

The Dark Side of Obsolescence: A Review of Environmental Impacts and Sustainable Management Practices for Waste CRTs

Innocent Chidi Nnorom ^{1,2}; Faluyi Ibukun³; and Solomon Chiemela Onuchukwu ²

¹Department of Pure and Industrial Chemistry, Abia State University, Uturu, Nigeria. ²Faculty of Science and Computing, Amadeus University, Amizi, Abia State, Nigeria. ³E-waste Producer Responsibility Organisation of Nigeria (EPRON).

Corresponding author: s.onuchukwu@amadeus.edu.ng

DOI: <https://doi.org/10.62154/ajesre.2026.022.01011>

Abstract

The accumulation of obsolete cathode ray tube (CRT) displays represents a persistent environmental and public health problem, with pronounced impacts in developing countries where electronic waste governance remains weak. This review addresses the growing burden of waste CRTs in Nigeria and examines their implications for environmental quality, human exposure, and sustainable waste management. The objective of the study is to synthesize available evidence on the environmental and health impacts of CRT waste, assess existing management practices, and identify sustainable strategies suitable for national and comparable developing country contexts. A structured review of peer reviewed journal articles, technical reports, and policy-oriented literature was conducted, focusing on CRT material composition, contamination pathways, recycling and disposal practices, and regulatory responses. The analysis integrates findings from environmental monitoring studies, occupational exposure assessments, and waste management evaluations. The review finds consistent evidence of lead dominated contamination in soils, surface water, groundwater, and informal recycling sites, alongside documented health risks among workers and nearby communities. Current management practices rely heavily on informal dismantling, uncontrolled dumping, and limited formal recycling capacity. Regulatory frameworks and institutional controls exist but show weak effectiveness due to enforcement gaps, infrastructure deficits, and limited producer accountability. The review concludes that prevailing CRT waste management approaches in Nigeria remain inadequate to address long term environmental contamination and human health risks. It recommends an integrated management framework combining enforceable regulation, formalization of recycling activities, extended producer responsibility, and investment in environmentally sound material recovery systems. Such measures support risk reduction, resource recovery, and progress toward sustainable electronic waste management.

Keywords: Cathode Ray Tube, Environmental Impact, Hazardous Substances, CRT Recycling, Sustainable Management, Extended Producer Responsibility, NESREA

Introduction

Rapid technological advancements and increasing consumer demand for the latest electronic devices have led to a rise in the disposal of older electronics across many states. Among the most concerning items are monitors and televisions that use cathode ray tube

(CRT) technology. These CRT units often contain hazardous metals like barium, lead, and cadmium which are known for their toxicity and environmental persistence (ASTSWMO, 2025). Lead, which constitutes a major component of CRT funnel glass, poses severe risks due to its potential to leach into soil and groundwater when disposed of in uncontrolled environments, leading to contamination of ecosystems and accumulation in living organisms (Iniaghe and Adie, 2018; Owusu-Sekyere *et al.*, 2024). The improper disposal of CRTs is further compounded by the absence of adequate collection and recycling systems in many regions, including Nigeria, thereby increasing the likelihood of environmental pollution and significant public health hazards such as neurotoxicity and renal damage (Ohajinwa *et al.*, 2017; Issah *et al.*, 2022).

Despite declining global use of CRT displays, large volumes of obsolete CRT devices continue to accumulate in developing countries like Nigeria, where waste management systems lack the capacity to handle their hazardous material profile. Existing e-waste research and policy frameworks largely treat CRTs as a minor component of mixed e-waste streams, resulting in limited, fragmented analysis of their specific environmental behaviour, health risks, and management challenges. This gap obscures the scale and persistence of CRT related contamination, particularly in countries such as Nigeria where informal recycling, uncontrolled disposal, and legacy stockpiles remain common. The absence of a focused synthesis on CRT waste constrains evidence-based decision making, weakens regulatory and technological targeting, and limits progress toward environmentally sound management of legacy e-waste. This review addresses this gap by systematically examining the environmental impacts and management practices associated specifically with waste CRTs in Nigeria, clarifying why CRTs require distinct consideration within e-waste governance and why targeted strategies matter for environmental protection, public health, and sustainable resource management.

