

E-Waste Toxicants in Nigeria: Multi-Pathway Exposure, Toxicological Mechanisms, Human Health, Ecological Consequences and Management Priorities

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Abstract

Electronic waste (e-waste) is a rapidly growing, chemically complex waste stream that poses interconnected environmental, occupational, and public-health challenges. Nigeria generated approximately 500 kt of e-waste in 2022, making it one of Africa's major generators. Although informal recycling provides economic benefits, unsound dismantling, burning, and disposal can release toxic metals, PAHs, PCBs, flame retardants, dioxins, furans, plasticizers, and other hazardous substances. This review synthesizes evidence on their occurrence, environmental fate, exposure pathways, toxicological mechanisms, human-health effects, ecological consequences, and management implications in Nigeria. Contaminants have been detected in soil, dust, water, sediment and vegetation, with exposure occurring through inhalation, ingestion, dermal contact, dietary transfer, occupational activities and maternal–infant pathways. Evidence is strongest for environmental contamination and metal-associated risks, while longitudinal evidence linking exposure to chronic disease remains limited. Toxicological mechanisms include oxidative stress, genotoxicity, inflammation, endocrine disruption, mitochondrial dysfunction, and neurotoxicity. Ecological concerns include phytotoxicity, microbial impairment, aquatic contamination, bioaccumulation, and food-web transfer. Despite stronger regulation and extended producer responsibility, implementation and integration into the informal sector remain challenges. Future research should emphasize longitudinal biomonitoring, mixture toxicology, bio accessibility, ecological effects, and regulatory evaluation within a One Health and circular-economy framework.

Keywords: *e-waste; Nigeria; toxic metals; persistent organic pollutants; flame retardants; exposure pathways; human health; ecological risk; informal recycling; One Health.*

1. Introduction

The rapid expansion of electrical and electronic equipment (EEE), driven by technological innovation, digitalization, rising consumption, and shorter replacement cycles, has accelerated the generation of waste electrical and electronic equipment (WEEE), or e-waste. Globally, approximately 62 million tonnes of e-waste were generated in 2022, yet only 22.3% was formally collected and recycled in an environmentally sound manner (Baldé et al., 2024). This disparity is concerning because e-waste contains valuable recoverable materials alongside

hazardous substances that may be released during inappropriate collection, dismantling, recycling, and disposal.

Nigeria generated approximately 500 kt of e-waste in 2022, among e-waste Africa's generating countries (Baldé et al., 2024). Its management system involves formal and informal actors, with informal collection, dismantling, and material recovery supporting livelihoods and resource recovery. However, unsafe practices can expose workers and nearby communities to contaminated dust, smoke, ash, soil, and wastewater. E-waste contains diverse toxicants, including lead, mercury, cadmium, chromium, nickel and arsenic, as well as flame retardants, plasticizers and persistent organic pollutants. Uncontrolled thermal processing may generate particulate matter, polycyclic aromatic hydrocarbons (PAHs) and other hazardous combustion products, while dismantling, crushing and leaching facilitate contaminant redistribution among environmental compartments. E-waste should therefore be considered a multi-compartment, multi-pathway exposure problem rather than solely a solid-waste-management concern.

Nigerian evidence demonstrates contamination across soil, water, surface dust, plants and blood, with inhalation, gastrointestinal and dermal pathways implicated in exposure (Owonikoko & Alimba, 2024). Recent studies have further documented organophosphate flame retardants, plasticizers, legacy halogenated compounds and alternative flame retardants in e-waste-impacted environments (Folarin et al., 2024), indicating that metal-focused assessments may underestimate the diversity of real-world exposures. Potential health concerns are particularly relevant for informal recyclers, nearby residents, children, and pregnant women. WHO evidence associates e-waste exposure during pregnancy and childhood with adverse birth, neurological, respiratory, and immune outcomes, although the strength and specificity of these associations vary (WHO, 2021). Importantly, Nigerian evidence is dominated by environmental contamination, biomarkers, intermediate biological responses and modelled risks rather than longitudinal evidence of chronic disease incidence.

