



OPEN ACCESS

EDITED BY
Nsikak U. Benson,
Université Claude Bernard Lyon 1, France

REVIEWED BY
Pankaj Kumar,
Parul University, India
Prem Rajak,
Kazi Nazrul University, India

*CORRESPONDENCE
Abubakari Said Mgelwa,
✉ abubakari.mgelwa@mnuat.ac.tz

RECEIVED 07 December 2025
REVISED 05 February 2026
ACCEPTED 16 February 2026
PUBLISHED 13 March 2026

CITATION
Maleko HS, Kafula YA, Mtemi WM,
Chappa LR and Mgelwa AS (2026)
Embracing sustainability: reducing
ecological and human health risks from e-
waste exposure through adoption of safer
management approaches.
Front. Environ. Sci. 14:1762578.
doi: 10.3389/fenvs.2026.1762578

COPYRIGHT
© 2026 Maleko, Kafula, Mtemi, Chappa
and Mgelwa. This is an open-access article
distributed under the terms of the [Creative Commons Attribution License \(CC BY\)](https://creativecommons.org/licenses/by/4.0/).
The use, distribution or reproduction in
other forums is permitted, provided the
original author(s) and the copyright
owner(s) are credited and that the original
publication in this journal is cited, in
accordance with accepted academic
practice. No use, distribution or
reproduction is permitted which does not
comply with these terms.

Embracing sustainability: reducing ecological and human health risks from e-waste exposure through adoption of safer management approaches

Happiness Stephano Maleko¹, Yusuph Aron Kafula²,
Wambura Mashauri Mtemi³, Luciana Raphael Chappa³ and
Abubakari Said Mgelwa^{4*}

¹Department of Computer Science, School of Business, Economics and Entrepreneurship Studies, Mwalimu Nyerere University of Agriculture and Technology, Musoma, Tanzania, ²Department of Aquaculture and Fisheries, College of Agriculture, Mwalimu Nyerere University of Agriculture and Technology, Musoma, Tanzania, ³Department of Agricultural Sciences, College of Agriculture, Mwalimu Nyerere University of Agriculture and Technology, Musoma, Tanzania, ⁴Department of Natural Resources, College of Agriculture, Mwalimu Nyerere University of Agriculture and Technology, Musoma, Tanzania

Electronic waste (e-waste) is one of the fastest-growing solid waste streams worldwide, increasing at an estimated annual rate of 3%–5% due to rapid technological advancement, rising consumption of electronic devices, shortened product lifespans and inadequate end-of-life management systems. E-waste comprises a complex mixture of valuable recoverable resources alongside numerous hazardous substances, including heavy metals, persistent organic pollutants and emerging contaminants. When improperly collected, recycled or disposed of, these materials pose substantial risks to environmental quality and human health across both developed and developing regions. This review synthesizes the current global status and trends of e-waste generation, collection and recycling, and critically examines recent evidence on the distribution and impacts of e-waste-derived contaminants in soil, air and dust environments, plants, animals, aquatic systems and human populations. Beyond documenting contamination patterns, the review highlights key exposure pathways, vulnerability hotspots and persistent knowledge gaps. To address these challenges, the paper systematically evaluates approaches for sustainable e-waste management, including policy and regulatory frameworks, collection systems, recycling and recovery technologies, eco-design strategies, integration of the informal sector, international cooperation and public awareness. Collectively, the review underscores that advancing sustainable e-waste management requires coordinated, circular-economy-oriented interventions that simultaneously reduce environmental toxicity, enhance resource recovery and protect human health.

KEYWORDS

circular economy, electronic waste, environmental contamination, human health risks, resource recovery, sustainable e-waste management

1 Introduction

Electrical and electronic equipment (EEE) refers to any product consisting of circuitry or electrical components that are powered by an energy source or battery (Parajuly et al., 2019; Shahabuddin et al., 2023). EEE products include a wide range of electrical appliances (e.g., hairdryers, refrigerators, stoves, and washing machines) and electronic devices (i.e., mobile phones, tablets, and wireless headphones) that are extensively used by households, commercial enterprises and institutions (Shahabuddin et al., 2023; Baldé et al., 2024). Accelerated technological innovation, shortened product lifespans and rising global consumption have led to a rapid increase in discarded electronics, making electronic waste (e-waste) or Waste Electrical and Electronic Equipment (WEEE) one of the fastest-growing waste streams worldwide (Parajuly et al., 2019; Thakur and Kumar 2022).

E-waste originates from multiple sources, including households, commercial and institutional users, industrial sectors and, increasingly, transboundary movement of end-of-life electronics from high-income countries to low- and middle-income countries (LMICs) (Baldé et al., 2024). In many LMICs, limited formal recycling infrastructure, economic incentives and weak regulatory enforcement have resulted in widespread informal recycling activities such as manual dismantling, open burning, acid leaching and uncontrolled dumping (Kiddee et al., 2013; Parajuly et al., 2019). Although formal recycling systems are more common in high-income countries, recent evidence indicates that even advanced waste management systems face persistent challenges related to low collection rates, complex product composition and incomplete control of pollutant emissions (Baldé et al., 2024), underscoring the global nature of the e-waste challenge.

From a compositional perspective, e-waste is a highly heterogeneous material stream, typically comprising approximately 30% organic components (e.g., flame retardants, glass fibers, and polymers), 30% ceramics (i.e., alumina, mica, and silica) and about 40% inorganic fractions, including base metals, precious metals, metalloids and rare earth elements (Thakur and Kumar 2022; Rautela et al., 2021). Alongside valuable recoverable resources, e-waste contains numerous hazardous substances, such as arsenic, cadmium, hexavalent chromium, lead, mercury, nickel, brominated flame retardants (BFRs) and other persistent organic pollutants, which pose significant risks to environmental and human health if improperly managed (Shahabuddin et al., 2023; Baldé et al., 2017). Conceptual frameworks developed for metal (loid)s-contaminated environments emphasize that beyond accumulation, factors such as bioavailability, trophic transfer and long-term exposure pathways critically determine ecological and human health risks, underscoring the need for integrated assessment and management strategies (Kumar et al., 2022). In light of these complex exposure pathways and associated long-term risks, the safe and sustainable management of e-wastes has become a major global environmental challenge (Rautela et al., 2021).

Recent research has increasingly demonstrated that e-waste-derived contaminants exert multi-media and multi-pathway impacts, affecting soils (e.g., Moeckel et al., 2020; Shi et al., 2020; Kumar and Fulekar, 2017), air and dust environments (e.g., Folarin

et al., 2024; Chakraborty et al., 2021; Mowla et al., 2021), plants (e.g., Wei et al., 2021; Bakare et al., 2013; Alabi et al., 2012), animals (e.g., Phoonaploy et al., 2019; Nie et al., 2015; Zheng et al., 2015), aquatic systems (e.g., Oloruntoba et al., 2022; Li et al., 2019; Quan et al., 2014) and human populations (e.g., Meng et al., 2020; Lu et al., 2016; Feldt et al., 2014). Studies show that soils near recycling sites act as long-term contaminant reservoirs, airborne particulates and dust facilitate inhalation exposure, plants and animals accumulate pollutants through uptake and biomagnification, aquatic systems serve as sinks and transport pathways, and humans experience chronic exposure through occupational, dietary and residential routes. While much of the available evidence originates from China, India and selected African countries, reflecting both exposure hotspots and stronger research capacity, large regions of Latin America, Southeast Asia and other rapidly urbanizing LMICs remain data-scarce rather than risk-free (Grant et al., 2013), suggesting that the global burden of e-waste pollution is likely underestimated.

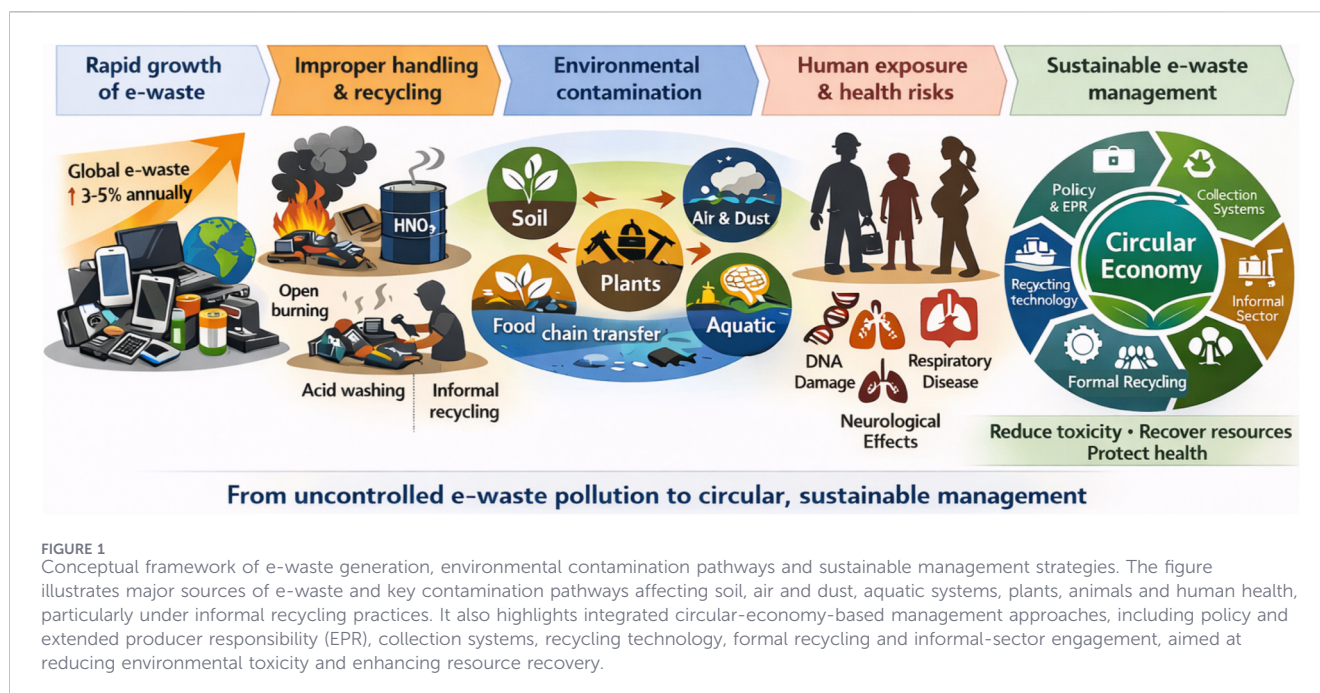
Although several reviews have examined aspects of e-waste generation, recycling technologies or specific pollutant classes, many remain compartmentalized, emphasize descriptive inventories or focus narrowly on technical recovery processes without fully integrating cross-environmental contamination pathways, mixture toxicity, long-term low-dose exposure and human health implications (Heacock et al., 2016; Grant et al., 2013). Moreover, relatively few reviews explicitly link observed environmental contamination patterns to upstream management failures or downstream governance and policy responses, limiting their utility for informing sustainable and circular e-waste management strategies. Against this backdrop, the novelty of the present review lies in its integrated and critically evaluative synthesis of e-waste-derived contamination across soil, air and dust environments, plants, animals, aquatic systems and human health, explicitly linked to management and governance responses (Figure 1). Rather than reiterating isolated case studies, this review systematically identifies knowledge gaps, inconsistencies and emerging research needs, while situating environmental and health impacts within the broader context of circular economy principles, life-cycle thinking and sustainable e-waste management.

Specifically, this review aims to: (i) synthesize current knowledge on global e-waste sources, generation trends and recycling practices; (ii) critically assess the distribution, pathways and effects of e-waste-derived pollutants across environmental and biological systems; and (iii) evaluate policy, technological and socio-economic approaches for mitigating e-waste risks and advancing safe, equitable and circular e-waste management systems. By explicitly linking environmental and health evidence with management strategies, this review provides a coherent framework for guiding future research, informing policy development and supporting evidence-based interventions to reduce the global impacts of e-waste.

2 Methodology

2.1 Review approach

This study adopted a narrative integrative review approach to synthesize multidisciplinary evidence on e-waste exposure



pathways, associated ecological and human health impacts, and sustainable management strategies. Integrative reviews are particularly appropriate for complex environmental health topics because they allow the inclusion of empirical, theoretical, and policy-oriented studies across diverse disciplines while promoting conceptual integration rather than purely statistical aggregation (Snyder 2019). This approach enabled the review to examine e-waste challenges from environmental science, toxicology, public health, waste management, and sustainability policy perspectives. Although the study was not designed as a strict systematic review or meta-analysis, structured literature identification, screening, and documentation procedures were applied to enhance transparency and methodological rigor. The review design was broadly informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, particularly in documenting literature search strategies, screening procedures, and eligibility assessment.

2.2 Scope and focus of the review

The scope of this review encompasses both global and regional literature addressing the current status, temporal trends, and geographic distribution of e-waste generation, collection, and recycling. The review also synthesizes evidence on major chemical contaminants released from e-waste and their ecological and human health consequences across environmental compartments, including soil, air, dust, aquatic systems, plants, animals, and humans. Additionally, the review evaluates policy, technological, socio-economic, and circular economy-oriented strategies designed to promote environmentally sound and sustainable e-waste management. Particular emphasis is placed on both legacy pollutants and emerging contaminants, as well as multidisciplinary exposure pathways linking environmental contamination, biological uptake, and management interventions.

2.3 Literature sources and search strategy

Relevant literature was identified through systematic searches of major academic databases, including Web of Science, Scopus, ScienceDirect, PubMed, and Google Scholar. To complement peer-reviewed publications, relevant grey literature was incorporated to capture global policy frameworks, statistical datasets, and implementation experiences. These sources included reports and technical documents produced by major international organizations such as the United Nations Environment Programme (UNEP), United Nations Development Programme (UNDP), Food and Agriculture Organization of the United Nations (FAO), International Telecommunication Union (ITU), World Health Organization (WHO), International Solid Waste Association (ISWA), Organisation for Economic Co-operation and Development (OECD), United Nations Statistics Division (UNSD–Environment Statistics Section), and the Basel Convention Secretariat. Literature searches were conducted using Boolean combinations of keywords including “electronic waste” OR “e-waste”, “toxic exposure”, “heavy metals”, “persistent organic pollutants”, “flame retardants”, “human health risks”, “ecological impacts”, “informal recycling”, “sustainable e-waste management”, “policy frameworks”, “circular economy”, and “resource recovery”. Additional relevant studies were identified through backward and forward citation tracking of key publications.

2.4 Study selection criteria

The selection of literature followed predefined qualitative eligibility criteria to ensure scientific relevance and credibility. Studies were included if they addressed environmental contamination, ecological risks, or human health impacts associated with e-waste, or if they examined management strategies, regulatory frameworks, technological recovery approaches, or sustainability interventions. Eligible publications

were required to provide empirical data, conceptual models, risk assessment findings, or policy-relevant insights and to be published in peer-reviewed journals, authoritative institutional reports, or internationally recognized databases. Although no strict publication year limitation was applied, priority was given to recent studies to capture emerging contaminants, evolving regulatory frameworks, and technological advancements in e-waste management. Publications were excluded if they focused solely on general solid waste without specific reference to electronic or electrical waste, lacked methodological transparency or scientific credibility, duplicated previously published findings without additional analytical contribution, addressed e-waste topics without clear environmental, health, or management relevance, or consisted exclusively of unsupported opinion-based discussions.

