyond the capacity of recycling hotspots.

5.4 Bioaccumulation and Ecological Risks

One of the most concerning environmental impacts of various heavy metals released from e-waste is their tendency to bioaccumulate and biomagnify within ecosystems. Plants grown on contaminated soils absorb metals through their root systems, which are then transferred to herbivores and higher trophic levels. Metals like Cd, Hg and As are particularly prone to bioaccumulation, resulting in elevated concentrations in predators which are present at the top of the food chain (Jaishankar et al., 2014).

Chronic exposure to many heavy metals can even cause physiological and behavioral changes in wildlife, including reduced reproductive success, immune suppression, and increased susceptibility to disease. These effects threaten biodiversity and ecosystem stability, especially in regions with intensive informal recycling activities.

5.5 Ecotoxicological and Long-Term Environmental Implications

From an ecotoxicological perspective, the combined presence of multiple heavy metals in e-waste creates complex exposure scenarios. Synergistic interactions among metals may enhance toxicity, making environmental impacts more severe than predicted based on individual metal concentrations alone. Long-term contamination can result in irreversible ecosystem damage, loss of biodiversity, and reduced resilience to environmental stressors.

Analytical Perspective

An integrated analysis of environmental studies reveals that informal and unregulated e-waste recycling practices are the primary drivers of heavy metal pollution. While the metal composition of e-waste determines contamination potential, the magnitude and spatial extent of environmental impacts are largely influenced by processing methods and regulatory enforcement. Addressing these challenges requires a combination of technological interventions, policy implementation, and environmental monitoring to mitigate the ecological risks posed by e-waste-derived heavy metals.

6. Regulatory Frameworks and Management Strategies

The escalating environmental and health risks associated with various heavy metals in electronic waste have prompted the development of regulatory frameworks at international, regional, and national levels. These regulations aim to control the generation, transboundary movement, recycling, and disposal of e-waste while minimizing heavy metal exposure. However, significant disparities exist in regulatory implementation and enforcement across different regions of the world, particularly in developing countries.

6.1 International Regulatory Frameworks

At the global level, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal serves as a primary legal instrument for governing e-waste movement across various countries. The convention restricts export of hazardous waste, including the e-waste containing toxic heavy metals, from developed to developing countries without prior informed consent. Amendments to the Basel Convention have strengthened controls on e-waste trafficking, recognizing its hazardous nature due to metals like Pb, Cd, Hg and Cr (Mihai et al, 2022).

The World Health Organization (WHO) and the United Nations Environment Programme (UNEP) provide guidelines on permissible exposure limits and risk assessment related to heavy metals. These guidelines form the scientific basis for national standards on drinking water quality, occupational exposure, and environmental protection.

6.2 Regional Regulations

European Union

The European Union has implemented some of the world's most exceptionally and comprehensive e-waste rules. The Restriction of Hazardous Substances (RoHS) Directive includes provisions that limit the use of specific heavy metals such as lead, mercury, cadmium, and hexavalent chromium in electrical and electronic equipment. Additionally, the Waste Electrical and Electronic Equipment (WEEE) Directive makes the extended producer responsibility (EPR) very obligatory, requiring the Electrical and Electronic Equipment manufacturers to finance the collection, recycling and safe disposal of e-waste. These regulations have significantly reduced heavy metal content in newer electronic products and improved recycling efficiency.

United States

United States e-waste regulation is largely decentralized, with individual states implementing their own laws. The Resource Conservation and Recovery Act (RCRA) governs hazardous waste management, while state-level EPR programs regulates collection and recycling of e-waste. However, the absence of a unified federal e-waste law has resulted in variability in enforcement and recycling outcomes across states.

Asia and Developing Regions

Asian countries, particularly China and India, are among the largest producers and recipients of e-waste. China has implemented strict import bans on foreign e-waste and strengthened domestic recycling regulations. India introduced the E-Waste (Management) Rules, which is emphasizing on the extended producer responsibility and formal recycling systems. Despite these efforts, informal recycling sectors remain dominant in many developing countries, leading to continued heavy metal exposure and environmental contamination (Awasthi et al., 2019).

6.3 Global Scenario and Challenges

Globally, there is a stark contrast between developed and developing countries in the terms of management of e-waste. Developed nations generally possess advanced recycling infrastructure and regulatory enforcement mechanisms, resulting in lower environmental release of various toxic metals. In contrast, developing countries often lack adequate infrastructure, regulatory oversight, and occupational safety measures, leading to widespread informal recycling and higher contamination levels (Forti et al., 2020; Baldé et al., 2024).

Illegal transboundary movement of e-waste further exacerbates the problem. Despite international regulations (Table 2), significant quantities of e-waste continue to be exported to regions with weak environmental controls, shifting the burden of heavy metal pollution to vulnerable communities.