However, this review article critically explores the environmental repercussions associated with waste CRTs, emphasizing the contamination risks posed by hazardous metals and the ecological burden of their accumulation in soils and water bodies. It also evaluates the current sustainable management practices, including repair, reuse, and particularly recycling technologies that have been adapted within the Nigerian context to mitigate these risks. For instance, pioneering efforts by companies like E-Terra Technologies have introduced internationally standardized CRT recycling facilities capable of safely processing CRT glass and components to reduce toxic exposure while supporting material recovery and circular economy objectives (E-Terra Technologies Limited, 2017). Innovative methods such as manual dismantling combined with mechanical separation and detoxification processes are examined for their efficacy in reducing the environmental footprint of CRT waste. The article further highlights the importance of establishing robust regulatory frameworks and community-level collection initiatives to ensure responsible CRT waste management while safeguarding human health and advancing a circular economy for electronic goods in Nigeria and similar settings.

Overview of Electronic Waste and CRT Waste in Nigeria

Electronic waste (e-waste) represents one of the fastest growing waste streams worldwide, bringing significant environmental and health challenges (Udousoro *et al.*, 2025), particularly in Africa. Nigeria, as the largest e-waste importer in Africa and the second-largest globally, faces critical issues with e-waste management, exacerbated by the proliferation of obsolete electronic devices such as Cathode Ray Tube (CRT) monitors and televisions. CRT devices are loaded with hazardous substances including lead, mercury, and cadmium, which pose severe risks when improperly discarded. These toxic elements have the potential to contaminate soil, water, and air, leading to substantial human health hazards, especially in communities near informal recycling sites where crude methods like burning and acid leaching are common.

Importance and Rationale of the Study in the Nigerian Context

Nigeria's e-waste management scenario reflects broader challenges of rapid urbanization, limited regulatory enforcement, and public awareness deficits (Osibanjo and Nnorom, 2007). The CRT waste problem exemplifies the dark side of technological obsolescence, where discarded products result in lasting environmental damage if improperly handled (USEPA, 2024). Understanding the environmental impacts, assessing current management practices, and exploring sustainable alternatives tailored to Nigeria's socio-economic and regulatory environment are essential to mitigating risks (Manhart *et al.*, 2011). This review paper aims to examine the environmental impacts of waste CRTs, evaluate sustainable management practices, and highlight innovative recycling technologies adapted to the Nigerian context.

This review addresses an underexamined area within the e-waste literature by concentrating specifically on CRT waste, which continues to persist in many developing countries despite declining global production and use. Existing studies on electronic waste largely emphasize mixed waste streams, emerging devices, or general recycling challenges, with limited attention to the distinct material composition, contamination pathways, and management challenges associated with legacy CRTs. Where CRTs are mentioned, they are often treated marginally within broader e-waste analyses rather than as a discrete waste category with unique environmental and health implications. By isolating CRT waste as the central focus and examining technological practices, health risks, and policy responses within the Nigerian context, this review clarifies gaps in current knowledge and practice. The analysis supports the development of targeted, evidence-based strategies for sustainable CRT waste management and aligns national priorities with international obligations on hazardous waste control.

Research Objectives and Scope

The primary objective of this review is to synthesize current knowledge on the environmental and health impacts of waste CRTs in Nigeria and critically evaluate existing management practices. The study aims to identify sustainable practices and policy interventions that can be adopted to enhance the safe handling, recycling, and disposal of CRT waste in the Nigerian context. Specifically, it will:

- Analyze the toxicological profile and environmental contamination linked to CRT waste in Nigeria;
- Assess the effectiveness and limitations of current CRT waste management systems, including informal recycling;
- Explore innovative recycling technologies and sustainable management strategies viable for Nigerian conditions;
- Review relevant Nigerian policies and international frameworks shaping CRT waste regulation;
- Provide actionable recommendations to policymakers, industry stakeholders, and communities for improved practices.