2.5 Screening and selection process

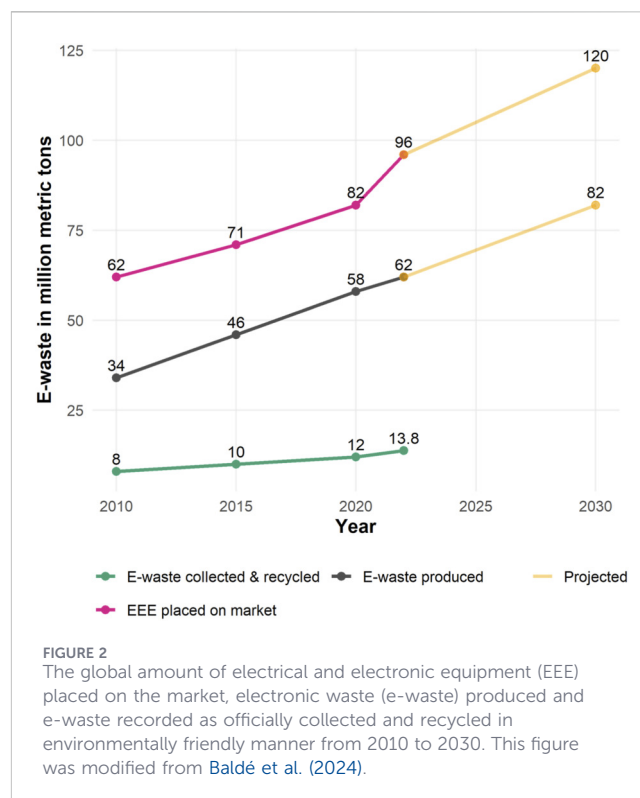
Literature screening followed a structured multi-stage process consistent with PRISMA-informed review procedures. Initially, titles and abstracts were screened to evaluate relevance to the review objectives. Studies meeting preliminary relevance criteria were subsequently subjected to full-text evaluation using the defined inclusion and exclusion criteria. When multiple studies reported similar datasets or overlapping findings, preference was given to publications with broader analytical scope, higher methodological rigor, or more recent and comprehensive datasets. This screening approach ensured that the selected literature represented diverse geographic regions, methodological frameworks, and environmental compartments while maintaining scientific robustness.

2.6 Data synthesis and analytical framework

The selected literature was synthesized using a thematic and pathway-based analytical framework that integrates evidence across the e-waste risk continuum. Studies were systematically categorized according to stages of e-waste production and generation, environmental release and exposure pathways, ecological and human health impacts, and sustainable management and circular economy strategies. Instead of quantitative meta-analysis, findings were integrated through comparative interpretation across disciplinary perspectives to identify converging evidence, inconsistencies, emerging risks, and research gaps. Particular emphasis was placed on mixture toxicity, chronic low-dose exposure, informal recycling dynamics, regional disparities in data availability, and policy implementation effectiveness. This integrative synthesis approach enabled comprehensive evaluation of how sustainable e-waste management strategies can simultaneously reduce environmental contamination, protect public health, enhance resource recovery efficiency, and support circular economy transitions.

3 Current status and trend of global e-waste production, collection and recycling

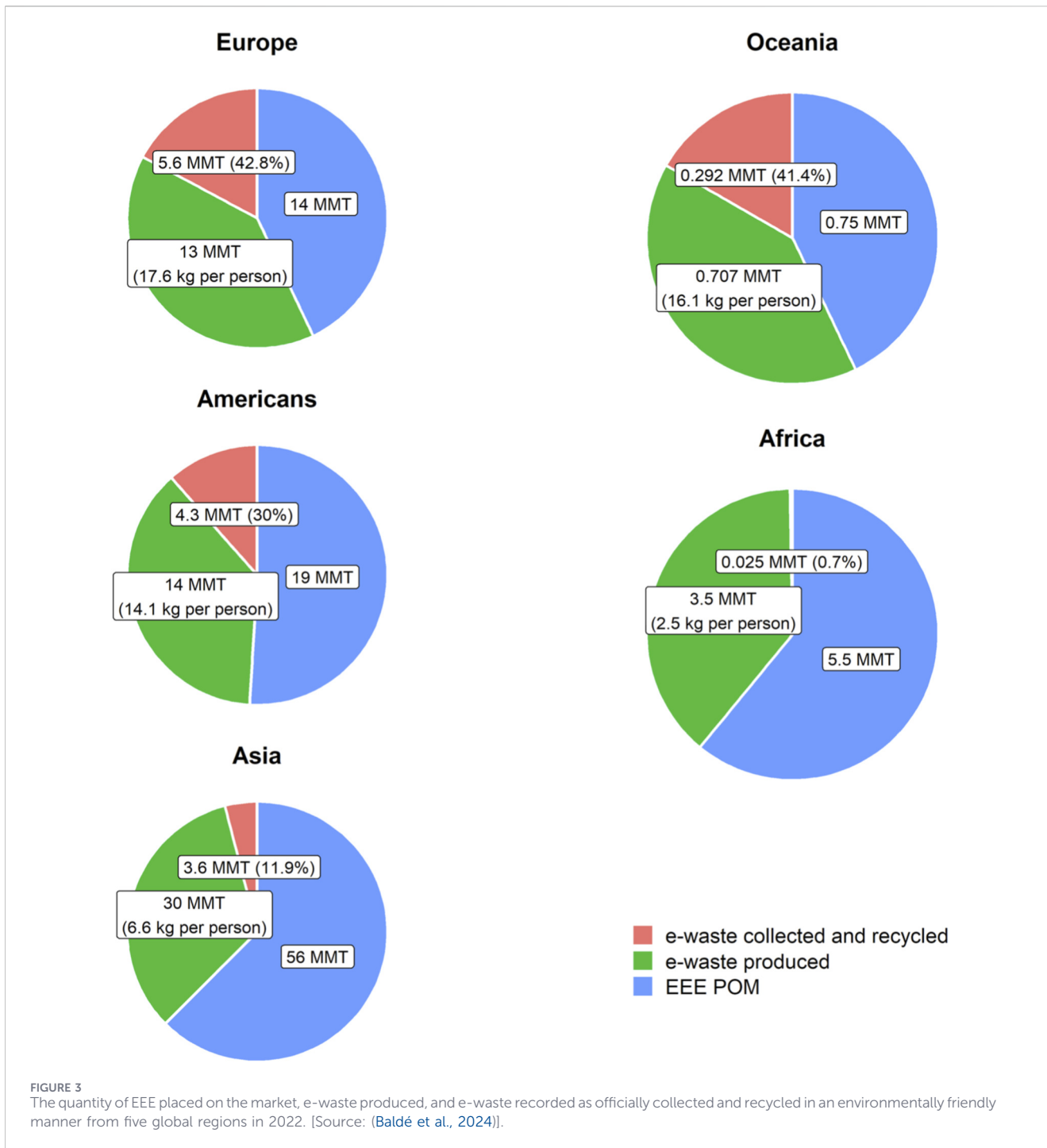
The global production of e-waste in 2010 was 34 million metric tonnes (MMT), with this amount generally experiencing an average annual growth rate of 2.3 MMT in the subsequent years (Figure 2).



In 2022, the aforementioned production amount of e-wastes nearly doubled, i.e. 62 MMT (Figure 2), being equivalent to an average yearly production of 7.8 kg (kg) per person worldwide. It should also be noted that the global quantity of EEE placed on the market increased from 62 MMT in 2010 to 96 MMT in 2022. Importantly, the projections reveal that the global quantity of EEE placed on the market and that of e-waste produced will, respectively, increase to 120 and 82 MMT by 2030 (Figure 2) (Baldé et al., 2024; ITU, 2022). The rise in global e-waste generation is driven by rapid technological advancements, increased consumption of e-devices, limited alternatives for repair and maintenance, shorter product life cycles, increasing electrification, and insufficient e-waste management infrastructure (Baldé et al., 2024; Rautela et al., 2021). Although the formal e-waste collection and recycling rates were also observed to increase from 8 MMT in 2010 to 13.8 MMT in 2022, with an average annual growth of 0.5 MMT, they were surpassed by e-waste production rates by nearly five times (Figure 2) (Baldé et al., 2024). For instance, of the 62 MMT produced e-wastes in 2022, only 22.3% was officially collected and recycled in an environmentally friendly manner (Baldé et al., 2024).

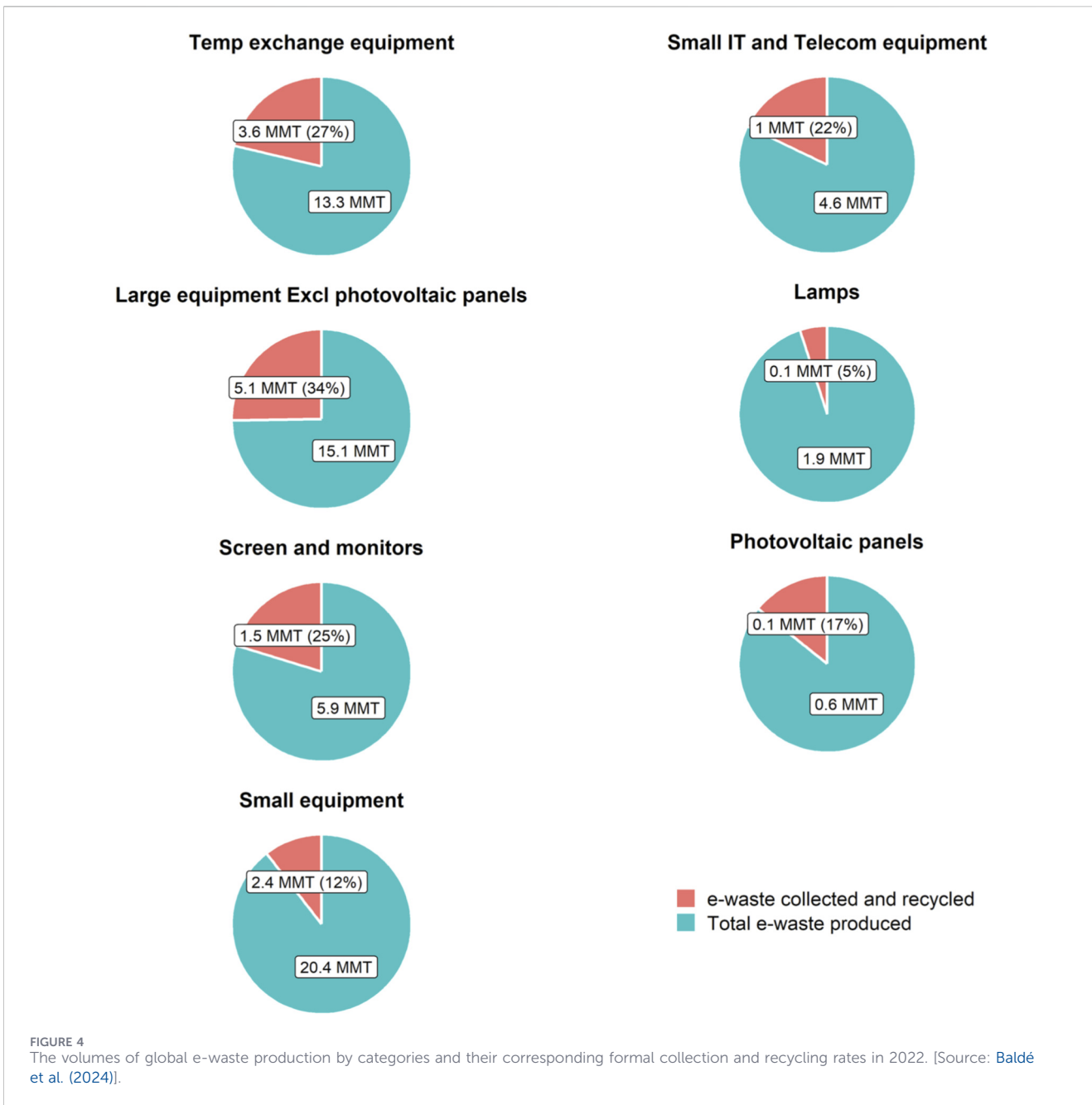
3.1 E-waste production and recycling rates in 2022 by regions

The rates of e-waste production may differ based on several factors, including time, location, population size, lifestyle choices, as well as socio-economic conditions (Rautela et al., 2021). The majority of e-wastes generated in 2022 were from Asia (i.e., 56 MMT), followed by Americas, Europe, Africa and Oceania, with 19, 14, 5.5 and 0.75 MMT, respectively. In 2022,



Europe, Oceania, and Americas produced a huge quantity of e-waste per person, with the quantity of 17.6, 16.1, and 14.1 kg, respectively. These regions exhibit significantly higher annual e-waste collection rates because they have more technologically advanced collection, treatment, and recycling infrastructures (Figure 3). Interestingly, various countries in the aforementioned regions are implementing e-waste legislation or policies, thereby regulating and enforcing proper and effective e-waste management. On the other hand, in most African and Asian countries, e-waste legislation or policies are either

not in place or are not effectively enforced, leading to lower collection and recycling rates of e-wastes (Figure 3). Furthermore, in various low-income regions, non-formal sectors are playing significant roles in the management of e-waste. Unfortunately, these sectors are generally not indicated in official records or monitored by respective governments. This may be because non-formal recycling practices have been attributed to resource-inefficiency rates, thus failing to adhere to the environmental and human health safety standards (Baldé et al., 2024).



3.2 E-waste production and recycling rates in 2022 by e-device categories

Small equipment, including video cameras, toys, microwave ovens, and e-cigarettes, represents the largest share of global e-waste by weight. In 2022, these items accounted for about 20 MMT, which was equivalent to one-third of the global total e-wastes (Figure 4). The second and third largest e-waste categories encompass large equipment (including washing machines, dishwashers, large printers and photocopiers, but excluding photovoltaic panels) and temperature exchange equipment (e.g., refrigerators, freezers, air conditioners, and heat pumps), which respectively accounted for 15 and

13 MMT in 2022. Lamps accounted for 2 MMT, which was the smallest contribution to global e-waste generation, next to photovoltaic panels. Moreover, screens and monitors constituted 10% (equivalent to 5.9 MMT) of the e-waste produced globally in 2022. Furthermore, small IT and telecommunication equipment, including mobile phones, GPS devices, routers, personal computers, printers, and telephones, collectively accounted for 5 MMT (Baldé et al., 2024; Baldé et al., 2022). It has been pointed out that formal collection and recycling rates tend to be significantly higher for e-devices with considerable unit weight, such as large equipment (34%), followed by temperature exchange devices (27%) (Figure 4). This could be due to the fact that suppliers in some regions

are required to retrieve these e-devices after being discarded or old while delivering new ones. In addition, most consumers do not prefer to store or keep the aforementioned e-appliances because of their huge size and weight (Baldé et al., 2022). Despite having large size, photovoltaic panels are characterized by lower formal collection and recycling rates (17%) when compared to other large equipment. This reflects the technical and economic challenges associated with photovoltaic panel recycling, including the high processing costs, presence of hazardous metals and the still-developing collection and recycling technologies. Despite their size, small IT and telecommunication devices were formally collected and recycled at a rate of 22%, surpassing that of other small equipment or lamps. This is possibly because more countries have recently established specific legislation governing the collection, recovery, and recycling of these e-devices. It could also be attributed to the valuable components contained in these devices that have made their collection a priority. However, their formal collection and recycling rates lag behind those of other equipment, especially large equipment (excluding photovoltaic panels), and temperature exchange equipment, as well as screen and monitor devices, possibly due to the fact that small IT and telecommunication devices often store personal data, making consumers hesitant to return them (Baldé et al., 2022; Baldé et al., 2024).

4 Major chemical compounds from e-wastes and their associated human health risks

Various precious metals (e.g., platinum, silver, gold, and palladium) together with other useful materials (i.e., aluminum, copper, iron, and plastic) are present in many e-devices (Rautela et al., 2021; Thakur and Kumar 2022). These metals and materials can possibly be reclaimed and reused through proper e-waste recycling (Rautela et al., 2021; Thakur and Kumar 2022). Nevertheless, improper e-waste recycling and disposal practices may not only cause permanent loss of the aforementioned metals and materials, but may also cause detrimental consequences on both the environment and human health (Eckhardt and Kaifie, 2024; Yekeen et al., 2016). The detrimental effects occur because e-waste releases various hazardous chemicals, including heavy metals (e.g., mercury, lead, and cadmium) and flame retardants [e.g., pentabromophenol (PBP), tetrabromobisphenol-A (TBBPA), and polybrominated diphenyl ethers (PBDEs)]. Also, during e-waste dismantling processes like tearing, shredding and burning, there is release of both dust and smoke particles. These particles contain carcinogenic and other hazardous substances that can induce acute inflammations and lesions, particularly affecting the skin and respiratory system (Selvakumar et al., 2023).

For instance, open burning of electronic circuits can result in the release and dispersion of valuable metals, including platinum, gold, palladium, cadmium and silver. On the other hand, the wire coat of these circuits has PCV and PCB, potentially producing carcinogenic contaminants (i.e., toner-derived erotic smoke and carbon particles) after being burnt, thereby leading to the skin and lung cancer (Thakur and Kumar 2022; Kumar et al., 2017; Perkins et al.,

2014; Feiteiro et al., 2021). The contamination of e-waste workers and local residents with e-waste-related pollutants and their significant health implications has been reported previously, as detailed in Table 1.