Table 2: Major regulatory frameworks addressing heavy metals in electronic waste

Region	Key regulation	Focus on heavy metals	Implementation status
Global	Basel Convention	Transboundary control of hazardous e-waste	Partial compliance
EU	RoHS, WEEE Directives	Restriction and recovery of Pb, Cd, Hg, Cr	Strong enforcement
USA	RCRA, State EPR laws	Hazardous waste control	Variable by state
India	E-Waste Management Rules	EPR and formal recycling	Emerging
China	Import bans, recycling laws	Domestic control and recovery	Strengthening

Analytical Perspective

A critical analysis of existing regulatory frameworks reveals that policy effectiveness is strongly influenced by enforcement capacity rather than regulatory presence alone. While stringent regulations in developed regions have reduced heavy metal emissions, regulatory gaps and informal recycling practices continue to undermine environmental protection efforts in developing countries. Strengthening international cooperation, improving enforcement mechanisms, and integrating informal recyclers into formal systems are essential to mitigating heavy metal risks from e-waste.

7. Research Gaps, Challenges and Future Perspectives

In the future, research should be focused on standardized assessment methods, cleaner recycling technologies, and integration of informal sectors into formal waste management systems.

7.1 Key Research Gaps

One of the major research gaps lies in the lack of standardized methodologies for assessing heavy metal composition in e-waste. Variations in sampling protocols, analytical techniques, and reporting units across studies limit direct comparability and hinder the development of reliable global datasets. Many studies focus on isolated components or specific metals, often overlooking the complex mixture of heavy metals present in e-waste.

Another critical gap is the limited availability of long-term epidemiological data linking heavy metal exposure from e-waste to chronic health outcomes. Most existing studies rely on short-term exposure assessments or biomonitoring data, which do not fully capture cumulative and synergistic effects of multiple metals over extended periods. Additionally, data from informal recycling sectors and low-income regions remain sparse, despite these areas experiencing the highest exposure levels.

Policy and Regulatory Gaps

Although international and national regulations addressing e-waste exist, implementation and enforcement remain inconsistent. Weak regulatory oversight, inadequate monitoring systems, and illegal transboundary movement of electronic waste undermine the effectiveness of existing frameworks. In many regions, informal recycling operates outside regulatory control, limiting the impact of policies designed to reduce heavy metal exposure.

Additionally, limited integration of public health considerations into e-waste policies reduces their effectiveness. Stronger collaboration between environmental authorities, public health agencies, and local communities is required to address multifaceted risks associated with various heavy metals present in e-waste.

7.2 Technical and Socioeconomic Challenges

The management of various heavy metals in e-waste is complicated by technical and socioeconomic challenges. Informal recycling practices persist due to economic incentives, lack of alternative livelihoods, and insufficient formal recycling infrastructure. The high cost of advanced recycling technologies and limited access to technical expertise further constrain the adoption of environmentally sound management practices in developing countries.

From a technical perspective, separating and recovering toxic heavy metals while minimizing environmental release remains challenging. Current recycling technologies often prioritize the recovery of valuable metals such as copper and gold, with less emphasis on safely handling toxic heavy metals like lead, cadmium and mercury. This imbalance increases the risk of environmental contamination and occupational exposure.

7.3 Future Research Directions

The future research should be more concentrated on heavy metals in electronic waste and prioritizing on the development of various standardized protocols for sampling, analysis, and reporting of various heavy metals present in the electronic waste to improve data comparability. Integrated studies combining environmental monitoring, biomonitoring, and health risk assessment are needed to better understand exposure pathways and long-term health outcomes.

Advancements in clean and sustainable recycling technologies, such as bioleaching, green solvents, and closed-loop systems, offer promising avenues for reducing heavy metal emissions.

Research should also focus on life cycle assessment and cost–benefit analysis to evaluate the environmental and economic viability of emerging recycling approaches.

A transition toward sustainable e-waste management requires a holistic approach that combines technological innovation, policy enforcement, and social inclusion. Integrating informal recyclers into formal systems through training, financial incentives, and protective regulations can significantly reduce heavy metal exposure. Public awareness campaigns and extended producer responsibility programs can further support safer handling and disposal of electronic products.

Analytical Perspective

From an analytical standpoint, the challenges associated with heavy metals in e-waste are not solely technical but deeply rooted in socioeconomic and governance structures. Bridging research gaps, strengthening regulatory enforcement, and promoting sustainable recycling practices are essential for mitigating the long-term environmental and health impacts of e-waste. Addressing these challenges presents an opportunity to convert e-waste from the source of various pollution into a resource for sustainable development.

8. Conclusion

The electronic waste contains significant concentration of hazardous metals like cadmium, chromium, lead, mercury, nickel, arsenic and antimony, which pose serious risks due to their toxicity, persistence, and bioaccumulative nature. Thus, effective management of electronic waste is very important for the reduction of heavy metals pollution and protecting human health and the environment.