By focusing on Nigeria, this review contributes to localized knowledge and supports national efforts to transform e-waste challenges into opportunities for sustainable development and environmental protection.

Theoretical and Conceptual Framework

This review adopts the Driver Pressure State Impact Response framework as the primary conceptual lens guiding the analysis of waste cathode ray tube management in Nigeria. The DPSIR framework provides a structured approach for linking human activities to environmental change and policy action. In this study, drivers refer to technological obsolescence, consumer replacement patterns, and continued importation of end-of-life electronic equipment. Pressures arise from improper disposal, informal dismantling, open dumping, and uncontrolled recycling of CRT devices. State describes the resulting conditions of environmental media, including heavy metal accumulation in soils, surface water, groundwater, and ambient air. Impacts capture the documented effects on ecosystem integrity and human health, particularly occupational exposure and community level risks. Responses encompass regulatory measures, management practices, technological interventions, and institutional actions aimed at mitigating identified risks. The DPSIR framework structures the review by organizing evidence across these linked components, allowing environmental impacts, management systems, and policy interventions to be evaluated within a coherent analytical sequence. This approach clarifies causal relationships between CRT obsolescence and environmental degradation, highlights point where current responses fall short, and supports identification of targeted intervention pathways. Circular economy principles and the waste management hierarchy

are integrated within the response component to assess the extent to which existing practices promote prevention, material recovery, and environmentally sound disposal. By applying DPSIR as the overarching framework, the review moves beyond descriptive synthesis and provides a systematic basis for evaluating why CRT waste remains a persistent problem and which policy and management responses offer the strongest potential for long term risk reduction and sustainability.

Methodology

This study adopts a narrative review approach. This choice reflects the study aim, which is to synthesize and critically interpret diverse evidence on environmental impacts, management practices, and policy responses related to waste cathode ray tubes, rather than to quantify effect sizes or conduct statistical meta-analysis. A narrative review is appropriate given the interdisciplinary nature of the topic and the uneven availability of empirical data, particularly for informal recycling activities in Nigeria.

Relevant literature was identified through targeted searches of major academic databases and institutional sources, including peer reviewed journals, technical reports, and policy documents. Key sources included multidisciplinary scientific databases, environmental science journals, and publications from international organizations and national regulatory agencies. Search terms combined keywords related to CRT waste, electronic waste, environmental contamination, health impacts, recycling technologies, waste management, and Nigeria. The search covered literature published from the early 2000s to 2024, reflecting the period of peak CRT use, decline, and post obsolescence management challenges.

Inclusion criteria comprised studies and reports that addressed CRT composition, environmental or health impacts, recycling and disposal practices, or regulatory and policy frameworks relevant to developing country contexts, with particular emphasis on Nigeria. Excluded materials included opinion pieces without empirical or analytical grounding, non-relevant electronics studies, and sources lacking clear methodological description. Literature was screened through title and abstract review, followed by full text assessment for relevance and analytical value. The selected literature was analyzed using thematic synthesis. Findings were organized around environmental contamination pathways, health risks, management practices, technological options, and policy responses. This approach allowed comparative interpretation across studies and supported identification of gaps, limitations, and priority areas for sustainable CRT waste management.

Environmental Impacts of Waste CRTs

Toxic Substances in CRTs and the Ecological Impacts

Cathode Ray Tube (CRT) devices contain hazardous substances such as lead oxide, which accounts for approximately 35% of the glass weight, alongside mercury, cadmium, and

phosphor coatings (Lima *et al.*, 2012; Meng *et al.*, 2016; Wielgus *et al.*, 2021). In Nigeria, the improper handling and disposal of these devices lead to the release of these toxic elements into the environment (Udousoro *et al.*, 2025). The high lead content, in particular, poses a significant risk as it is persistent and bioaccumulative, contaminating soil, water, and air (Sawyerr and Oladeji, 2020).