5 Effects of e-waste-related pollutants on soil, air and dust environments, plants, animals, aquatic systems and human health

E-wastes comprise more than 1,000 distinct chemical constituents, many of which are toxic, persistent or bioaccumulative. Consequently, inadequate handling, recycling and disposal of e-wastes can generate multifaceted ecological and human health risks across environmental compartments. These risks are summarized in Supplementary Table S1 and critically discussed below.

5.1 Soil environments

Soils represent one of the primary environmental sinks for contaminants released during e-waste dismantling, recycling and disposal, and therefore provide an integrated record of both historical and ongoing e-waste activities. Evidence from major e-waste recycling hubs consistently demonstrates substantial enrichment of heavy metals and persistent organic pollutants in contaminated soils compared with background or reference sites. A study by Shi et al. (2020) reported that the average Cd and Cu concentrations of 0.42 and 52.83 mg kg⁻¹ in paddy soils of the Wenling city, which is not only one of the large e-waste dismantling sites but also a commercial grain production area in China, exceeded their standard concentration values of 0.4 and 50 mg kg⁻¹ in accordance with the Chinese soil environmental quality standard (GB15618-2018), highlighting the dual risk to food security and human exposure in agricultural landscapes affected by e-waste activities. There were elevated concentrations of heavy metals and toxic organic compounds in the e-waste contaminated soil sites than in the corresponding reference soil sites in Guiyu town (Liu et al., 2015). For example, the soil concentrations of Cu were over 30 times higher in the e-waste dumping sites and those of Pb were 6 times greater in the e-waste burning sites in comparison to their corresponding reference sites. Moreover, the e-waste contaminated farmland soils were characterized by higher concentrations of PCBs (391 µg kg⁻¹) and PBDEs (2,205 µg kg⁻¹) than their corresponding reference soils (6.6 and 8.5 µg kg⁻¹, respectively). The authors also reported that, among all investigated representative contaminated soil sites, the acid stripping soils exhibited much higher concentration levels of PCBs (726 µg kg⁻¹) and PBDEs (4,892 µg kg⁻¹), while the contaminated mudflat soils had several times lower concentrations of these toxic organic pollutants (23.9 and 98.6 µg kg⁻¹, respectively). In Lagos State, the levels of all examined heavy metals in soils were markedly enhanced from the e-waste burning area than from the control area, indicating the effects of informal recycling activities on soil properties (Isimekhai et al., 2017). The measured heavy metal concentrations in the aforementioned study decreased consistently in the order of

TABLE 1 Major e-waste-derived chemical compounds and their associated adverse effects in human health.

Chemical compounds	Associated e-wastes	Human-related health risks	References
Mercury (Hg)	Batteries, fluorescent lamps, liquid crystal display (LCD) screens, relays, and switches	Neurological problems, e.g., Minamata disease incident in Japan in 1956	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Cadmium (Cd)	Batteries, cathode ray tubes (CRTs), coatings, light-emitting diodes (LEDs), pigments, and semiconductors	Interruption of endocrine activities, itai-itai disease, as well as kidney, lung, and prostate cancer	Wei and Cen. (2020); Mishra et al. (2019); Yadav et al. (2017); Järup (2003); Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Lead (Pb)	Batteries, cables, CRTs, solder, and wiring	Blood and neurobehavioral disorders, damages in reproductive organs, and renal defects	Mishra et al. (2019); Yadav et al. (2017); Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Arsenic (As)	CRTs, diodes, printed circuit boards, and screens	Arsenicosis, cancer, and distortion of vital intracellular activities [e.g., oxidative phosphorylation and adenosine triphosphate (ATP) synthesis in mammals]	Mishra et al. (2019); Yadav et al. (2017); Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Chromium (Cr)	Batteries, CRTs, computer housing, and disks	Allergy, asthma, diarrhea, hair loss, kidney malfunction, lung cancer, as well as skin irritation	Mishra et al. (2019); Yadav et al. (2017); Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Lithium (Li)	Batteries	Distortion of intestinal and nervous systems	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Copper (Cu)	Printed circuit boards	Abdominal inflammations, distortion of brain, hepatic, and renal functions, as well as prolonged anaemia	Mishra et al. (2019); Yadav et al. (2017); Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Nickel (Ni)	Batteries and CRTs	Cancer, as well as skin and lung diseases	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Pentabromophenol	Flame retardants and polymeric additives	Endocrine disruption	Chen et al. (2017)
Polybrominated diphenyl ethers (PBDEs)	Cables, insulation, plastic casings, and printed circuit boards	Disrupt brain and sexual developments, as well as growth hormones, and impede the functionality of immune systems	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Tetrabromobisphenol-A (TBBPA)	Housings, plastics and printed circuit boards	Cardiovascular and oncological illnesses, damage of endocrine system, failure of thyroid functions, impairment of reproductive organs and immunological systems, and neurobehavior and development malfunctions	Feiteiro et al. (2021)
Brominated flame retardants (BFRs)	Household appliances (e.g., freezers, microwaves, refrigerators, and washing machine) and mobile phones	Damage the nervous systems in children, and deteriorate the functionality of liver, thyroid, as well as reproductive and endocrine systems	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Polychlorinated Biphenyls (PCBs)	Computers, mobile phones, monitors, tablets, and televisions	Cancer, behavioral alterations, destruction of immune system, liver and reproductive organs of both male and female, as well as immune system impairment	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
Polyvinyl Chloride (PCV)	Connectors, electronic casings, and plugs	Endocrine disruption	Martinez-Arguelles et al. (2013)
Polyaromatic hydrocarbons (PAHs)	Ethernet cables, power cords, universal serial bus (USB) cables, and wires	Cancer and damages of developmental and reproductive systems	Liao et al. (2012); Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)
per- and polyfluoroalkyl substances (PFAS)	Non-stick coatings on circuit boards, protective coatings on e-displays, and water-resistant coatings on e-devices like smartphones and laptops	Carcinogenic effects, disruption of reproductive and developmental activities, lipid and insulin malfunctions, liver and kidney illnesses and malfunctions of immune and thyroid	Fenton et al. (2021); Ojo et al. (2021)
Polychlorinated dibenzodioxins (PCDDs)	Combustion byproducts	Cancer and impairment of nervous system functions	Thakur and Kumar (2022); Kumar et al. (2017); Perkins et al. (2014)

Cu > Pb > Zn > Mn > Ni > Sb > Cr > Cd both during the dry and wet seasons. They also found consistently higher concentration values of Cu (329–9,277 mg kg⁻¹), Pb (115–9,623 mg kg⁻¹) and Zn (508–8,178 mg kg⁻¹) than their international soil guideline values (Isimekhai et al., 2017).

A study of Moeckel et al. (2020) revealed that surface soils from the Agbogbloshie site in Accra, where e-waste processing and dumping activities have been taking place, contained PBDEs, PAHs, PCBs and SCCPs at the concentration ranges of 6.3–7,700, 850–10000, 6.5–83 and 150–28000 ng g⁻¹, respectively.

Moreover, the Agboglobshie soils had elevated concentrations of several heavy metals, including Zn ($2,300 \mu\text{g g}^{-1}$), Cu ($1,500 \mu\text{g g}^{-1}$), Pb ($1,100 \mu\text{g g}^{-1}$), Ni ($70 \mu\text{g g}^{-1}$), Cd ($6.2 \mu\text{g g}^{-1}$), Ag ($4.5 \mu\text{g g}^{-1}$) and Hg ($0.47 \mu\text{g g}^{-1}$). The principal component analyses associated these soil compound pollutants with pyrogenic PAHs, thus suggesting that burning of e-waste, which is a common practice of isolating valuable metals, may have contaminated the studied soils. Furthermore, in their study, the authors also observed extremely high concentrations, which in some cases exceeded the action guideline levels for soils, in several of the assessed e-waste associated pollutants, especially PBDEs, SCCPs and heavy metals. The surface soils in multiple informal e-waste recycling sites (dismantling, shredding or grinding and metal recovery) of four major metropolitan cities from North, East, West and South of India had concentrations of PCBs and PCDD/Fs ranging from 0.4 to 488 and 1.0–10.6 ng g^{-1} , respectively, being significantly higher than those from the nearby open dumpsites, i.e., 0.3–21 and 0.2–7.3 ng g^{-1} , respectively (Chakraborty et al., 2018).

Moreover, the intensive informal e-waste recycling activities in four sites from Karachi City have resulted in elevated soil concentrations of PBDEs, OPFRs, NBRFs and DP of up to 12754, 1,689, 8,110 and 26239 ng g^{-1} , respectively (Iqbal et al., 2017). Most of these harmful organic flame retardants exhibited significant positive correlations, indicating a shared emission source, most likely informal e-waste recycling activities. A study from Hong Kong showed that the soils of the e-waste dismantling workshop and e-waste open burning site on former agricultural land were contaminated with PBDEs (6,875 and 32337 $\mu\text{g kg}^{-1}$, respectively) and PCBs (1,061 and 144 $\mu\text{g kg}^{-1}$, respectively) (Man et al., 2011). The e-waste open burning site was characterized by the elevated concentration levels of BDE-47 (2,287 $\mu\text{g kg}^{-1}$) and BDE-99 (1,410 $\mu\text{g kg}^{-1}$), which are the two PBDE congeners that have attracted the most public concern owing to their higher persistence and toxicity, than the e-waste storage site (BDE-47, 5.7 $\mu\text{g kg}^{-1}$; BDE-99, 5.0 $\mu\text{g kg}^{-1}$), open burning site (12.9 $\mu\text{g kg}^{-1}$; 9.3 $\mu\text{g kg}^{-1}$) and e-waste dismantling workshop (384 $\mu\text{g kg}^{-1}$; 236 $\mu\text{g kg}^{-1}$). The authors further revealed that the concentrations of total PCBs in electronic waste dismantling workshop (1,061 $\mu\text{g kg}^{-1}$) far exceeded the global background concentrations (5.4 $\mu\text{g kg}^{-1}$). Moreover, in Bui Dau, the total soil concentrations of PAHs and MePAHs decreased in the order of e-waste recycling workshop soils (870–42000 ng g^{-1}) > open burning soils (840–4,200 ng g^{-1}) > paddy field soils (530–6,700 ng g^{-1}), suggesting informal e-waste recycling and processing activities as a potential source of polycyclic aromatic hydrocarbons and their derivatives (Hoa et al., 2020). Comparable ecological risk assessments from other anthropogenically contaminated soils have likewise reported elevated heavy-metal burdens and significant ecological risks, indicating that the soil contamination patterns observed at e-waste sites reflect a broader global trend of metal-driven soil degradation rather than isolated local phenomena (Ngaba and Mgelwa, 2020). Beyond chemical enrichment alone, emerging evidence further demonstrates that e-waste-contaminated soils undergo pronounced shifts in microbial community composition and functional structure, reflecting biological stress responses to heavy-metal loading and complex pollutant mixtures (Kumar et al., 2020). Collectively, these findings indicate that informal e-waste recycling generates broadly

comparable soil contamination signatures across diverse socio-economic and climatic contexts.

Despite the growing body of evidence documenting severe soil contamination at e-waste recycling sites, several critical knowledge gaps remain. Most available studies rely on cross-sectional sampling designs, limiting understanding of the long-term persistence, temporal evolution and natural attenuation of e-waste-derived contaminants in soils (Kumar and Fulekar, 2019). While individual pollutants such as Pb, Cu, PBDEs and PCBs are well characterized, far fewer studies address mixture toxicity, despite soils at e-waste sites containing complex chemical assemblages whose combined effects may exceed those predicted from single-compound assessments. Geographic coverage is also uneven, with intensive research in China and selected African hotspots reflecting both high exposure intensity and stronger monitoring capacity, whereas large parts of Latin America and Southeast Asia remain poorly characterized primarily due to limited data availability. Moreover, most soil studies emphasize total contaminant concentrations, with comparatively little attention given to speciation, bioavailability and mobility, which ultimately govern ecological uptake and human exposure, particularly in agricultural settings where food-chain transfer is critical. Emerging evidence from farmlands adjacent to e-waste sites indicates that even moderate soil contamination can result in substantial crop uptake, underscoring the need for integrated soil-plant-human exposure frameworks. Overall, while soils are clearly established as long-term reservoirs and secondary sources of e-waste-derived contaminants, advancing from descriptive inventories toward predictive and preventive management will require long-term monitoring, mixture-based risk assessment, bioavailability-focused analyses and regionally inclusive investigations to support effective remediation and evidence-based regulation.

5.2 Dust and air environments

Dust and air environments represent critical exposure pathways for e-waste-derived contaminants, particularly in informal recycling settings where dismantling, open burning and poor ventilation prevail. Evidence from multiple regions consistently demonstrates that both indoor and outdoor dust and ambient air near e-waste recycling activities are heavily enriched with toxic metals and persistent organic pollutants compared with background environments. For instance, indoor dust of the three informal e-waste recycling shops in Dhaka city were found to contain 63.9, 4,728.3, 3,886.0, 1,639.5 and 385.0 mg kg^{-1} of Cr, Cu, Pb, Mn and Ni, respectively, being 1.8, 138.8, 51.3, 8.3 and 47.8 times higher than the concentrations of these heavy metals in the control site. Such findings revealed the high degree of influence of heavy metals derived from e-waste on indoor dust contamination (Mowla et al., 2021). The pronounced variability in metal concentrations among individual workshops further suggests that the type of e-waste processed and specific recycling practices strongly influence contamination intensity, underscoring the heterogeneity of exposure even within the same urban setting. The authors also calculated the geo-accumulation index for each examined heavy metal in e-waste polluted indoor dust to ascertain their contamination levels. Their findings revealed that the severity of heavy metal contamination ranges from moderate to extreme levels

of severity, indicating a significant level of concern owing to the potential exposure of investigated heavy metals to the e-waste recycling workers, as well as to the surrounding environment and residents. In the same study, the concentrations of heavy metals in indoor air at the e-waste site were found to be higher compared to those at the control site, suggesting the accumulation of e-waste-derived heavy metal pollutants in the atmospheric environments around e-waste recycling areas. For instance, the indoor air concentrations of Cu from the e-waste site were 191 ng m^{-3} , which was about 70 times higher than those from the control site (Mowla et al., 2021).

In four Indian megacities, Chakraborty et al. (2021) reported high concentrations of atmospheric PCBs, plasticizers and PAHs in the informal e-waste recycling sites than in the residential sites and open municipal dumpsites. The atmospheric concentrations of total particulate and gaseous PCB concentrations at an abandoned e-waste recycling site from South China were 454.3 and $3,695.5 \text{ pg m}^{-3}$, respectively (Wang et al., 2017). The authors stated that the atmospheric PCB concentrations at this site were much lower compared to those obtained at the nearby Longtang village (25612 pg m^{-3}), where there were still ongoing e-waste dismantling activities in the small recycling factories. These findings indicate that local government enforcement of environmental regulations, including banning open burning and acid washing practices in small family workshops and centralizing e-waste recycling activities in technologically advanced facilities, has contributed to partial reductions in ambient air PCB concentrations. However, the practice of covering exposed contaminated soils with non-contaminated soils, while effective in limiting immediate emissions, may entail drawbacks, including the creation of abandoned sites and the potential spread of contamination to additional soils. Significantly higher concentration values of atmospheric Pb and Cd were observed in Guiyu (160 and 5.7 ng m^{-3} , respectively), where there were open burning and numerous other e-waste recycling operations, than in Haojiang reference area (69 and 3.4 ng m^{-3} , respectively), where there was no record of e-waste recycling activities (Zheng X. et al., 2016). Nevertheless, there were no significant differences in atmospheric Cr and Mn levels between the informal e-waste recycling site and the reference site. Zheng and colleagues mainly attributed these lacks of concentration differences between the two sites to extensive utilization of coal resources for energy production in thermal power plants in the reference area. It is well known that combustion of coals in these plants is one of the major sources of atmospheric pollution because it emits enormous quantities of air pollutants into the atmosphere, including heavy metals.