Ecologically, e-waste-derived contaminants may enter soil, vegetation, drainage systems, surface waters and sediments, with potential effects on microorganisms, plants and aquatic organisms. Persistent and bioaccumulative contaminants may also undergo food-web transfer, creating linkages between ecosystem contamination and dietary human exposure. Moreover, e-waste toxicity cannot be adequately understood through single-contaminant assessment because exposed populations encounter complex mixtures whose interactive effects remain incompletely characterized (Eze & Vinken, 2024). Accordingly, this review critically evaluates e-waste toxicants in Nigeria, focusing on contaminant classes and sources, environmental transport and transformation, exposure pathways, toxicological mechanisms, human and ecological outcomes, risk assessment, and policy and research priorities. Particular emphasis is placed on distinguishing evidence generated in Nigeria from evidence derived primarily from African, international, or experimental studies.

2. Review Methodology

2.1 Review Design and Reporting Framework

This review synthesized evidence on e-waste-associated toxicants, environmental transport, exposure pathways, toxicological mechanisms, human health and ecological outcomes, and risk management in Nigeria. The report aligned with the PRISMA 2020 framework to promote transparency in information sources, study selection, quality assessment, and evidence synthesis. The review addressed four questions: which hazardous substances occur in Nigerian e-waste environments; how they are released and transported; what exposure pathways and toxicological

outcomes are documented; and what ecological effects, risk estimates, and management responses have been reported.

2.2 Information Sources and Search Strategy

Literature was searched in Scopus, Web of Science Core Collection, PubMed/MEDLINE, ScienceDirect, and Google Scholar, supplemented by backward citation searching. Searches combined terms relating to e-waste, Nigeria, toxicants, exposure, health, toxicology, and ecological effects. Additional searches addressed environmental matrices, exposure pathways, vulnerable populations, and informal recycling. The search period covered January 2000–2026, with emphasis on evidence published since 2020, alongside authoritative sources including the Global E-waste Monitor and WHO assessments.

2.3 Eligibility and Evidence Classification

Eligible studies addressed e-waste activities or contamination in Nigeria and reported relevant contaminants, exposure pathways, health or ecological outcomes, or risk estimates. Evidence was categorized as Nigerian environmental evidence, Nigerian human evidence, African contextual evidence, experimental/mechanistic evidence, or authoritative evidence. This classification prevented mechanistic plausibility or evidence from other populations from being interpreted as direct evidence of disease effects in Nigeria.

2.4 Data Extraction and Synthesis

Extracted information included study location, design, e-waste activity, contaminant class, environmental or biological matrix, analytical approach, exposure estimate, pathway, endpoint, risk metric and study limitations. Because studies differed substantially in populations, contaminants, methods and outcomes, evidence was synthesized narratively according to toxicant class, environmental compartment, exposure pathway, health endpoint and ecological outcome.

2.5 Quality and Risk-of-Bias Considerations

Study quality was evaluated according to exposure characterization, sampling representativeness, analytical quality control, comparison groups, confounding, statistical methods and transparency of risk assumptions. Epidemiological findings based solely on occupation or residence were interpreted cautiously, as were modelled risks, which represent estimates under specified exposure assumptions rather than direct measures of disease probability.

3. Major Toxicants in Nigerian E-Waste

3.1 Toxic Metals and Metalloids

Metals, including lead, cadmium, mercury, arsenic, chromium, nickel and copper, are the most extensively documented e-waste contaminants in Nigeria. They originate from components such as circuit boards, batteries, cables, solder and displays, with environmental mobility influenced by chemical form, pH, redox conditions and matrix characteristics. Nigerian evidence demonstrates metal contamination across soil, water, dust, plants and biological matrices (Owonikoko & Alimba, 2024). However, total concentration alone may not represent internal exposure; bioavailability, speciation and biomonitoring should therefore receive greater attention.