Several studies have reviewed the challenges and prospects of recycling cathode ray tube (CRT) waste, emphasizing that CRT devices, such as old TVs and monitors, contain hazardous materials like lead, barium, and strontium (Nnorom *et al.*, 2011). These materials pose significant environmental risks if CRT waste is improperly managed. The transition from CRT to newer display technologies (LCD, LED) has resulted in a large accumulation of CRT waste worldwide, which cannot economically be reused as raw materials due to toxicity concerns. Instead, closed-loop recycling approaches, which confine toxic components in glass ceramic structures for use in various industrial applications, are being explored.

Other studies have noted that CRT waste volumes are considerable, with tens of thousands of tons generated annually in regions like Europe, the United States, and China. Babayemi *et al.* (2025) reported that over a 32-year period (1990 to 2022) Nigeria imported 2,558,043 tonnes of CRT televisions (56 % of total EEE imports) along with significant CRT monitor imports. Consequently, several studies have reported that informal and unregulated recycling, especially in developing countries, leads to environmental contamination and health hazards from lead exposure. Most researchers have emphasised the need for regulatory control, advanced recycling technologies, and global cooperation to address the growing CRT waste problem effectively.

Iniaghe *et al.* (2013) reported that obsolete computer monitors containing cathode ray tubes (CRTs) are increasingly discarded at dumpsites across Nigeria, reflecting the rapid replacement of older display technologies with newer liquid crystal display (LCD) and light-emitting diode (LED) screens. CRT waste is a major environmental concern mainly because the glass used in the funnel and neck sections contains a high amount of lead, around 22% to 25% by weight (Meng *et al.*, 2016; Wielgus *et al.*, 2021). When CRTs are discarded through open dumping or landfilling, toxic metals like lead and cadmium can leach into surrounding soil and water, posing risks to both ecosystems and human health (Adesokan *et al.*, 2016; Adeyi and Oyeleke, 2017). Although several recycling technologies such as lead recovery, glass smelting, and chemical detoxification have been explored, most remain at the experimental stage, are expensive to operate, or can create secondary pollutants (Nnorom *et al.*, 2011). Traditional closed-loop recycling, where CRT glass is reused to make new CRTs, is now largely obsolete due to modern display technologies. However, recent studies suggest that using CRT glass as an additive in cement, mortar, or concrete offers a practical and environmentally friendly way to repurpose the material on a large scale (Wielgus *et al.*, 2021; Lima *et al.*, 2012).

Environmental Risks in Nigeria

Improper disposal and informal recycling methods, including open burning and crude dismantling, result in soil contamination and water pollution around e-waste recycling sites in Nigeria. Lead, along with other heavy metals such as cadmium, copper, nickel, chromium, and zinc, leaches into the soil and groundwater, threatening agriculture and drinking water safety. For instance, studies at major e-waste sites such as Alaba International Market in Lagos have documented significant soil contamination with concentrations of heavy metals greatly exceeding background levels and safety limits (Adeyi and Oyeleke, 2017). These metals persist in soils and can bioaccumulate, posing risks to soil microbial communities and reducing soil fertility critical for crop production (Udousoro *et al.*, 2025). Research shows that soil concentrations of these toxic metals often exceed natural background levels by several folds, amplifying ecological risks and threatening the health of local communities (Bankole *et al.*, 2024).

Moreover, air pollution is a significant concern in informal CRT recycling operations. Open burning of plastics and circuit components releases toxic compounds including dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), and brominated flame retardants into the atmosphere, which degrade air quality and pose carcinogenic and respiratory health risks to nearby populations (Adeyi and Oyeleke, 2017; Owen and Scougall, 2025). These harmful emissions can travel long distances, impacting communities beyond immediate recycling areas. The release of up to 1,000 toxic chemicals during these informal processes contaminates not only air but also soil and water resources, due to deposition and runoff, further exacerbating environmental and public health challenges (Owen and Scougall, 2025).

In Nigeria, the absence of effective CRT collection and recycling systems has left many communities vulnerable to lead and cadmium poisoning linked to CRT components (E-Terra Technologies, 2017). The hazardous dismantling and disposal techniques, combined with increased e-waste imports and lack of regulation enforcement, amplify the environmental burden and health threats associated with CRT waste.