The improper handling and informal recycling practices are primary drivers for the release of various heavy metals into the soil, water, and air. These pathways facilitate widespread environmental contamination and increase human exposure through various modes like inhalation, ingestion or dermal contact. Informal recyclers, nearby communities, children, and pregnant women are identified as the most vulnerable populations, facing heightened risks of neurological, renal, respiratory, reproductive, and carcinogenic health effects. The cumulative and synergistic impacts of multiple heavy metals further intensify these risks, complicating health risk assessment and management.

From an environmental perspective, heavy metal contamination from electronic waste degrades soil quality, contaminates water resources, disrupts aquatic and terrestrial ecosystems, and promotes bioaccumulation and biomagnification within food chains. These impacts threaten ecosystem stability, biodiversity, and long-term environmental sustainability, particularly in regions lacking effective waste management infrastructure.

There are substantial disparities in regulatory effectiveness across regions. While stringent policies in developed countries have reduced heavy metal emissions from electronic products, inadequate enforcement, informal recycling, and illegal transboundary movement of e-waste which continue to shift the environmental and health burden to developing nations. This underscores the need for stronger international cooperation, improved regulatory enforcement, and integration of public health considerations into e-waste management policies.

Overall, this study emphasizes that addressing the challenges posed by heavy metals in electronic waste requires a holistic and interdisciplinary approach. Advancing standardized research methodologies, promoting environmentally sound recycling technologies, strengthening policy implementation, and integrating informal recycling sectors into formal systems are essential steps toward mitigating risks. By synthesizing existing knowledge and identifying critical gaps, this review provides a comprehensive scientific basis for researchers, policymakers, and practitioners to develop sustainable strategies for minimizing the environmental and health impacts of electronic waste.

References

1. Abubakar, A., Zangina, A. S., Maigari, A. I., Badamasi, M. M., Ishak, M. Y., Abdullahi, A. S., & Haruna, J. A. (2022). Pollution of heavy metal threat posed by e-waste burning and its assessment of human health risk. *Environmental Science and Pollution Research*, *29*(40), 61065-61079.
2. Andeobu, L., Wibowo, S., & Grandhi, S. (2023). Environmental and health consequences of e-waste dumping and recycling carried out by selected countries in Asia and Latin America. *Sustainability*, *15*(13), 10405.
3. Anselm, O. H., Cavoura, O., Davidson, C. M., Oluseyi, T. O., Oyeyiola, A. O., & Togias, K. (2021). Mobility, spatial variation and human health risk assessment of mercury in soil from an informal e-waste recycling site, Lagos, Nigeria. *Environmental Monitoring and Assessment*, *193*(7), 416.
4. Awasthi, A. K., Li, J., Koh, L., & Ogunseitan, O. A. (2019). Circular economy and electronic waste. *Nature Electronics*, *2*(3), 86-89.
5. Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in pharmacology*, *12*, 643972.
6. Baldé, C. P., Forti, V., Gray, V., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S & Wagner, M. (2024). *The global e-waste monitor 2024: Quantities, flows and the circular economy potential*. United Nations Institute for Training and Research and International Telecommunication Union (ITU).
7. Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). *The global e-waste monitor 2020: Quantities, flows and the circular economy potential*. United Nations University (UNU).
8. Grant, K., Goldizen, F. C., Sly, P. D., Brune, M. N., Neira, M., van den Berg, M., & Norman, R. E. (2013). Health consequences of exposure to e-waste: a systematic review. *The lancet global health*, *1*(6), e350-e361.
9. Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary toxicology*, *7*(2), 60.
10. Kumar, A., Holuszko, M., & Espinosa, D. C. R. (2017). E-waste: An overview on generation, collection, legislation and recycling practices. *Resources, conservation and recycling*, *122*, 32-42.
11. Mihai, F. C., Gnoni, M. G., Meidiana, C., Schneider, P., Ezeah, C., & Elia, V. (2022). A global outlook on the implementation of the Basel Convention and the Transboundary Movement of E-waste. In *Paradigm shift in E-waste management* (pp. 49-75). CRC Press.
12. Onwosi, C. O., Igbokwe, V. C., Nwagu, T. N., Odimba, J. N., & Nwuche, C. O. (2019). E-waste management from macroscopic to microscopic scale. *E-waste Recycling and Management: Present Scenarios and Environmental Issues*, 143-157.
13. Pradhan, J. K., & Kumar, S. (2014). Informal e-waste recycling: environmental risk assessment of heavy metal contamination in Mandoli industrial area, Delhi, India. *Environmental Science and Pollution Research*, *21*(13), 7913-7928.

14. Singh, N., Duan, H., Yin, F., Song, Q., & Li, J. (2018). Characterizing the materials composition and recovery potential from waste mobile phones: A comparative evaluation of cellular and smart phones. *ACS Sustainable Chemistry & Engineering*, *6*(10), 13016-13024.
15. World Health Organization. (2023). *Exposure to lead: a major public health concern. Preventing disease through healthy environments*. World Health Organization.
16. Zhang, S., Ding, Y., Liu, B., & Chang, C. C. (2017). Supply and demand of some critical metals and present status of their recycling in WEEE. *Waste Management*, *65*, 113-127.