In another study, Folarin et al. (2024) reported the contamination of outdoor surface dust by several persistent organic pollutants, such as the flame retardants (PBDEs, DBDPE and DP) and the chlorinated POPs (PCBs and OCPs), at four e-waste dismantling sites in Lagos and Ogun States, Nigeria. The total concentration range of these e-waste-derived pollutants (in unit of ng g^{-1}) followed a decreasing order of PBDEs (44–12300) > DBDPE (4.9–3,032) > DP (0.7–278) > PCBs (4.9–148) > OCPs (1.9–25), indicating the presence of elevated concentrations of PBDEs, which were in turn the most significant contributors to POP pollution in the investigated outdoor surface dust samples. In the study by Xu et al. (2015) in Wenling City, they observed higher

concentrations of PBDEs and DBDPE of up to 27400 and $4,800 \text{ ng g}^{-1}$ in indoor dust and 7,060 and 670 ng g^{-1} in outdoor dust, respectively, at the family-run e-waste recycling workshops, which were up to several orders of magnitude higher than those found at the non-e-waste recycling reference site. In their study, they also investigated the heavy metal contamination status in indoor and outdoor dust samples. They found extremely elevated Cu and Pb concentration levels, which significantly exceeded the New Dutch List action value (Xu et al., 2015). In Thailand, the PBDEs and DBDPE at elevated concentrations of 320–290000 and $43\text{--}8,700 \text{ ng g}^{-1}$, respectively, were recorded in indoor dust samples from e-waste storage facilities (Muenhor et al., 2010). Across regions, PBDEs frequently dominate pollutant profiles, reflecting their extensive use in electronic components and strong affinity for dust. The co-occurrence of flame retardants, plastic additives and metals indicates that real-world exposures involve complex chemical mixtures rarely considered in current risk assessments.

Despite robust evidence of dust and air contamination at e-waste sites, several gaps limit translation into comprehensive health and policy frameworks. Most studies rely on short-term or cross-sectional measurements, offering limited insight into long-term exposure trajectories, seasonal variability and chronic low-dose inhalation risks. Although contaminant levels are frequently compared with guideline values, few investigations integrate toxicological evidence to evaluate cumulative or synergistic effects arising from concurrent exposure to metals and organic pollutants. Geographic representation remains uneven, with data concentrated in China, India and selected African urban centers, reflecting both major informal recycling hubs and stronger research presence, while much of Latin America and smaller cities in Southeast Asia remain underrepresented due to limited monitoring infrastructure. Furthermore, epidemiological evidence linking dust- and air-mediated exposures to long-term health outcomes, particularly among vulnerable populations such as children, pregnant women and informal workers, remains scarce, as most studies infer risk from environmental concentrations rather than direct biomarkers or clinical endpoints. Addressing these limitations will require coordinated research combining long-term air and dust monitoring, mixture-based toxicological assessment, personal exposure measurements and longitudinal health studies to support evidence-based air-quality standards, occupational safety regulations and targeted exposure-reduction interventions.

5.3 Plants

A growing body of evidence demonstrates that plants growing in and around e-waste recycling and disposal sites accumulate a wide range of e-waste-derived contaminants, including heavy metals and persistent organic pollutants, with important implications for ecosystem integrity and food safety. The PAH concentrations in the plant samples obtained around an e-waste disposal site in Taizhou City and near an e-waste recycling site in Longtang Town were found to be $29.7\text{--}2,170$ and $199\text{--}2,420 \text{ ng g}^{-1}$, respectively (Wang et al., 2012; Wei et al., 2021), which were higher than those in the vegetable plants ($65.7\text{--}458 \text{ ng g}^{-1}$) grown near industrial facilities in Shanghai (Jia et al., 2018). Study has shown that the heavy metals, PAHs, PCBs and PBDEs

were present at elevated levels in the edible *Amaranthus hybridus* and *Talinum triangulare* vegetables grown in the vicinity of a major informal e-waste dumpsite in Lagos State (Alabi, 2024). This suggests that the e-waste-derived pollutants may certainly have contaminated the adjacent environmental media. His study has also revealed that the most predominant contaminants among the heavy metals in these two investigated vegetable species were Pb, Fe, Cu and Cd. Moreover, he found the levels of the hazard quotient, lifetime cancer risk and hazard index to be above the suggested guideline values, thereby possibly posing significant carcinogenic and non-carcinogenic hazardous risks, especially in children. Collectively, these findings indicate that plants act as effective receptors and transfer vectors of e-waste-derived pollutants from contaminated soils and atmospheric deposition into terrestrial food webs.

Across studies, a consistent pattern emerges in which contamination levels and uptake differ markedly among plant species, tissue types and pollutant classes. For example, shoots of wild plants contained the highest average concentrations of Pb, Cu and Zn at 54.8, 94.3 and 143 mg kg⁻¹, respectively, and those of vegetable plants had the highest average concentration of Cd (a metal characterized by high soil-to-plant transfer efficiency) at 2.62 mg kg⁻¹, when grown in soils near the former e-waste incineration sites that contained the highest concentrations of Pb, Cu, Zn and Cd at average values of 4,500, 11,140, 3,690 and 17.1 mg kg⁻¹, respectively (Luo et al., 2011). The authors reported that the average concentration levels of Pb and Cd pollutants in most of their studied vegetables were, respectively, 2.6 and 4.7 times those of the maximum permissible levels in China, suggesting that these concentrations exceeded the Chinese food safety limit and that this exceedance of limit concentrations in vegetables, especially in their edible parts, could be a matter of grave concern for food industry and public health. In another study by Alabi et al. (2012), it was found that the plant samples from e-waste dumping and processing sites in Lagos State and Guiyu town were highly contaminated with hazardous PAHs, PBDEs, PCBs and heavy metals, indicating that e-waste contaminants can accumulate in surrounding plants to toxic levels that could potentially induce harmful health consequences in exposed biota. The Cd and Pb concentrations in rice grown in paddy soils from a typical e-waste recycling town in Zhejiang Province were 2–4 times higher compared with the 0.2 mg kg⁻¹, which is the maximum permissible concentration of the aforementioned two heavy metals in food samples in China (Fu et al., 2008). These interspecific and tissue-specific differences highlight the need for crop-sensitive risk assessment approaches rather than reliance on generalized contamination thresholds.

In Taizhou, the rice seeds suffered reductions in their germination rate after being sown in paddy soils around the e-waste processing sites (Jun-hui and Hang, 2009). In the same study, the micronucleus assay in root cells of *Vicia faba* indicated that e-waste contaminated soils can significantly induce the clastogenic effects in the cells of the exposed plants. Their study demonstrates that soil contamination can impair early plant development and induce genotoxic stress. The pollutants potentially present at different concentrations in raw and simulated e-waste leachates as well as e-waste contaminated underground waters from Alaba International Electronic Market in Lagos State were found to markedly induce the cytogenotoxic

effects in *Allium cepa* (Bakare et al., 2013). Similarly, the *A. cepa* plants were observed to experience chromosomal aberrations in cells and inhibition of root growth resulting from exposures to e-waste leachate concentrations from Iloabuchi e-waste market in Rivers State (Babatunde and Anabuikwe, 2015). These findings suggest that plant toxicity is not limited to contaminant accumulation alone, but also includes functional and genetic damage that may affect crop productivity and ecosystem resilience.

Despite growing evidence of plant contamination in e-waste-affected environments, the current literature remains fragmented and geographically skewed. Most studies are short-term and site-specific, limiting understanding of chronic low-dose exposure, long-term plant adaptation or recovery, and potential intergenerational effects. Research largely focuses on individual contaminants, even though plants are simultaneously exposed to complex mixtures of metals and organic pollutants whose interactive effects on uptake, toxicity and translocation remain poorly understood. Geographic coverage is dominated by studies from China and parts of West Africa, reflecting both high exposure intensity and research concentration, whereas large regions of Latin America, Southeast Asia and rapidly urbanizing LMICs remain data-poor rather than risk-free. Moreover, few investigations explicitly link plant contamination to human dietary exposure or ecosystem-level impacts, constraining translation into food safety assessments and land-use management. Addressing these gaps will require integrated approaches combining long-term field monitoring, mixture-based phytotoxicity assessment, mechanistic studies of uptake and translocation, and explicit linkage to human exposure and nutritional risk. Such efforts are essential for informing agricultural advisories, land-use planning and regulatory policies in e-waste-affected regions.

5.4 Animals

A substantial body of evidence demonstrates that animals inhabiting or foraging near e-waste recycling and disposal sites accumulate high burdens of e-waste-derived contaminants, with clear implications for ecosystem integrity, food safety and human health. Elevated concentrations of persistent organohalogenated pollutants (POPs), particularly PCBs, PBDEs and emerging brominated flame retardants, have been consistently reported in domestic, wild and aquatic animals associated with informal e-waste activities. For example, the levels of several POPs were found to be elevated in various tissues of chickens free-raised within the farmyard, which was surrounded by the e-waste recycling workshops in southern China (Zheng et al., 2015), reflecting chronic environmental exposure and trophic transfer within contaminated landscapes. Such findings are particularly concerning given the direct relevance of domestic animals to human diets in many e-waste-affected communities. Comparative studies across species and tissues reveal pronounced heterogeneity in contaminant accumulation, underscoring the importance of biological and ecological traits in shaping exposure outcomes. In the e-waste recycling region in Taizhou, Zhao et al. (2016) investigated the accumulation levels of PBDEs in the tissues (i.e., brain, liver and muscle) of the five vertebrates, such as mice (0.45–206 ng g⁻¹), chickens (0.06–18.8 ng g⁻¹), ducks (1.83–112 ng g⁻¹), frogs (2.75–108 ng g⁻¹) and fish

(0.02–32.0 ng g⁻¹). However, while PBDEs were preferentially distributed in liver and muscle tissues than in brain tissue in mice, ducks, chickens and frogs, they were largely retained in the brain tissue relative to the liver and muscle tissues in fish. Generally, the results of Zhao and colleagues revealed the differential accumulation rates of PBDEs among vertebrates and their tissues. In Qingyuan City, the concentration levels of PBDEs and PCBs were elevated (52.7–1702 and 20.2–25958 ng g⁻¹, respectively) in several wild aquatic biota species (i.e., Chinese mystery snail, Crucian carp, Mud carp, Northern snakehead, Prawn and Water snake) collected from the reservoir surrounded by several e-waste dismantling and recycling workshops than in biota samples obtained from the reference reservoir (13.0–20.5 and 75.4–82.8 ng g⁻¹ for PBDEs and PCBs, respectively) (Wu et al., 2008). Their study also reported the bioaccumulation factor as high as 5.3 for PBDEs and 8.4 for PCBs. These findings collectively indicate that e-waste-derived contaminants readily biomagnify within aquatic and terrestrial food webs.

Evidence from terrestrial wildlife further highlights habitat- and species-dependent accumulation patterns. For instance, in an e-waste study by Nie et al. (2015), which was conducted in the same city as that of Wu et al. (2008), samples of several terrestrial species, including goose, turtledove, dragonfly, chicken, butterfly, grasshopper and ant, were collected to assess the contamination levels of PBDEs in these species. They found elevated concentrations of PBDEs (101–4,725 ng g⁻¹) in the investigated terrestrial biota, indicating that animal-related foods obtained from the e-waste burning site may pose potential health risks to the local populations. The concentrations of POPs in three granivorous species (i.e., spotted dove, scaly-breasted munia and reed vole) from the former e-waste recycling site were in the range 41.5–1,370 ng g⁻¹ for PCBs and 21.1–3,890 ng g⁻¹ for PBDEs (Wu et al., 2023). It was also found that the biomagnification factors of most POPs were greater in vole than in birds, suggesting that the biomagnification of POPs is species-specific, and is potentially affected by the physiochemical properties, as well as the metabolic capability of the POPs. Liu et al. (2018) measured the contamination levels of dichlorodiphenyltrichloroethanes (DDTs), PCBs and halogenated flame retardants (HFRs) in 10 wildlife species, including aquatic, amphibious and terrestrial species, from the heavily e-waste polluted pond and its adjacent area in Guangdong Province. Their study revealed that the target chemicals had total concentrations ranging from 1,300 to 480,000 ng g⁻¹, with PCBs being the predominant (72%–95%) contaminants. They also showed that aquatic organisms and terrestrial birds had elevated concentrations of PCBs and most HFRs compared with amphibians and lizards. This study of Liu and colleagues also observed relatively high DDT levels in amphibious toads and terrestrial birds, but high decabromodiphenyl ethane (DBDPE) levels in most aquatic species. The observed variation among aquatic, amphibious and terrestrial species emphasizes the need for habitat-specific exposure assessment frameworks rather than uniform risk assumptions.

Beyond accumulation, experimental and field-based studies increasingly demonstrate that e-waste-derived contaminants exert tangible adverse effects on animal health. For example, a recent study found decreased sperm numbers and concentrations and increased sperm chromatin damage and morphological

abnormalities in mice following their exposure to e-waste leachates that were collected from several sites near the above-mentioned Alaba International Market (Raja et al., 2024). The post-exposure risk assessment revealed reductions in the serum testosterone levels in e-waste-exposed mice, indicating that the adverse animal health effects associated with e-waste may persist over a longer period of time even following exposure cessation. Raja and colleagues suggested that men living or working in or closer to the e-waste recycling sites may experience harmful reproductive health effects and that the development and implementation of prevention and intervention strategies is critically needed to minimize the potential harms arising from e-waste exposures. Even within the U.S.-based modern e-waste recycling facility, which utilizes mechanical processing, the e-waste-released airborne particulate matter, especially the coarse fraction particle matter, induced substantial pro-inflammatory effects in the mouse lung via both *in vivo* and *ex vivo* post-exposure settings (Kim et al., 2015), highlighting that e-waste-related risks are not confined solely to informal settings. In another study, thyroid endocrine disorder and erythrocyte DNA damage in crucian carp juveniles, which were obtained from the river near the e-waste dismantling site in Zhejiang Province, were significantly associated with higher levels of exposure to PBDEs, raising concerns about population-level impacts on growth, reproduction and survival (Song et al., 2012). An increasing number of studies have also reported the toxicity in animals after exposure to e-waste toxicants (Alabi and Bakare, 2011; Bakare et al., 2013; Alabi and Bakare, 2014; Zhang et al., 2019; Phoonaploy et al., 2019).

Despite substantial advances, several gaps limit a comprehensive understanding of animal health risks associated with e-waste exposure. Most studies focus on single contaminant classes, whereas real-world exposures involve complex mixtures of metals, legacy POPs and emerging flame retardants whose cumulative and interactive effects remain poorly characterized. Long-term and multigenerational studies are rare, constraining insight into chronic low-dose exposure, adaptive responses and transgenerational impacts. Geographic coverage is similarly uneven, with research concentrated in East Asia and selected African sites that represent both exposure hotspots and stronger research capacity, while large regions of South Asia, Southeast Asia and Latin America remain underrepresented due to limited surveillance. In addition, few studies explicitly link animal contamination to human dietary exposure or ecosystem services, limiting relevance for food safety and conservation policy. While existing evidence clearly establishes animals as sensitive bioindicators and key vectors of e-waste-derived contaminants within food webs, advancing toward preventive management will require integrated research combining mixture-based toxicology, long-term monitoring, mechanistic studies of bioaccumulation and explicit linkage to human exposure pathways.

5.5 Aquatic systems

Aquatic systems represent major receptors and secondary redistribution pathways for e-waste-derived contaminants, particularly in regions where informal recycling, dumping and acid leaching occur in close proximity to rivers, ponds and coastal environments. Evidence from multiple geographic settings

demonstrates that sediments and surface waters adjacent to e-waste sites are heavily contaminated with persistent organic pollutants and metals at levels far exceeding those observed in reference locations. For example, the PBDEs concentrations in the sediments from 3 e-waste dumpsites and water from the rain water ponds within the vicinity of these e-waste dumping sites in Lagos State were in the range of 51.4–85.8 and 14.4–27.4 ng g⁻¹, respectively, which were much greater than those in the sediment and water samples obtained from the control site (11.5 and 2.43 ng g⁻¹, respectively) (Oloruntoba et al., 2022). They also pointed out that the ranges of e-waste-derived PBDEs reported in their study were comparable to those observed in studies from USA and Europe, but were lower than those reported in studies from China. The total concentrations of PAHs and their methylated derivatives (MePAHs) were present at elevated levels (370–2,500 ng g⁻¹) in the e-waste contaminated river sediments from a rural village in northern Vietnam (Hoa et al., 2020), raising concerns on the potential ecotoxicological risks to the large number of aquatic lives. Their study found e-waste activities, such as combustion of cable wires and other e-waste materials, to be among the main sources of PAHs and MePAHs in the studied river sediments. Collectively, these findings underscore the global consistency of aquatic contamination signatures associated with informal e-waste activities, despite regional differences in absolute concentration levels. Sediment-focused investigations further reveal pronounced spatial heterogeneity and source-specific contamination patterns within affected watersheds. Zhou et al. (2019) detected all eight investigated PBDE congeners in watershed sediments near e-waste sites and in mangrove sediments furthest away from these e-waste sites, indicating that the PBDEs contamination was both common and severe with significant spatial variability. Zhou and colleagues also suggested that although the sediments from e-waste sites were characterized by higher levels of PBDEs (230–36392 ng g⁻¹) compared with those from mangrove sites (33–327 ng g⁻¹), mangrove forests could be a potential sink of PBDE contaminants, as evidenced by the aforementioned relatively high PBDE concentrations in the examined mangrove sediments.