Human Health Effects Related to CRT Waste in Nigeria

The environmental contamination from CRT waste directly impacts human health, particularly among informal sector workers and surrounding communities in Nigeria (Akeju and Omotoso, 2023). CRT waste contains various hazardous substances, including lead, cadmium, phosphorus, and brominated flame retardants (Prata, 2024; Onuchukwu *et al.*, 2024). These substances are released into the environment during informal recycling activities, posing severe threats to human health. Exposure to lead from CRT waste is a primary health risk. Lead is a highly toxic heavy metal; even low levels of exposure can cause irreversible damage to the nervous system, particularly in children, leading to developmental delays and cognitive impairments (Prata, 2024; Udousoro *et al.*, 2025). In

informal e-waste recycling sites in locations such as Lagos, Nigeria, widespread contamination of soil and water bodies with hazardous chemicals has been observed (Akeju and Omotoso, 2023; Ramadan *et al.*, 2024). Informal recycling operations often lack appropriate protective measures, leading to direct exposure of workers to these toxic substances, thereby increasing health risks (Akeju and Omotoso, 2023). Furthermore, prolonged exposure to CRT waste has been linked to kidney dysfunction and an elevated risk of cancer due to the bioaccumulation of heavy metals (Verma and Prakash, 2020). Informal recycling practices of CRT waste result in the emission of toxic substances into the air, soil, dust, and water (Prata, 2024). For instance, toxic fumes released during the dismantling and burning processes expose communities living near recycling centers to the risk of inhaling harmful pollutants. This contributes to an increased prevalence of respiratory illnesses and skin diseases in these areas (Prata, 2024). In Nigeria, inadequate enforcement and awareness of environmental regulations facilitate widespread informal recycling activities, further intensifying the adverse effects on workers and neighbouring communities (Akeju and Omotoso, 2023). The rapid urbanization and growth of the second-hand electronics trade in Nigerian cities exacerbate informal e-waste recycling (Ike, 2025). While coastal cities like Lagos and Port Harcourt receive some attention, inland centers such as Aba, which play an increasing role in the national e-waste flow, have been less studied (Nwazue *et al.*, 2025). In these informal recycling zones, workers, including scavengers, frequently operate without necessary health and safety equipment, facing risks of injury and various health hazards.

Integrated Analysis of Environmental and Health Risks

The improper management of e-waste leads to multifaceted impacts on both the environment and human health. According to the Driver-Pressure-State-Impact-Response (DPSIR) framework, the high demand for electrical and electronic equipment acts as a driver, leading to increased global e-waste production and low recycling rates (pressures). This, in turn, results in high concentrations of e-waste pollutants accumulating in the environment (state). Ultimately, these hazardous pollutants enter the internal tissues of organisms and cause adverse effects on these organisms, microflora, and human health (impacts) (Prata, 2024). Figure 1 illustrates the DPSIR model for e-waste microplastics.



Figure 1: DPSIR model for e-waste microplastics. Modified from Prata, (2024)

The informal recycling sector is prevalent in developing countries and, while it provides livelihoods and employment opportunities for impoverished populations, also undertakes basic services like waste collection and recycling to some extent (Salim *et al.*, 2023). However, it is simultaneously characterized by harsh working conditions, low incomes, and a lack of protection (Salim *et al.*, 2023).

Current Management Practices for Waste CRTs in Nigeria

Existing CRT Waste Management Systems in Nigeria

The management of CRT waste in Nigeria operates through a dual system, comprising both formal and informal sectors (Egwali, 2013; Abogunrin-Olafisoye *et al.*, 2025). While formal approaches are developing, they currently have a limited capacity to address the substantial volume of CRT waste generated and imported into the country (Sanjo Kazeem *et al.*, 2021; Abogunrin-Olafisoye *et al.*, 2025). In contrast, the informal sector handles the majority of CRT waste, often employing rudimentary and environmentally hazardous methods (Agu, 2023).