3.2 PAHs and PCBs

PAHs are particularly associated with open burning of cables and plastics and may occur in particulate matter, ash, soil and sediments. Their toxicity depends on individual compounds and their metabolic activation. PCBs are persistent, lipophilic contaminants associated historically with electrical equipment and remain relevant through legacy materials. However, Nigerian evidence specifically linking PCB contamination to e-waste remains less extensive than evidence for metals (Orisakwe, 2019).

3.3 Flame Retardants, Plasticizers and Emerging Organics

Brominated flame retardants, including PBDEs and alternative compounds, occur in plastics, cable insulation and electronic components. Folarin et al. (2024) documented legacy and alternative halogenated pollutants in Nigerian e-waste-site dust and soil. Organophosphate flame retardants and plasticizers have also been detected in Nigerian dismantling and dumpsite environments (Folarin et al., 2024, Abogunrin-Olafisoye, & Adeyi, 2025). These findings demonstrate that substitution of restricted chemicals may alter rather than eliminate chemical risks and highlight the need to monitor emerging contaminants.

3.4 Combustion-Derived and Insufficiently Characterized Contaminants

Uncontrolled thermal treatment can generate mixtures of particulate matter, metals, PAHs, volatile organic compounds and halogenated combustion products. Other potentially relevant contaminants include phthalates, bisphenols, chlorinated paraffins, PFAS, battery electrolytes and other emerging chemicals. Evidence for several of these compounds in Nigeria remains limited, emphasizing the need for periodically updated analytical programmes.

4. Environmental Release, Transport and Transformation

Informal dismantling, crushing and cutting generate contaminated dust and fragments that may remain airborne or accumulate on surfaces (Parvin et al., 2026). Open burning converts relatively contained contaminants into mobile atmospheric and ash-associated pollutants. Uncontrolled disposal facilitates leaching and runoff, transferring dissolved and particle-bound contaminants to soil, drainage systems, surface waters and sediments (Lopez et al., 2024). Flooding may further redistribute contaminated soil, ash and sediment into residential, agricultural and aquatic environments (Xu, & Wang, 2026). Soil can act as both a contaminant sink and secondary source, while vegetation may receive contaminants through root uptake, irrigation and atmospheric deposition. Aquatic systems can receive contaminants through runoff and leachate, creating potential pathways for bioaccumulation and food-web transfer (Babaniyi et al., 2024).

5. Human Exposure Pathways

Major exposure routes include inhalation of contaminated dust and combustion emissions, ingestion of contaminated soil and dust, dietary consumption, contact with contaminated water and dermal exposure (Boahen, 2024). Occupational exposure is particularly relevant during dismantling and burning, while contaminated clothing, tools and household surfaces can facilitate take-home exposure (Narayanan, 2026). Children and pregnant women warrant particular attention because of developmental susceptibility. WHO evidence associates e-waste exposure during pregnancy and childhood with adverse developmental, respiratory, immune and birth outcomes, although evidence strength varies across outcomes and populations (WHO, 2021). Nigerian research should therefore prioritize maternal–infant biomonitoring and

longitudinal assessment.

6. Toxicological Mechanisms

E-waste-associated contaminants can act through interconnected mechanisms, including oxidative stress, mitochondrial dysfunction, genotoxicity, epigenetic alterations, endocrine disruption, neurotoxicity, inflammation and immune dysregulation (Parvin et al., 2026). Lead and mercury are established neurotoxins, while metals, PAHs and persistent organic pollutants can affect cardiovascular, renal and hepatic systems (Wu et al., 2025). However, mechanistic evidence should not be equated with demonstrated clinical disease in exposed Nigerian populations. African evidence indicates respiratory and cardiopulmonary concerns among informal recyclers, although longitudinal evidence remains limited (Issah et al., 2022).

7. Human-Health Outcomes

Reported concerns include acute respiratory and ocular irritation, headache, cough, dizziness and skin irritation, as well as potential neurological, developmental, respiratory, reproductive, renal, hepatic, hematological and carcinogenic effects. WHO evidence identifies neurodevelopmental, respiratory, immune and birth-related outcomes as important concerns associated with e-waste exposure (WHO, 2021). Nigerian evidence, however, is stronger for environmental contamination, biomarkers and modelled risks than for longitudinal disease incidence. Heavy-metal studies have estimated carcinogenic and non-carcinogenic risks in Nigerian e-waste environments (Owonikoko & Alimba, 2024), but modelled cancer risk should not be interpreted as observed cancer incidence.