More strikingly, a study conducted along the Lian River through the Guiyu e-waste recycling zone believed that the concentration levels of 26 hazardous FRs, including 18 BFRs and 8 OPEs, in Guiyu sediments may be among the highest ever reported globally to date for the e-waste-derived FRs concentrations (Li et al., 2019). Additionally, Li's study revealed that the concentrations of OPEs far exceeded those of BFRs in most surficial sediments of the studied river. For instance, in the abovementioned e-waste zone, the sediment concentrations were up to 2120000 ng g⁻¹ for OPEs, but were up to 337000 ng g⁻¹ for BFRs. The dominance of OPEs over BFRs in many surficial sediments highlights a shift in contaminant profiles linked to changes in industrial formulations and regulatory restrictions on legacy flame retardants, emphasizing the dynamic nature of e-waste-derived pollution. Moreover, their study showed obvious variations in the FRs levels from upstream to downstream sediments. For example, while the tris(1-chloro-2-propyl) phosphate, decabromodiphenyl ethane and Deca-BDE dominated in upstream sites, the triphenyl phosphate, Penta-BDE and 1,2-bis(2,4,6-tribromophenoxy)ethane prevailed in midstream and at many downstream sites. Furthermore, Li and colleagues highlighted that the Guiyu e-waste recycling zone may be the

dominant source of various FRs contaminants in the Lian River and that some of these contaminants in Lian River sediments could pose unacceptable ecological risks. Emerging contaminants further complicate the aquatic contamination landscape. In a recent study by Tao et al. (2022), the pollution status of liquid crystal monomers (LCMs), which are considered as a group of the emerging e-waste chemicals of concern due to their potential negative ecological and health effects, was assessed in the Pearl River Estuary that receives contaminants from the Pearl River Delta region, where there is widespread of primitive e-waste handling. It was found that the LCMs exhibited a widespread occurrence in the estuary sediments, with total detected LCMs concentrations ranging from 0.9 to 31.1 ng g⁻¹. The LCMs also exhibited a clear inshore-offshore contamination gradient, indicating land-based origins. Tao's study also pointed out that the total concentrations of LCMs were relatively higher than those of many other legacy and emerging contaminants, including per- and polyfluoroalkyl substances (PFASs), PBDEs, hexachlorocyclohexanes (HCHs) and DDTs. Furthermore, their study recommended not only further assessment of the ecological effects of LCMs on marine systems, but also further identification of the potential sources of these contaminants, as well as exploration of their control measures.

Beyond chemical inventories, several studies provide direct evidence of ecological toxicity associated with e-waste-contaminated sediments and waters. The surface sediments of the Nanguan River, which passes through the area in Taizhou characterized by the e-waste disassembly activities, were seriously contaminated with PAHs, PCBs and heavy metals/metalloids (Chen et al., 2010). Additionally, these sediments revealed significant e-waste-induced acute and genetic toxicities, thereby remarkably threatening both aquatic life and human health. The elutriate and whole sediment toxicity tests demonstrated that the uncontrolled acid discharges from the Guiyu e-waste recycling centre into the Nanyang and Lianjiang rivers resulted not only in low pH and elevated PAHs and heavy metal levels, but also in acute toxicity in most investigated sediments (Wang et al., 2009). This may cause adverse effects on local populations of several aquatic organisms as exemplified by the crustacean survival rates, which correlated negatively with the total concentrations of PAHs in river sediments. The pond and stream water samples from the vicinity of the abandoned Longtang e-waste recycling site were seriously contaminated with heavy metals (Wu et al., 2015). Therefore, immediate remediation of these contaminated waters is necessary to prevent the potential dissemination of their heavy metal pollutants to various areas. For example, irrigating paddy soils with heavy metal-contaminated pond waters was found to cause considerable contamination of these soils, potentially leading to ecological and public health disasters. A heavy metal-related study showed that the e-waste contaminated sediments obtained from the acid leaching site in Chaoyang district were highly polluted with both common (Cu, Zn, Cd and Pb) and uncommon (Sn and Sb) pollutants (Quan et al., 2014). The results of their study suggested that the uncommon Sn and Sb pollutants may exert ecological risks owing to their extremely enhanced total sediment concentrations (i.e., 2,660 and 5690 mg kg⁻¹, respectively). They also suggested that there is an urgent need to identify and control the emission sources of heavy metals, as well as to remediate contaminated sediments.

Despite increasing documentation of contamination, several gaps limit comprehensive assessment of e-waste impacts on aquatic systems. Most studies rely on snapshot sampling, providing limited insight into long-term trends, seasonal variability and chronic low-dose exposure effects on aquatic organisms. Mixture toxicity remains poorly addressed, even though sediments and waters typically contain complex combinations of metals, legacy POPs and emerging contaminants whose ecological effects may differ substantially from single-compound predictions. Geographic coverage is strongly skewed toward East and Southeast Asia, reflecting intense recycling activity and monitoring capacity, while aquatic systems in Africa, Latin America and small island states remain understudied largely due to data scarcity rather than low exposure risk. Furthermore, few investigations integrate chemical contamination data with population-level biological endpoints, such as reproduction, growth or community structure. Advancing from descriptive contamination mapping toward effective prevention and remediation will require integrated approaches combining long-term monitoring, mixture-based ecotoxicology, assessment of emerging contaminants and explicit linkage between chemical exposure and biological responses to inform water management and biodiversity protection.

5.6 Humans

Human exposure to e-waste-derived contaminants has been documented across multiple biomarkers, exposure routes and population groups, with particularly elevated burdens among occupationally exposed workers and residents living in close proximity to informal recycling sites. Biomonitoring studies consistently report higher concentrations of persistent organic pollutants in e-waste workers compared with urban and rural reference populations. For instance, while the median total PBDEs and PCBs concentrations in the fingernails of e-waste dismantling workers from Longtang town in Qingyuan city were 412 and 108 ng g⁻¹, respectively, those in the fingernails of both urban residents from Guangzhou city were 129 and 8.4 ng g⁻¹, respectively, and rural residents from Shijiao town in Qingyuan city were 82.1 and 22.1 ng g⁻¹, respectively (Meng et al., 2020). The significantly higher levels of fingernail PBDEs and PCBs in the e-waste dismantling workers than in the urban and rural residents suggested that e-waste workers are experiencing the continuous greater exposure to these POPs chemicals. Meng and colleagues also reported that the BDE 209 (92%–98%) and CB 52 (26%–51%) were the main PBDE and PCB congeners in the examined fingernail samples, respectively. A study by Zheng J. et al. (2016) reported that the median concentrations of PCBs were elevated in human hair (894 ng G⁻¹) and serum (2,868 ng g⁻¹) samples obtained from the e-waste recycling workers in rural southern China. The study also revealed the difference in hair but not in serum PCB concentrations among male and female e-waste workers. Beyond exposure biomarkers, accumulating evidence links e-waste-related chemical exposure to measurable adverse health outcomes. Recent study showed that the populations working at e-waste dismantling sites or residing around these sites are characterized by liver dysfunction due to the combined impacts of inhalational exposures to volatile organic compounds (VOCs) and semi-volatile organic compounds

(SVOCs) (Yu et al., 2024). This was evidenced not only by the increased activities of serum alanine aminotransferase (ALT) and aspartate aminotransferase (AST), but also by the decreased levels of globulin (GLB). These findings raise concerns about chronic organ-specific toxicity in e-waste-affected communities and underscore the need to move beyond exposure assessment toward outcome-oriented epidemiological research.

Urinary biomonitoring further reveals elevated exposure to emerging contaminants and combustion-derived pollutants. The median total concentrations of OPEs metabolites (mOPEs) in urine samples were found to be significantly higher in the e-waste recycling employees compared with the Ziya Town residents (7 km away from the core e-waste site) and Jinghai downtown residents (25 km away from the e-waste core site) (Li et al., 2022). However, no significant difference in these concentrations was detected between residents of the two above-mentioned non-e-waste towns. These findings may generally suggest that the health effects of e-waste-related contaminants are much stronger on communities located within a few kilometers (mostly <5 km) from the core e-waste recycling areas. Nevertheless, Li and colleagues cautioned against using their suggestion as a solid conclusion due to the small sample size of residents. Moreover, the exposure to OPEs was less intense in the employees from centralized management plants than in the employees from family workshops, but it was close to those in the residents from both Ziya Town and Jinghai downtown. This indicated that the centralized management plants, where good disassembly practices (e.g., mechanical dismantling and active ventilating measures) are in place, can reduce the human occupational exposure to hazardous chemicals present in e-waste areas. Significantly higher urinary levels of ten hydroxylated polycyclic aromatic hydrocarbons ($\Sigma_{10}\text{OH-PAHs}$) of oxidative stress were observed in people from the e-waste dismantling site (25.4 $\mu\text{g g}^{-1}$ Cre) than in people from both rural and urban reference sites (11.7 and 10.9 $\mu\text{g g}^{-1}$ Cre, respectively) (Lu et al., 2016). Moreover, Lu and colleagues found significantly higher urinary $\Sigma_{10}\text{OH-PAHs}$ concentrations in the occupationally exposed e-waste workers (36.6 $\mu\text{g g}^{-1}$ Cre) than in the non-occupationally exposed people residing in the e-waste dismantling site (23.2 $\mu\text{g g}^{-1}$ Cre). Significant differences in urinary $\Sigma_{10}\text{OH-PAHs}$ levels between smokers and non-smokers were observed in rural and urban reference areas but not at e-waste dismantling sites, suggesting that smoking may not be a major contributor to elevated PAHs exposure in e-waste-affected settings. Overall, their results indicate that exposure to polycyclic aromatic hydrocarbons in e-waste dismantling areas may induce oxidative DNA damage, although validation through larger epidemiological studies is required.

The concentration levels of hair Cd, Pb and Cu were found to be significantly higher in residents from the e-waste area than in residents from the control area (Zheng et al., 2011), implying that the individuals working at e-waste recycling areas may be affected by exposure to the elevated toxic metal pollutants. The Cd, Pb and Cu contents in hair samples from the e-waste area residents were significantly positively correlated with each other, suggesting that these three heavy metals may have originated from the e-waste-related activities. The authors also observed similarity in the patterns of heavy metals between children and occupationally exposed e-waste workers, suggesting high vulnerability of children

to e-waste-related heavy metal pollution. A study from Guiyu showed that e-waste-exposed children are experiencing elevated hydroxylated PAH (OH-PAH) levels, which affected their growth negatively and impaired their intestinal immune function (Chen et al., 2021). The concentrations of the hydroxylated PAH metabolites were generally significantly elevated in the urine of exposed group from Agbogbloshie compared to the urine of control group from a suburb of Accra (Feldt et al., 2014). Using a multivariate linear regression analysis, Feldt and colleagues revealed that exposure to e-waste-related activities was the key determinant for exposure to PAHs. These observations emphasize that e-waste exposure is not confined to workers but extends to entire communities, with disproportionate impacts on vulnerable populations.

Despite growing evidence of human exposure to e-waste-related pollutants, substantial gaps remain in understanding the full public health burden. Most studies are cross-sectional, limiting causal inference and obscuring long-term effects of chronic low-dose exposure and chemical mixtures. Although individuals are simultaneously exposed to metals, persistent organic pollutants and emerging contaminants, mixture toxicity and cumulative risk are rarely assessed. Geographic evidence is dominated by China and parts of West Africa, reflecting both exposure hotspots and stronger research infrastructure, while rapidly expanding e-waste hubs in South Asia, Southeast Asia and Latin America remain underrepresented due to limited epidemiological capacity. Moreover, few studies integrate exposure biomarkers with longitudinal clinical outcomes, constraining translation into robust public health guidance. While current evidence clearly indicates elevated risks for workers and nearby residents, advancing from descriptive exposure assessment toward effective prevention will require longitudinal epidemiological studies, mixture-based risk assessment, improved exposure modeling and intervention studies evaluating the effectiveness of engineering controls and regulatory measures to protect vulnerable populations.

6 Approaches for safe management of e-wastes

Effective e-waste management requires integrated strategies grounded in sustainability, circular economy principles and life-cycle thinking. Beyond safe disposal, sustainable management must combine robust regulatory frameworks with clean-up and resource recovery technologies to simultaneously reduce environmental toxicity, enhance material recovery and prevent the displacement of environmental risks across regions (Kumar et al., 2024). Accordingly, this section synthesizes policy, technological, socio-economic and educational approaches, highlighting their demonstrated effectiveness, implementation barriers and region-specific realities, particularly in LMICs where informal recycling remains prevalent, in order to advance safe, circular and context-responsive e-waste management.

6.1 Effective e-waste policy and legislation

Different countries will be able to address the challenges associated with e-wastes, including improper dumping, non-formal recycling and release of hazardous chemicals into the

environment, through establishment of relevant e-waste management frameworks. Such frameworks, include the extended producer responsibility (EPR) (Khatriwal et al., 2009; Grandhi et al., 2024; Widmer et al., 2005), safe recycling standards (Widmer et al., 2005), formal collection and recycling infrastructure (Manomaivibool, 2009), public awareness and participation (Grandhi et al., 2024; Heacock et al., 2016), international cooperation (Grandhi et al., 2024; Basel Action Network, 2002), as well as eco-friendly e-waste practices (Kuo and Smith 2018). From a circular economy perspective, these policy instruments are essential for internalizing environmental costs across the entire product life cycle, promoting closed material loops and improving recovery efficiency of secondary raw materials. It is very crucial to have in place the EPR policies for both developed and low- and middle-income countries as these policies always mandate that producers need to be fully accountable for the whole lifecycle of their products, including post-consumer stages and/or disposal. For instance, countries in the European Union (EU) have effectively succeeded in implementing the EPR policies through the WEEE directive that requires manufacturers to pay for the e-waste collection and recycling (Khatriwal et al., 2009; Grandhi et al., 2024; Widmer et al., 2005). Empirical evidence from the EU indicates that EPR has led to measurable improvements in formal collection rates, recycling efficiency and recovery of valuable metals such as copper and precious elements, thereby supporting circular economy targets. Also, EPR promotes eco-design, lowers utilization of dangerous materials and enhances effective recycling activities (Khatriwal et al., 2009; Grandhi et al., 2024; Widmer et al., 2005). Furthermore, it is very important for the countries to have legislation that reinforces compliance with the international recycling standards, including “the ISO 14001 and the Basel Convention on the control of transboundary movement of hazardous wastes and their disposal”. This is due to the fact that this legislation can not only help to lessen environmental contamination, but also guarantee safe working environments for workers in the recycling industries (Widmer et al., 2005). However, in many LMICs, weak enforcement capacity, limited monitoring and heavy dependence on informal recycling significantly constrain the effectiveness of these policies despite their formal adoption. Moreover, governments can have strong regulations governing the establishment of various centers for formal e-waste collection and recycling activities, thereby regulating the on-going non-formal recycling activities, which usually engage unsafe techniques, e.g., open burning (Manomaivibool, 2009). There should also be policies enforcing public education campaigns to enhance knowledge and understanding of the risks and benefits associated with inappropriate and appropriate e-waste practices, respectively. In turn, these policies will enhance community engagement and compliance with e-waste recycling efforts (Grandhi et al., 2024; Heacock et al., 2016). Policies that reinforces adherence to the existing international treaties, e.g., the Basel Convention that prevents the transboundary movement of hazardous e-wastes to less developed countries, should be formulated and implemented. This will lessen illegal e-waste disposal in less developed countries besides guaranteeing environmentally friendly disposal activities worldwide (Grandhi et al., 2024; Basel Action Network, 2002). In addition, legislation pertaining to tax benefits and/or subsidies targeting companies that practice sustainable production and

take-back programs also needs to be established and implemented. Such legislation stimulates innovation in sustainable e-waste management strategies and activities (Kuo and Smith 2018).