Formal waste management efforts in Nigeria, though nascent, are exemplified by companies like E-Terra Technologies Limited in Lagos. These entities utilize modern recycling technologies to dismantle CRTs, recover valuable materials, and detoxify hazardous components in accordance with international standards (Abogunrin-Olafisoye *et al.*, 2025). This formal approach aims to mitigate the risks associated with toxic heavy metals such as lead and cadmium found in CRTs (Iniaghe and Adie, 2015). However, the

scale of formal CRT recycling remains insufficient relative to the continuous influx and usage of electronic equipment (Sanjo Kazeem *et al.*, 2021).

The informal sector in Nigeria dominates CRT waste handling, characterized by unregulated practices (Egwali, 2013; Agu, 2023). These often involve manual dismantling, smashing, crushing, shredding, hammering, and open-air burning of e-waste components to recover valuable materials like copper, gold, silver, palladium, aluminum, nickel, and lead (Erdiaw-Kwasie *et al.*, 2024). Such crude processing releases harmful substances, including lead from CRT funnel glass and polybrominated diphenyl ethers (PBDEs) from plastic casings, into the environment (Pauzi *et al.*, 2021). These practices pose severe environmental and health risks to workers and surrounding communities. For example, studies have measured concentrations of PBDE congeners in top soils and dusts at e-waste recycling sites in Nigeria, highlighting the environmental contamination from these informal activities (Ohajinwa *et al.*, 2019).

The challenges in Nigeria's e-waste management system are compounded by legislative gaps, inadequate infrastructure, and the prevalence of primitive recycling methods (Abogunrin-Olafisoye *et al.*, 2025). Effective e-waste legislation worldwide often includes restrictions on import/export, regulations for specific categories of e-waste, and Extended Producer Responsibility (EPR) schemes (Patil and Ramakrishna, 2020). The absence or weak enforcement of such policies in developing countries contributes to the uncontrolled dumping and processing of e-waste (Egwali, 2013). One potential alternative for managing CRT glass waste involves its use in construction materials. Research has explored the incorporation of crushed or melted CRT funnel glass into concrete as a coarse aggregate (Pauzi *et al.*, 2021). However, this approach faces challenges such as lead leaching and concrete expansion. Another innovative strategy involves synthesizing humidity control materials from alumino-silicate raw materials extracted from stone sludge and CRT waste panel glass, demonstrating potential for energy-efficient building applications (Hung *et al.*, 2024). These examples highlight that while CRTs pose environmental risks, they also represent a source of recoverable materials (Tsebe and Steenkamp, 2024).

Household solid waste management systems provide an important entry point for understanding how obsolete cathode ray tube devices enter waste streams and how early handling decisions shape downstream environmental outcomes (Rao and Parsai, 2023). Although Figure 2 presents a general household solid waste management framework, its relevance lies in illustrating the stages at which discarded CRTs are generated, stored, collected, and either diverted toward recycling or lost to uncontrolled disposal. The figure supports the CRT focused argument by showing how gaps in household level segregation, collection infrastructure, and awareness contribute to the mixing of CRTs with municipal waste, thereby increasing the likelihood of informal processing and environmental release of hazardous materials. By situating CRT disposal within broader household waste management processes, the figure helps explain why interventions at the point of

generation and collection are critical for improving CRT waste control and reducing environmental and health risks.