8. Ecological Outcomes

E-waste contaminants may disrupt soil microbial activity, nutrient cycling and plant growth and may contaminate aquatic systems (Chowdhury et al., 2025; Shaaban et al., 2024). Metals and persistent organic pollutants can accumulate in sediments and aquatic organisms and potentially transfer through food webs (Igharo *et al.*, 2021). Nevertheless, Nigeria-specific evidence for population-level effects on wildlife, microbial communities and ecosystem functioning remains limited. Future studies should incorporate native Nigerian organisms and environmentally realistic contaminant mixtures.

9. Risk Assessment

Human-health assessments commonly use the hazard quotient ($HQ = ADD/RfD$) and hazard index ($HI = \sum HQ$). Values above unity indicate potential non-carcinogenic concern under the assumptions of the assessment, but values below unity do not establish the absence of risk. Cancer risk may be estimated as $CR = LADD \times SF$. Interpretation depends strongly on exposure duration, bioavailability, body weight, exposure frequency and toxicity-reference values. Ecological assessments may use contamination factors, pollution indices, sediment-quality guidelines and bioassays. A major limitation is the assessment of contaminants individually despite real-world exposure to mixtures. Eze and Vinken (2024) emphasize that the toxicological behaviour of complex e-waste mixtures remains incompletely characterized, supporting the use of cumulative and mixture-oriented approaches.

10. Vulnerable Populations and Environmental Justice

Informal recyclers, burners, waste pickers and nearby residents may experience elevated

occupational or community exposure. Children and pregnant women are particularly important populations because of developmental susceptibility (WHO, 2021). Because informal recycling also provides livelihoods, interventions should emphasize safer formalization and inclusion rather than exclusion alone, supported by safer technologies, occupational protection, traceability and equitable economic arrangements.

11. Policy and Management Implications

Nigeria's National Environmental (Electrical/Electronic Sector) Regulations, S.I. No. 79 of 2022, incorporate extended producer responsibility (NESREA, 2022). Key challenges now concern implementation, financing, traceability, collection coverage, formal recycling capacity and integration of informal actors (Simpson et al., 2025). Priorities include expanding traceable collection systems, formalizing informal recyclers, eliminating open burning, strengthening engineering and occupational controls, characterizing and remediating contaminated sites, and linking biomonitoring with environmental measurements and health outcomes. A One Health and circular-economy approach should integrate resource recovery with environmental protection, occupational safety, food safety and public health (Quinto et al., 2025).

12. Critical Evidence Gaps and Research Priorities

Major priorities include longitudinal human studies, mixture-exposure assessment, bioavailability and bioaccessibility measurements, harmonized national monitoring, maternal and childhood biomonitoring, flood-mediated contaminant transport, native-species ecotoxicology, surveillance of emerging contaminants and systematic evaluation of the 2022 regulatory framework. A national environmental-health database linking contaminant concentrations, biomarkers, health outcomes, geographic locations and management practices would strengthen evidence-based risk prioritization.

13. Conclusion

E-waste in Nigeria represents a complex environmental-health challenge involving diverse toxicants, multiple exposure pathways and interconnected human and ecological risks. Evidence is strongest for environmental contamination and modelled or intermediate biological effects, whereas longitudinal evidence directly linking e-waste exposure to chronic disease remains limited. Consequently, contamination should not automatically be interpreted as disease causation. Effective management requires stronger implementation of existing regulations, elimination of open burning, environmentally sound material recovery, producer accountability, occupational protection, systematic environmental and biomonitoring, contaminated-site management and safer integration of informal recyclers. Future research should prioritize longitudinal epidemiology, mixture toxicology, bioaccessibility, emerging contaminants, ecological effects and flood-mediated transport within an integrated One Health and circular-economy framework.

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