6.2 E-waste collection systems

Various systems for collecting e-wastes are critical elements for more efficient and effective implementation of e-waste management approaches. These systems consist of the well-structured facilities for e-waste collection, transportation, and intermediate storage, which further guarantee safety during e-waste handling, recycling and/or dumping. Efficient collection systems are a major determinant of overall resource recovery efficiency, as low collection rates remain one of the primary bottlenecks limiting circular e-waste management worldwide. Therefore, the presence of vigorous e-waste collection systems can considerably lessen the adverse effects related to inappropriate dumping of e-wastes. The critical components of e-waste collection systems include community collection centres (Baldé et al., 2017), manufacturer or producer take-back programs (Cucchiella et al., 2015), mobile collection points (Zeng et al., 2015), joint public-private partnerships (Widmer et al., 2005), as well as e-waste drop-off occasions (Parajuly et al., 2020). In many LMICs, decentralized and mobile collection systems have proven particularly effective in rural and peri-urban areas where access to fixed infrastructure is limited. The establishment of reachable and effective e-waste collection centres in both rural and urban regions offers appropriate e-waste drop-off points, thus ensuring that e-wastes are collected and piled up in a controlled and monitored environment, which in turn reduces the adverse impacts related to leaching of hazardous compounds present in e-wastes into the environment (Baldé et al., 2017). Moreover, numerous manufacturers and/or producers are implementing and enforcing take-back programs, whereby consumers are required to send back outdated electronic devices to retailers and/or producers. This strategy enhances the EPR where the manufacturers are held accountable for the whole lifecycle of their products (Cucchiella et al., 2015). Furthermore, the presence of mobile collection points, especially in rural and remote areas, serves as an important innovative approach towards e-waste collection. Indeed, these collection points bring the collection practices in the vicinity of communities, thereby guaranteeing outstanding engagement necessary for lowering the rate of improper disposal (Huang et al., 2014). There should also be collaborative joint efforts between public, private, and NGO sectors during the implementation and enforcement of e-waste collection systems. These collaborations usually attract funding opportunities, enhance community awareness, and ensure effective planning and execution, hence increasing efficiency and effectiveness in e-waste collection activities (Widmer et al., 2005). In addition, the periodic e-waste collection events can inspire local communities to obediently and consistently dump their e-wastes in designated collection points. This approach is crucial for enhancing community awareness and escalating e-waste collection volumes (Parajuly et al., 2020). Generally, the availability of effective and sufficient e-waste collection systems in a particular place enhances public health (Breivik et al., 2014), environmental protection and conservation (Van Yken et al., 2021), recovering of beneficial resources (Forti et al., 2020) and economic opportunities (Awasthi and Li, 2017).

Nevertheless, persistent behavioral barriers, such as household stockpiling of obsolete electronics and preference for informal collectors offering immediate cash incentives, continue to limit overall collection efficiency.

6.3 Recycling and recovery technologies

Innovative recycling technologies are crucial in recovering useful and/or beneficial resources from dumped e-wastes while lowering emission-related effects and guaranteeing safe discard of toxic constituents. The application of these technologies not only lessens the e-waste associated environmental footprint, but also enhances efficient resource conservation and economic sustainability (Gupta et al., 2022). From a life-cycle assessment perspective, formal recycling systems consistently exhibit lower environmental footprints and higher metal recovery efficiencies than informal recycling practices. The essential e-waste recycling and recovery technologies include physical separation (Kiddee et al., 2013), pyrolysis and thermal treatment (Song and Li, 2014), hydrometallurgical processes (Cucchiella et al., 2015), bioleaching (Ilyas and Lee, 2014), plasma arc (Chancerel et al., 2013), and cryogenic processing technologies (Baldé et al., 2017). Physical separation technologies involve dismantling of e-waste into its several constituent parts, including metals, plastics and glass, which is being done through shredding, crushing, and sorting processes. Modern techniques such as eddy current separation and magnetic separation are effective in recovering both ferrous and non-ferrous metals and/or elements (Kiddee et al., 2013). Furthermore, pyrolysis and thermal treatment technology involves both recovering of beneficial metals and production of energy through heating of e-waste anaerobically. This technology is especially efficient in treating printed circuit boards and other constituents while preventing the generation of toxic substances (Song and Li, 2014). Moreover, hydrometallurgical processes utilize chemical leaching compounds, especially acids and/or bases, to enhance dissolution of valuable metals from e-wastes. Therefore, this technology seems to be very effective in recovering precious metal elements, such as gold, silver and platinum, through precipitation or electrodeposition (Cucchiella et al., 2015). Furthermore, bioleaching technology involves the use of microorganisms, including bacteria and fungi, to pull out metals from e-wastes. This technology is both less costly and environmentally friendly compared to traditional chemical approaches (Ilyas and Lee, 2014). The plasma arc technology involves utilization of high-temperature plasma to disintegrate e-waste into its various elemental compositions. The aforementioned technique has been reported to be especially efficient in transforming hazardous compounds into non-dangerous end products (Chancerel et al., 2013). In addition, cryogenic processing technique involves subjecting e-waste into extremely low temperatures, thereby making it breakable and easier to grind. This technology enhances the disentangling of materials and averts the generation of harmful compounds during the processing (Baldé et al., 2017). Indeed, it should be noted that there are many benefits associated with e-waste recycling and recovery technologies, including enhancing environmental conservation and protection (Van Yken et al., 2021), resources conservation (Widmer et al., 2005), boosting of economic value

(Forti et al., 2020), as well as preventing the release of greenhouse gases (Kumar et al., 2023). However, high capital costs, energy requirements and technical complexity limit large-scale adoption of advanced technologies in many LMICs, reinforcing continued reliance on low-efficiency informal recycling.

6.4 Product design and eco-innovation technologies

Through incorporating sustainable approaches during designing and innovation activities, producers have the ability of making products that considerably minimizes the e-waste production. This in turn will lower environmental and health risks associated with e-waste disposal (Kumar et al., 2017). Eco-design directly supports circular economy objectives by extending product lifespans, improving recyclability and reducing dependence on virgin raw materials. The critical constituents of product design and eco-innovation approach include design for disassembly and recycling (Kiddee et al., 2013), utilization of eco-friendly materials (Binnemans et al., 2013), EPR compliance (Widmer et al., 2005), durable and repairable products (Widmer et al., 2005), as well as smart and sustainable innovation components (Baldé et al., 2017). Market barriers such as limited access to repair services, consumer preference for rapid replacement and weak regulatory pressure reduce the effectiveness of eco-design, particularly in LMICs. Designing e-device products that can easily be dismantled enhances effective recovery of beneficial materials by averting ecosystem footprint associated with dumping of e-wastes. For instance, modular designs amplify speedy disassembling of e-device constituents, making recycling and maintenance processes to be easily achieved (Kiddee et al., 2013). Furthermore, substituting toxic materials, such as mercury and lead, with non-hazardous and biodegradable compounds in electronic devices could prevent e-waste-related hazards. The integration of recyclable materials in e-devices guarantees that these devices will have less environmental effects at the end of their lifecycle (Binnemans et al., 2013). Moreover, eco-innovation during product design corresponds with the EPR policy that reinforce manufacturers to be accountable for the whole lifecycle of their products (Cucchiella et al., 2015). Also, designing durable e-device products, which can easily be upgraded and/or repaired, would prevent not only the desire for regular displacement, but also the resultant piling up of e-wastes (Widmer et al., 2005). In addition, integrating modern and improved technologies like Internet of Things (IoT) permits devices to flexibly self-monitor and alert users when there is a need for repair, thereby extending product lifecycles and lowering e-waste production (Baldé et al., 2017). Overall, product design and eco-innovation technologies have numerous benefits, including waste minimization (Kiddee et al., 2013), cost efficiency (Binnemans et al., 2013), environmental protection (Song and Li, 2014), and consumer involvement (Forti et al., 2020).

6.5 Integrating the informal sector into formal e-waste management technologies

This approach is suitable for counteracting the problems of e-waste management, especially in LMICs. Although the informal

e-waste sector is always operating under risk and environmentally unfriendly conditions, it contributes hugely in e-waste collection, dismantling, and recycling activities. Exclusionary enforcement approaches have often proven ineffective, whereas inclusive integration models tend to improve both environmental performance and social equity. Therefore, through incorporating these potential actors into formal e-waste management systems, their knowledge, skills, competence and broader connections can be fully utilized, leading into prevention of e-waste-related environmental and health hazards (Tsydenova and Bengtsson, 2011). Important elements of integrating informal into formal e-waste sector include capacity building and training (Chi et al., 2011), incentives for formalization (Manhart and Schleicher 2015), partnership with formal systems (Wilson et al., 2006), as well as policy and regulatory support (Sthiannopkao and Wong, 2013). Equipping informal workers with technical training can help them to acquire skills and knowledge needed for safe recycling activities and proper handling of toxic substances. This strategy is vital for safeguarding the environment and humans against hazards from e-waste contamination (Chi et al., 2011).

Furthermore, providing financial incentives, as well as access to improved infrastructure and social welfare (e.g., healthcare and insurance), could motivate informal workers to venture into formal e-waste management schemes (Manhart and Schleicher 2015). Moreover, having strong collaborations between informal e-waste collectors and formal recycling centers would ensure a stable supply of e-wastes for risk-free processing (Wilson et al., 2006). Also, different countries can impose supportive policies and legislations that acknowledge the efforts of the informal e-waste sector through establishment of channels for involving them in national e-waste management plans (Sthiannopkao and Wong, 2013). Key barriers to integration include mistrust, lack of access to finance and absence of social protection mechanisms for informal workers. Addressing these barriers requires coordinated policy support, targeted financial mechanisms and inclusive governance structures that balance environmental protection with social protection for informal workers.

6.6 International cooperation

E-waste management is a worldwide challenge as considerable cases of transboundary movement of dumped electronic materials have been observed, especially from high-income nations to low- and middle-income nations. International cooperation therefore plays a central role in harmonizing regulations, enhancing global recycling efficiency and preventing environmental burden shifting across regions. This necessitates joint efforts between and among countries and international organizations, thereby fostering enhanced policies, training and capacity building, technology sharing and transfer, as well as sustainable e-waste management activities. There are numerous important approaches regarding e-waste management under international cooperation, including the policy harmonization and regulatory schemes (Grandhi et al., 2024; Basel Action Network, 2002; Kumar et al., 2017; Thakur and Kumar 2022), knowledge and technology transfer and sharing

(Baldé et al., 2017), worldwide e-waste monitoring (Baldé et al., 2017), training and capacity building (Grandhi et al., 2024), collaborative research and development (Kumar et al., 2017) and financial support and investment (Widmer et al., 2005). Having harmonized regulations, which can be between and/or among nations, helps to avoid improper e-waste discarding by guaranteeing safe e-waste handling (Grandhi et al., 2024; Basel Action Network, 2002; Kumar et al., 2017; Thakur and Kumar 2022). Furthermore, high-income countries should transfer and share their modern recycling technologies with LMICs. For instance, it is important for these high-income countries to transfer and share knowledge and skills pertaining to safe methods of e-waste disassembling, recycling, and recovery to reduce environmental and health related effects (Baldé et al., 2017). This can also enhance technical capacities, guarantee compliance with international standards and improve indigenous recycling abilities (Grandhi et al., 2024). Moreover, cooperative efforts and/or programs like the “Global E-waste Statistics Association” ensure the availability of data related to e-waste production, and discarding, as well as e-waste recycling and recovery rates, thereby fostering a worldwide evidence-based decision-making and a close follow-up in e-waste management status (Forti et al., 2020). Persistent data gaps and inconsistent reporting remain major barriers to evaluating global progress toward circular e-waste management. Furthermore, partnerships in research and development enhance innovations in designing environmentally friendly electronic devices, e-waste recycling and recovery technologies, as well as effective e-waste management strategies. Collaborative projects that engage several nations can also foster mobilization and/or pooling of available resources and expertise (Kumar et al., 2017). In addition, LMICs usually experience financial constraints in such a way that they are unable to initiate and practice sustainable e-waste management schemes. Therefore, international organizations and high-income countries can potentially address this concern by providing financial support or investments in these LMICs to boost their facilities and/or infrastructure development, as well as program implementation (Widmer et al., 2005).

6.7 Enhancing public awareness and education

A well-educated public regarding e-waste management can considerably minimize the potential environmental and health hazards associated with e-wastes by engaging in safe and environmentally sustainable recycling activities, dumping techniques and manufacturing practices (Borthakur and Govind, 2017). Public awareness is a key behavioral driver that determines participation in take-back schemes, collection systems and sustainable consumption patterns. Furthermore, incorporating e-waste-related courses in curricula in schools, colleges or universities can enhance environmental accountability among students. Long-term educational integration is essential for sustaining behavioral change beyond short-term awareness campaigns and for reinforcing circular economy values across generations. This initiative nurtures a generation that will be responsible for implementing

sustainable and environmentally friendly practices (Baldé et al., 2017), including recycling and take-back schemes (Kiddee et al., 2013), as well as sustainable utilization of electronics (Widmer et al., 2005). Moreover, various online platforms, including social media and social networks, should be used as essential tools for effectively disseminating information to the public regarding e-waste management (Forti et al., 2020). In addition, grassroots initiatives, including workshops, seminars and “door-to-door campaigns”, which should be spearheaded by both local organizations and non-governmental organizations (NGOs), can stimulate community-based e-waste collection motives, leading to accountability towards proper e-waste dumping (Ongondo et al., 2011).

7 Conclusion

This review demonstrates that e-waste has become a pervasive and escalating global challenge, driven by rapid technological change, expanding electronic consumption and insufficient end-of-life management. Despite notable progress in formal collection and recycling systems, particularly in high-income regions, global e-waste generation continues to far outpace recovery rates, with the imbalance most pronounced in low- and middle-income countries where informal recycling remains dominant. Evidence synthesized in this review clearly shows that e-waste-derived contaminants persist across environmental compartments, such as soils, air and dust, plants, animals and aquatic systems, and pose significant risks to ecosystem integrity and human health, especially for workers and communities living near informal recycling sites. Beyond these documented impacts, the review identifies several critical research gaps that must be addressed to reduce future e-waste contamination. These include the need for long-term and longitudinal studies to capture chronic low-dose exposure effects, greater emphasis on mixture toxicity rather than single-compound assessments, improved understanding of contaminant bioavailability and transfer through food webs, and expanded geographic coverage in underrepresented regions such as large parts of Africa, Latin America and Southeast Asia. Strengthening links between environmental measurements, biological responses and epidemiological outcomes remains a key priority for translating scientific evidence into effective risk management. From a practical perspective, the findings highlight that no single intervention is sufficient to address the complexity of e-waste pollution. Effective mitigation requires integrated and context-specific strategies that combine robust policy enforcement, efficient collection systems, environmentally sound recycling and recovery technologies, circular product design, formalization of informal recycling activities, international collaboration and sustained public education. Future research and policy efforts should therefore focus on evidence-based evaluation of these interventions, life-cycle-oriented management approaches and scalable solutions tailored to regional socio-economic realities. Such coordinated actions are essential for reducing the environmental and health burdens of e-waste while supporting a transition toward sustainable and circular electronic economies.

Author contributions

HM: Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing, Data curation, Formal Analysis, Investigation. YK: Writing – review and editing. WM: Writing – review and editing. LC: Writing – review and editing. AM: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgements

We thank the Mwalimu Nyerere University of Agriculture and Technology (MNUAT) for its in-kind support.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Alabi, O. A. (2024). Edible vegetables grown in the vicinity of electronic wastes: a study of potential health risks and DNA damage in consumers. *Toxicology* 509, 153963. doi:10.1016/j.tox.2024.153963
- Alabi, O. A., and Bakare, A. A. (2011). Genotoxicity and mutagenicity of electronic waste leachates using animal bioassays. *Toxicol. and Environ. Chem.* 93 (5), 1073–1088. doi:10.1080/02772248.2011.561949
- Alabi, O. A., and Bakare, A. A. (2014). Cytogenotoxic effects and reproductive abnormalities induced by e-Waste contaminated underground water in mice. *CYTOLOGIA* 79 (3), 331–340. doi:10.1508/cytologia.79.331
- Alabi, O. A., Bakare, A. A., Xu, X., Li, B., Zhang, Y., and Huo, X. (2012). Comparative evaluation of environmental contamination and DNA damage induced by electronic-waste in Nigeria and China. *Sci. Total Environ.* 423, 62–72. doi:10.1016/j.scitotenv.2012.01.056
- Awasthi, A. K., and Li, J. (2017). Management of electrical and electronic waste: a comparative evaluation of China and India. *Renew. Sustain. Energy Rev.* 76, 434–447. doi:10.1016/j.rser.2017.02.067
- Babatunde, B., and Anabuiki, F. (2015). *In vivo* cytogenotoxicity of electronic waste leachate from iloabuchi electronic market, diobu, Rivers State. *Niger. Allium Cepa. Challenges* 6 (1), 173–187. doi:10.3390/challe6010173
- Bakare, A. A., Alabi, O. A., Gbadebo, A. M., Ogunsuyi, O. I., and Alimba, C. G. (2013). *In vivo* cytogenotoxicity and oxidative stress induced by electronic waste leachate and contaminated well. *Water. Challenges* 4 (2), 169–187. doi:10.3390/challe4020169
- Baldé, C. P., Forti, V., Gray, V., Kuehr, R., and Stegmann, P. (2017). *The global E-waste monitor*. Bonn/Geneva/Vienna: United Nations University (UNU), International Telecommunication Union (ITU), International Solid Waste Association ISWA.
- Baldé, C. P., Iattoni, G., Xu, C., and Yamamoto, T. (2022). *Update of WEEE Collection Rates, targets, Flows, and Hoarding- 2021 in the EU-27, United Kingdom, Norway, Switzerland, and Iceland, 2022*. Bonn, Germany: SCYCLE Programme. United Nations Institute for Training and Research UNITAR.
- Baldé, P. C., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S., et al. (2024). *Global E-waste monitor*. Geneva/Bonn: International Telecommunication Union (ITU), United Nations Institute for Training and Research UNITAR.
- Basel Action Network (2002). Exporting Harm: the high-tech Trashing of Asia. Available online at: <http://www.ban.org/E-waste/technotrashfinalcomp.pdf> (Accessed July 07, 2025).

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2026.1762578/full#supplementary-material>

- Binnemans, K., Jones, P. T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., et al. (2013). Recycling of rare earths: a critical review. *J. Clean. Prod.* 51, 1–22. doi:10.1016/j.jclepro.2012.12.037
- Borthakur, A., and Govind, M. (2017). Emerging trends in consumers' E-waste disposal behaviour and awareness: a worldwide overview with special focus on India. *Resour. Conserv. Recycl.* 117, 102–113. doi:10.1016/j.resconrec.2016.11.011
- Breivik, K., Armitage, J. M., Wania, F., and Jones, K. C. (2014). Tracking the global generation and exports of e-waste. Do existing estimates add up? *Environ. Sci. Technol.* 48 (15), 8735–8743. doi:10.1021/es5021313
- Chakraborty, P., Selvaraj, S., Nakamura, M., Prithiviraj, B., Cincinelli, A., and Bang, J. J. (2018). PCBs and PCDD/Fs in soil from informal e-waste recycling sites and open dumpsites in India: levels, congener profiles and health risk assessment. *Sci. Total Environ.* 621, 930–938. doi:10.1016/j.scitotenv.2017.11.083
- Chakraborty, P., Gadhavi, H., Prithiviraj, B., Mukhopadhyay, M., Khuman, S. N., Nakamura, M., et al. (2021). Passive air sampling of PCDD/Fs, PCBs, PAEs, DEHA, and PAHs from informal electronic waste recycling and allied sectors in Indian megacities. *Environ. Sci. and Technol.* 55 (14), 9469–9478. doi:10.1021/acs.est.1c01460
- Chancerel, P., Rotter, V. S., Ueberschaar, M., Marwede, M., Nissen, N. F., and Lang, K.-D. (2013). Data availability and the need for research to localize, quantify and recycle critical metals in information technology, telecommunication and consumer equipment. *Waste Manag. and Res.* 31 (10_Suppl. 1), 3–16. doi:10.1177/0734242X13499814
- Chen, L., Yu, C., Shen, C., Zhang, C., Liu, L., Shen, K., et al. (2010). Study on adverse impact of e-waste disassembly on surface sediment in East China by chemical analysis and bioassays. *J. Soils Sediments* 10 (3), 359–367. doi:10.1007/s11368-009-0176-8
- Chen, C.-L., Yang, P.-H., Kao, Y.-C., Chen, P.-Y., Chung, C.-L., and Wang, S.-W. (2017). Pentabromophenol suppresses TGF- β signaling by accelerating degradation of type II TGF- β receptors via caveolae-mediated endocytosis. *Sci. Rep.* 7 (1), 43206. doi:10.1038/srep43206
- Chen, G., Huo, X., Luo, X., Cheng, Z., Zhang, Y., and Xu, X. (2021). E-waste polycyclic aromatic hydrocarbon (PAH) exposure leads to child gut-mucosal inflammation and adaptive immune response. *Environ. Sci. Pollut. Res.* 28 (38), 53267–53281. doi:10.1007/s11356-021-14492-3
- Chi, X., Streicher-Porte, M., Wang, M. Y. L., and Reuter, M. A. (2011). Informal electronic waste recycling: a sector review with special focus on China. *Waste Manag.* 31 (4), 731–742. doi:10.1016/j.wasman.2010.11.006

- Cucchiella, F., D'Adamo, I., Lenny Koh, S. C., and Rosa, P. (2015). Recycling of WEEE: an economic assessment of present and future e-waste streams. *Renew. Sustain. Energy Rev.* 51, 263–272. doi:10.1016/j.rser.2015.06.010
- Eckhardt, B., and Kaifie, A. (2024). Bridging the knowledge gap! health outcomes in informal e-waste workers. *J. Occup. Med. Toxicol.* 19 (1), 11. doi:10.1186/s12995-024-00410-z
- Feiteiro, J., Mariana, M., and Cairro, E. (2021). Health toxicity effects of brominated flame retardants: from environmental to human exposure. *Environ. Pollut.* 285, 117475. doi:10.1016/j.envpol.2021.117475
- Feldt, T., Fobil, J. N., Wittsiepe, J., Wilhelm, M., Till, H., Zoufaly, A., et al. (2014). High levels of PAH-metabolites in urine of e-waste recycling workers from Agbogbloshie, Ghana. *Sci. Total Environ.* 466–467, 369–376. doi:10.1016/j.scitotenv.2013.06.097
- Fenton, S. E., Ducatman, A., Boobis, A., DeWitt, J. C., Lau, C., Ng, C., et al. (2021). Per- and polyfluoroalkyl substance toxicity and human health review: current state of knowledge and strategies for informing future research. *Environ. Toxicol. Chem.* 40 (3), 606–630. doi:10.1002/etc.4890
- Folarin, B. T., Poma, G., Yin, S., Altamirano, J. C., Oluseyi, T., Badru, G., et al. (2024). Assessment of legacy and alternative halogenated organic pollutants in outdoor dust and soil from e-waste sites in Nigeria: concentrations, patterns, and implications for human exposure. *Environ. Pollut.* 342, 123032. doi:10.1016/j.envpol.2023.123032
- Forti, V., Balde, C. P., Kuehr, R., and Bel, G. (2020). *The global E-waste monitor 2020: quantities, flows and the circular economy potential*. Bonn/Geneva/Rotterdam: United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) and International Solid Waste Association ISWA.
- Fu, J., Zhou, Q., Liu, J., Liu, W., Wang, T., Zhang, Q., et al. (2008). High levels of heavy metals in rice (*Oryzasetiva* L.) from a typical E-waste recycling area in southeast China and its potential risk to human health. *Chemosphere* 71 (7), 1269–1275. doi:10.1016/j.chemosphere.2007.11.065
- Grandhi, S. P., Dagwar, P. P., and Dutta, D. (2024). Policy pathways to sustainable E-waste management: a global review. *J. Hazard. Mater. Adv.* 16, 100473. doi:10.1016/j.hazadv.2024.100473
- Grant, K., Goldizen, F. C., Sly, P. D., Brune, M.-N., Neira, M., van den Berg, M., et al. (2013). Health consequences of exposure to e-waste: a systematic review. *Lancet Glob. Health* 1 (6), e350–e361. doi:10.1016/S2214-109X(13)70101-3
- Gupta, M., A. K., Upadhyaya, V., and Nigam, S. (2022). “Metal recovery from E-Waste by recycling techniques: a review,” in *2022 8th international conference on smart structures and systems (ICSSS)*, 1–5. doi:10.1109/ICSSS54381.2022.9782219
- Heacock, M., Kelly, C. B., Asante Kwadwo, A., Birnbaum, L. S., Bergman Åke, L., Bruné, M.-N., et al. (2016). E-Waste and harm to vulnerable populations: a growing global problem. *Environ. Health Perspect.* 124 (5), 550–555. doi:10.1289/ehp.1509699
- Hoa, N. T. Q., Anh, H. Q., Tue, N. M., Trung, N. T., Da, L. N., Van Quy, T., et al. (2020). Soil and sediment contamination by unsubstituted and methylated polycyclic aromatic hydrocarbons in an informal e-waste recycling area, northern Vietnam: occurrence, source apportionment, and risk assessment. *Sci. Total Environ.* 709, 135852. doi:10.1016/j.scitotenv.2019.135852
- Ilyas, S., and Lee, Jc (2014). Biometallurgical recovery of metals from waste electrical and electronic equipment: a review. *ChemBioEng Rev.* 1 (4), 148–169. doi:10.1002/cben.201400001
- Iqbal, M., Syed, J. H., Breivik, K., Chaudhry, M. J. I., Li, J., Zhang, G., et al. (2017). E-Waste driven pollution in Pakistan: the first evidence of environmental and human exposure to flame retardants (FRs) in Karachi City. *Environ. Sci. Technol.* 51 (23), 13895–13905. doi:10.1021/acs.est.7b03159
- Isimekhai, K. A., Garelick, H., Watt, J., and Purchase, D. (2017). Heavy metals distribution and risk assessment in soil from an informal E-waste recycling site in Lagos State, Nigeria. *Environ. Sci. Pollut. Res.* 24 (20), 17206–17219. doi:10.1007/s11356-017-8877-9
- ITU (2022). “Measuring digital development,” in *Facts and figures*. Geneva, Switzerland: International Telecommunication Union ITU.
- Järup, L. (2003). Hazards of heavy metal contamination. *Br. Med. Bull.* 68 (1), 167–182. doi:10.1093/bmb/ldg032
- Jia, J., Bi, C., Zhang, J., Jin, X., and Chen, Z. (2018). Characterization of polycyclic aromatic hydrocarbons (PAHs) in vegetables near industrial areas of Shanghai, China: sources, exposure, and cancer risk. *Environ. Pollut.* 241, 750–758. doi:10.1016/j.envpol.2018.06.002
- Jun-hui, Z., and Hang, M. (2009). Eco-toxicity and metal contamination of paddy soil in an e-wastes recycling area. *J. Hazard. Mater.* 165 (1), 744–750. doi:10.1016/j.jhazmat.2008.10.056
- Khetriwal, D. S., Kraeuchi, P., and Widmer, R. (2009). Producer responsibility for e-waste management: key issues for consideration – learning from the Swiss experience. *J. Environ. Manag.* 90 (1), 153–165. doi:10.1016/j.jenvman.2007.08.019
- Kiddee, P., Naidu, R., and Wong, M. H. (2013). Electronic waste management approaches: an overview. *Waste Manag.* 33 (5), 1237–1250. doi:10.1016/j.wasman.2013.01.006
- Kim, Y. H., Wyrzykowska-Ceradini, B., Touati, A., Krantz, Q. T., Dye, J. A., Linak, W. P., et al. (2015). Characterization of size-fractionated airborne particles inside an electronic waste recycling facility and acute toxicity testing in mice. *Environ. Sci. and Technol.* 49 (19), 11543–11550. doi:10.1021/acs.est.5b03263
- Kumar, P., and Fulekar, M. H. (2017). Assessment of physico-chemical, microbial characteristics and heavy metals contamination at e-waste dumping sites at Ahmedabad, Gujarat. *Int. J. Adv. Res.* 5 (6), 1601–1609. doi:10.21474/IJAR01/4577
- Kumar, P., and Fulekar, M. H. (2019). Multivariate and statistical approaches for the evaluation of heavy metals pollution at e-waste dumping sites. *SN Appl. Sci.* 1, 1559. doi:10.1007/s42452-019-1559-0
- Kumar, A., Holuszko, M., and Espinosa, D. C. R. (2017). E-waste: an overview on generation, collection, legislation and recycling practices. *Resour. Conservation Recycl.* 122, 32–42. doi:10.1016/j.resconrec.2017.01.018
- Kumar, P., Fulekar, M. H., Hiranmai, R. Y., Kumar, R., and Kumar, R. (2020). 16S rRNA molecular profiling of heavy metal tolerant bacterial communities isolated from soil contaminated by electronic waste. *Folia Microbiol.* 65, 995–1007. doi:10.1007/s12223-020-00808-2
- Kumar, P., Gacem, A., Ahmad, M. T., Yadav, V. K., Singh, S., Yadav, K. K., et al. (2022). Environmental and human health implications of metal(loid)s: source identification, contamination, toxicity, and sustainable clean-up technologies. *Front. Environ. Sci.* 10, 949581. doi:10.3389/fenvs.2022.949581
- Kumar, A., Thakur, A. K., Gaurav, G. K., Klemeš, J. J., Sandhwar, V. K., Pant, K. K., et al. (2023). A critical review on sustainable hazardous waste management strategies: a step towards a circular economy. *Environ. Sci. Pollut. Res.* 30 (48), 105030–105055. doi:10.1007/s11356-023-29511-8
- Kuo, T.-C., and Smith, S. (2018). A systematic review of technologies involving eco-innovation for enterprises moving towards sustainability. *J. Clean. Prod.* 192, 207–220. doi:10.1016/j.jclepro.2018.04.212
- Kumar, P., Singh, S., Gacem, A., Yadav, K. K., Bhutto, J. K., Alreshidi, M. A., et al. (2024). A review on e-waste contamination, toxicity, and sustainable clean-up approaches for its management. *Toxicology* 508, 153904. doi:10.1016/j.tox.2024.153904
- Li, H., La Guardia, M. J., Liu, H., Hale, R. C., Mainor, T. M., Harvey, E., et al. (2019). Brominated and organophosphate flame retardants along a sediment transect encompassing the Guiyu, China e-waste recycling zone. *Sci. Total Environ.* 646, 58–67. doi:10.1016/j.scitotenv.2018.07.276
- Li, X., Wang, L., Wang, Y., Yao, Y., Zhang, P., Zhao, H., et al. (2022). Occupational exposure to organophosphate esters in e-waste dismantling workers: risk assessment and influencing factors screening. *Ecotoxicol. Environ. Saf.* 240, 113707. doi:10.1016/j.ecoenv.2022.113707
- Liao, C., Lv, J., Fu, J., Zhao, Z., Liu, F., Xue, Q., et al. (2012). Occurrence and profiles of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) in soils from a typical e-waste recycling area in Southeast China. *Int. J. Environ. Health Res.* 22 (4), 317–330. doi:10.1080/09603123.2011.634392
- Liu, J., He, X.-x., Lin, X.-r., Chen, W.-c., Zhou, Q.-x., Shu, W.-s., et al. (2015). Ecological effects of combined pollution associated with E-Waste recycling on the composition and diversity of soil microbial communities. *Environ. Sci. and Technol.* 49 (11), 6438–6447. doi:10.1021/es5049804
- Liu, Y., Luo, X.-J., Huang, L.-Q., Tao, L., Zeng, Y.-H., and Mai, B.-X. (2018). Halogenated organic pollutants in aquatic, amphibious, and terrestrial organisms from an e-waste site: Habitat-dependent accumulation and maternal transfer in watersnake. *Environ. Pollut.* 241, 1063–1070. doi:10.1016/j.envpol.2018.06.038
- Lu, S.-y., Li, Y.-x., Zhang, J.-q., Zhang, T., Liu, G.-h., Huang, M.-z., et al. (2016). Associations between polycyclic aromatic hydrocarbon (PAH) exposure and oxidative stress in people living near e-waste recycling facilities in China. *Environ. Int.* 94, 161–169. doi:10.1016/j.envint.2016.05.021
- Luo, C., Liu, C., Wang, Y., Liu, X., Li, F., Zhang, G., et al. (2011). Heavy metal contamination in soils and vegetables near an e-waste processing site, south China. *J. Hazard. Mater.* 186 (1), 481–490. doi:10.1016/j.jhazmat.2010.11.024
- Man, Y. B., Lopez, B. N., Wang, H. S., Leung, A. O. W., Chow, K. L., and Wong, M. H. (2011). Cancer risk assessment of polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) in former agricultural soils of Hong Kong. *J. Hazard. Mater.* 195, 92–99. doi:10.1016/j.jhazmat.2011.08.010
- Manhart, A., and Schleicher, T. (2015). The recycling chain for used lead-acid batteries in Ghana: observations and general considerations. Freiburg, Germany. Available online at: <http://www.oeko.de/oekodoc/2316/2015-487-en.pdf> (Accessed October 10, 2025).
- Manomaivibool, P. (2009). Extended producer responsibility in a non-OECD context: the management of waste electrical and electronic equipment in India. *Resour. Conservation Recycl.* 53 (3), 136–144. doi:10.1016/j.resconrec.2008.10.003
- Martinez-Arguelles, D. B., Campioli, E., Culty, M., Zirkin, B. R., and Papadopoulos, V. (2013). Fetal origin of endocrine dysfunction in the adult: the phthalate model. *J. Steroid Biochem. Mol. Biol.* 137, 5–17. doi:10.1016/j.jsbmb.2013.01.007
- Meng, H.-J., Tang, B., Zheng, J., Ma, S.-X., Cai, F.-S., Zhuang, X., et al. (2020). Levels and sources of PBDEs and PCBs in human nails from e-waste, urban, and rural areas in South China. *Environ. Sci. Process. and Impacts* 22 (8), 1710–1717. doi:10.1039/D0EM00221F
- Mishra, S., Bharagava, R. N., More, N., Yadav, A., Zainith, S., Mani, S., et al. (2019). “Heavy metal contamination: an alarming threat to environment and human health,” in

- Environmental biotechnology: for sustainable future*. Editors R. C. Sobti, N. K. Arora, and R. Kothari (Singapore: Springer Singapore), 103–125. doi:10.1007/978-981-10-7284-0_5
- Moeckel, C., Breivik, K., Nøst, T. H., Sankoh, A., Jones, K. C., and Sweetman, A. (2020). Soil pollution at a major West African E-waste recycling site: contamination pathways and implications for potential mitigation strategies. *Environ. Int.* 137, 105563. doi:10.1016/j.envint.2020.105563
- Mowla, M., Rahman, E., Islam, N., and Aich, N. (2021). Assessment of heavy metal contamination and health risk from indoor dust and air of informal E-waste recycling shops in Dhaka, Bangladesh. *J. Hazard. Mater. Adv.* 4, 100025. doi:10.1016/j.hazadv.2021.100025
- Muenhor, D., Harrad, S., Ali, N., and Covaci, A. (2010). Brominated flame retardants (BFRs) in air and dust from electronic waste storage facilities in Thailand. *Environ. Int.* 36 (7), 690–698. doi:10.1016/j.envint.2010.05.002
- Ngaba, M. J. Y., and Mgelwa, A. S. (2020). Ecological risk assessment of heavy metal contamination of six forest soils in China. *Int. J. Innovation Appl. Stud.* 30 (1), 1–10.
- Nie, Z., Tian, S., Tian, Y., Tang, Z., Tao, Y., Die, Q., et al. (2015). The distribution and biomagnification of higher brominated BDEs in terrestrial organisms affected by a typical e-waste burning site in South China. *Chemosphere* 118, 301–308. doi:10.1016/j.chemosphere.2014.09.062
- Ojo, A. F., Peng, C., and Ng, J. C. (2021). Assessing the human health risks of per- and polyfluoroalkyl substances: a need for greater focus on their interactions as mixtures. *J. Hazard. Mater.* 407, 124863. doi:10.1016/j.jhazmat.2020.124863
- Oloruntoba, K., Sindiku, O., Osibanjo, O., and Weber, R. (2022). Polybrominated diphenyl ethers (PBDEs) concentrations in soil, sediment and water samples around electronic wastes dumpsites in Lagos, Nigeria. *Emerg. Contam.* 8, 206–215. doi:10.1016/j.emcon.2022.03.003
- Ongondo, F. O., Williams, I. D., and Cherrett, T. J. (2011). How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Manag.* 31 (4), 714–730. doi:10.1016/j.wasman.2010.10.023
- Parajuly, K., Kuehr, R., Awasthi, A., Fitzpatrick, C., Lepawsky, J., Smith, E., et al. (2019). Future E-Waste Scenarios. STEP (Bonn), UNU ViE-SCYCLE (Bonn) and UNEP IETC (Osaka)
- Parajuly, K., Fitzpatrick, C., Muldoon, O., and Kuehr, R. (2020). Behavioral change for the circular economy: a review with focus on electronic waste management in the EU. *Resour. Conservation and Recycl.* X 6, 100035. doi:10.1016/j.rcrx.2020.100035
- Perkins, D. N., Brune Drisse, M.-N., Nxele, T., and Sly, P. D. (2014). E-Waste: a global hazard. *Ann. Glob. Health* 80 (4), 286–295. doi:10.1016/j.aogh.2014.10.001
- Phoonaploy, U., Tengjaroenkul, B., and Neeratanaphan, L. (2019). Effects of electronic waste on cytogenetic and physiological changes in snakehead fish (*Channa striata*). *Environ. Monit. Assess.* 191 (6), 363. doi:10.1007/s10661-019-7509-x
- Quan, S.-X., Yan, B., Lei, C., Yang, F., Li, N., Xiao, X.-M., et al. (2014). Distribution of heavy metal pollution in sediments from an acid leaching site of e-waste. *Sci. Total Environ.* 499, 349–355. doi:10.1016/j.scitotenv.2014.08.084
- Raja, A., Costa, P., Blum, J. L., Doherty-Lyons, S., Igbo, J. K., Meltzer, G., et al. (2024). *In vivo* exposure to electronic waste (e-waste) leachate and hydraulic fracturing fluid adversely impacts the male reproductive system. *Reprod. Toxicol.* 124, 108533. doi:10.1016/j.reprotox.2023.108533
- Rautela, R., Arya, S., Vishwakarma, S., Lee, J., Kim, K.-H., and Kumar, S. (2021). E-waste management and its effects on the environment and human health. *Sci. Total Environ.* 773, 145623. doi:10.1016/j.scitotenv.2021.145623
- Selvakumar, S., Adithe, S., Isaac, J. S., Pradhan, R., Venkatesh, V., and Sampath, B. (2023). “A study of the Printed Circuit Board (PCB) E-Waste recycling process,” in *Sustainable approaches and strategies for E-Waste management and utilization* (Hershey, Pennsylvania, United States: IGI Global Scientific Publishing), 159–184.
- Shahabuddin, M., Uddin, M. N., Chowdhury, J. I., Ahmed, S. F., Uddin, M. N., Mofijur, M., et al. (2023). A review of the recent development, challenges, and opportunities of electronic waste (e-waste). *Int. J. Environ. Sci. Technol.* 20 (4), 4513–4520. doi:10.1007/s13762-022-04274-w
- Shi, A., Shao, Y., Zhao, K., and Fu, W. (2020). Long-term effect of E-waste dismantling activities on the heavy metals pollution in paddy soils of southeastern China. *Sci. Total Environ.* 705, 135971. doi:10.1016/j.scitotenv.2019.135971
- Snyder, H. (2019). Literature review as a research methodology: an overview and guidelines. *J. Bus. Res.* 104, 333–339. doi:10.1016/j.jbusres.2019.07.039
- Song, Q., and Li, J. (2014). Environmental effects of heavy metals derived from the e-waste recycling activities in China: a systematic review. *Waste Manag.* 34 (12), 2587–2594. doi:10.1016/j.wasman.2014.08.012
- Song, Y., Wu, N., Tao, H., Tan, Y., Gao, M., Han, J., et al. (2012). Thyroid endocrine dysregulation and erythrocyte DNA damage associated with PBDE exposure in juvenile crucian carp collected from an e-waste dismantling site in Zhejiang Province, China. *Environ. Toxicol. Chem.* 31 (9), 2047–2051. doi:10.1002/etc.1915
- Sthiannopkao, S., and Wong, M. H. (2013). Handling e-waste in developed and developing countries: initiatives, practices, and consequences. *Sci. Total Environ.* 463–464, 1147–1153. doi:10.1016/j.scitotenv.2012.06.088
- Tao, D., Jin, Q., Ruan, Y., Zhang, K., Jin, L., Zhan, Y., et al. (2022). Widespread occurrence of emerging E-waste contaminants – liquid crystal monomers in sediments of the Pearl River Estuary, China. *J. Hazard. Mater.* 437, 129377. doi:10.1016/j.jhazmat.2022.129377
- Thakur, P., and Kumar, S. (2022). Evaluation of e-waste status, management strategies, and legislations. *Int. J. Environ. Sci. Technol.* 19 (7), 6957–6966. doi:10.1007/s13762-021-03383-2
- Tsydenova, O., and Bengtsson, M. (2011). Chemical hazards associated with treatment of waste electrical and electronic equipment. *Waste Manag.* 31 (1), 45–58. doi:10.1016/j.wasman.2010.08.014
- Van Yken, J., Boxall, N. J., Cheng, K. Y., Nikoloski, A. N., Moheimani, N. R., and Kaksonen, A. H. (2021). E-waste recycling and resource recovery: a review on technologies, barriers and enablers with a focus on Oceania. *Metals* 11 (8), 1313. doi:10.3390/met11081313
- Wang, F., Leung, A. O. W., Wu, S. C., Yang, M. S., and Wong, M. H. (2009). Chemical and ecotoxicological analyses of sediments and elutriates of contaminated rivers due to e-waste recycling activities using a diverse battery of bioassays. *Environ. Pollut.* 157 (7), 2082–2090. doi:10.1016/j.envpol.2009.02.015
- Wang, Y., Tian, Z., Zhu, H., Cheng, Z., Kang, M., Luo, C., et al. (2012). Polycyclic aromatic hydrocarbons (PAHs) in soils and vegetation near an e-waste recycling site in South China: concentration, distribution, source, and risk assessment. *Sci. Total Environ.* 439, 187–193. doi:10.1016/j.scitotenv.2012.08.018
- Wang, Y., Wu, X., Hou, M., Zhao, H., Chen, R., Luo, C., et al. (2017). Factors influencing the atmospheric concentrations of PCBs at an abandoned e-waste recycling site in South China. *Sci. Total Environ.* 578, 34–39. doi:10.1016/j.scitotenv.2016.08.131
- Wei, J., and Cen, K. (2020). Content and dietary exposure of cadmium among residents in Northeast China: a case study based on the 5th China Total Diet Study. *Environ. Sci. Pollut. Res.* 27 (8), 8224–8230. doi:10.1007/s11356-019-07016-7
- Wei, B., Liu, C., Bao, J., Wang, Y., Hu, J., Qi, M., et al. (2021). Uptake and distributions of polycyclic aromatic hydrocarbons in cultivated plants around an E-waste disposal site in Southern China. *Environ. Sci. Pollut. Res.* 28 (3), 2696–2706. doi:10.1007/s11356-020-10642-1
- Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., and Böni, H. (2005). Global perspectives on e-waste. *Environ. Impact Assess. Rev.* 25 (5), 436–458. doi:10.1016/j.eiar.2005.04.001
- Wilson, D. C., Velis, C., and Cheeseman, C. (2006). Role of informal sector recycling in waste management in developing countries. *Habitat Int.* 30 (4), 797–808. doi:10.1016/j.habitatint.2005.09.005
- Wu, J.-P., Luo, X.-J., Zhang, Y., Luo, Y., Chen, S.-J., Mai, B.-X., et al. (2008). Bioaccumulation of polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) in wild aquatic species from an electronic waste (e-waste) recycling site in South China. *Environ. Int.* 34 (8), 1109–1113. doi:10.1016/j.envint.2008.04.001
- Wu, Q., Leung, J. Y. S., Geng, X., Chen, S., Huang, X., Li, H., et al. (2015). Heavy metal contamination of soil and water in the vicinity of an abandoned e-waste recycling site: implications for dissemination of heavy metals. *Sci. Total Environ.* 506 (507), 217–225. doi:10.1016/j.scitotenv.2014.10.121
- Wu, X., Tong, F., Yu, S., Cai, J., Zheng, X., and Mai, B. (2023). Concentrations and biomagnification of persistent organic pollutants in three granivorous food chains from an abandoned e-waste recycling site. *Environ. Sci. Pollut. Res.* 30 (55), 117340–117348. doi:10.1007/s11356-023-30547-z
- Xu, F., Liu, Y., Wang, J., Zhang, G., Zhang, W., Liu, L., et al. (2015). Characterization of heavy metals and brominated flame retardants in the indoor and outdoor dust of e-waste workshops: implication for on-site human exposure. *Environ. Sci. Pollut. Res.* 22 (7), 5469–5480. doi:10.1007/s11356-014-3773-z
- Yadav, A., Chowdhary, P., Kaithwas, G., and Bharagava, R. N. (2017). “Toxic metals in the environment: threats on ecosystem and bioremediation approaches,” in *Handbook of metal-microbe interactions and bioremediation*. Editors S. Das and Singh (Boca Raton: CRC Press/Taylor and Francis Group), 128–141.
- Yekeen, T. A., Xu, X., Zhang, Y., Wu, Y., Kim, S., Reponen, T., et al. (2016). Assessment of health risk of trace metal pollution in surface soil and road dust from e-waste recycling area in China. *Environ. Sci. Pollut. Res.* 23 (17), 17511–17524. doi:10.1007/s11356-016-6896-6
- Yu, H., Ma, J., Chen, D., Gao, Y., Li, G., and An, T. (2024). Associations between inhalation of typical volatile and semi-volatile organic compounds in e-waste dismantling workers with liver function damage. *J. Hazard. Mater.* 464, 133004. doi:10.1016/j.jhazmat.2023.133004
- Zeng, X., Song, Q., Li, J., Yuan, W., Duan, H., and Liu, L. (2015). Solving e-waste problem using an integrated mobile recycling plant. *J. Clean. Prod.* 90, 55–59. doi:10.1016/j.jclepro.2014.10.026
- Zhang, W., Xie, H. Q., Zou, X., Li, J., Xu, L., Li, Y., et al. (2019). The toxic effects of *in situ* exposure of a native fish species (*Anabas testudineus*) to electronic waste pollution. *Sci. Total Environ.* 690, 1170–1177. doi:10.1016/j.scitotenv.2019.06.479
- Zhao, Y., Li, Y., Qin, X., Lou, Q., and Qin, Z. (2016). Accumulation of polybrominated diphenyl ethers in the brain compared with the levels in other tissues among different vertebrates from an e-waste recycling site. *Environ. Pollut.* 218, 1334–1341. doi:10.1016/j.envpol.2016.08.091
- Zheng, J., Luo, X.-J., Yuan, J.-G., He, L.-Y., Zhou, Y.-H., Luo, Y., et al. (2011). Heavy metals in hair of residents in an E-Waste recycling area, south China: contents and

assessment of bodily State. *Archives Environ. Contam. Toxicol.* 61 (4), 696–703. doi:10.1007/s00244-011-9650-6

Zheng, X.-B., Luo, X.-J., Zheng, J., Zeng, Y.-H., and Mai, B.-X. (2015). Contaminant sources, gastrointestinal absorption, and tissue distribution of organohalogenated pollutants in chicken from an e-waste site. *Sci. Total Environ.* 505, 1003–1010. doi:10.1016/j.scitotenv.2014.10.076

Zheng, J., Yu, L.-H., Chen, S.-J., Hu, G.-C., Chen, K.-H., Yan, X., et al. (2016a). Polychlorinated biphenyls (PCBs) in human hair and serum from E-Waste recycling workers in Southern China: concentrations, chiral signatures, correlations, and

source identification. *Environ. Sci. and Technol.* 50 (3), 1579–1586. doi:10.1021/acs.est.5b04955

Zheng, X., Xu, X., Yekeen, T. A., Zhang, Y., Chen, A., Kim, S. S., et al. (2016b). Ambient air heavy metals in PM_{2.5} and potential human health risk assessment in an informal electronic-waste recycling site of China. *Aerosol Air Qual. Res.* 16 (2), 388–397. doi:10.4209/aaqr.2014.11.0292

Zhou, H., Tam, N. F. Y., Cheung, S. G., Wei, P., Li, S., and Wu, Q. (2019). Contamination of polybrominated diphenyl ethers (PBDEs) in watershed sediments and plants adjacent to e-waste sites. *J. Hazard. Mater.* 379, 120788. doi:10.1016/j.jhazmat.2019.120788