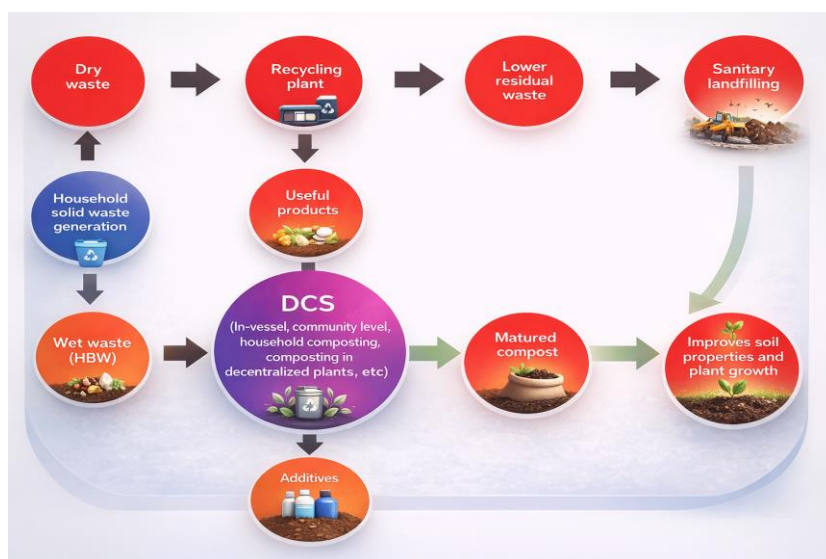


Figure 2: Household solid waste management system.

The development of sustainable waste management systems requires a comprehensive approach that considers technical, environmental, economic, socio-cultural, institutional, and policy aspects (Hjul-Nielsen *et al.*, 2023). The Drivers-Pressures-State-Impacts-Responses (DPSIR) model can be applied to understand the factors contributing to solid waste management challenges in remote communities, which often share similarities with informal e-waste processing areas (Salim *et al.*, 2023).



Figure 3: DPSIR framework for remote community waste management. Modified from Salim *et al.*, (2023)

Addressing the issue of CRT waste in Nigeria necessitates strengthening formal recycling infrastructure, implementing robust policy frameworks, and fostering awareness and participation among stakeholders (Abogunrin-Olafisoye *et al.*, 2025). This includes discouraging illegal disposal methods and promoting environmentally sound practices to safeguard human health and the environment from hazardous substances.

Recycling Technologies and Processing Methods Used in Nigeria

In Nigeria, CRT waste recycling is characterized by a significant disparity between informal and formal processing methods. The informal sector predominantly employs rudimentary techniques, such as manual dismantling with basic hand tools, open burning to recover valuable metals, and indiscriminate disposal of hazardous residues. While these methods are cost-effective, they inflict substantial environmental damage and pose severe health risks due to the release of toxic substances (Abogunrin-Olafisoye *et al.*, 2025). Conversely, formal recycling facilities, such as E-Terra Technologies Limited in Lagos, represent a nascent but growing effort to manage CRT waste in an environmentally sound manner. These facilities integrate advanced mechanical separation, chemical treatments, and enclosed processing equipment designed to safely isolate leaded glass and plastics for either controlled disposal or reuse (Abogunrin-Olafisoye *et al.*, 2025). Since 2017, E-Terra has operated a dedicated CRT recycling plant, which incorporates European technology and possesses the capacity to process approximately 200 CRTs daily while adhering to European environmental standards (Abogunrin-Olafisoye *et al.*, 2025). This approach is crucial given that CRTs are classified as hazardous waste due to the presence of mercury and lead.

Despite the advanced capabilities of formal recyclers like E-Terra, their operational capacity currently addresses only a marginal fraction of Nigeria's substantial annual CRT waste stream. Nigeria is estimated to generate around 500,000 tons of Waste Electrical and Electronics Equipment (WEEE) annually, including a significant proportion of CRTs, largely due to the massive importation of used electronic equipment (Ukem, 2008; Abogunrin-Olafisoye *et al.*, 2025). The global shift towards thinner and lighter flat panel displays has resulted in an increasing volume of waste CRT glass, which contains poisonous and harmful substances like lead, necessitating proper disposal to prevent environmental and human health threats (Qi *et al.*, 2019).

The disparity in recycling technologies and processing methods highlights critical gaps in Nigeria's waste management infrastructure and legislative enforcement (Egwali, 2013; Agu, 2023). The informal processing of e-waste, including CRTs, without adequate safety or environmental controls, is a widespread issue in many developing countries (Egwali, 2013). This uncontrolled processing often results in direct exposure to hazardous materials, affecting workers and nearby communities (Agu, 2023). Addressing this challenge requires a multi-faceted approach, including strengthening regulatory frameworks, enhancing formal recycling infrastructure, and implementing awareness campaigns. Effective e-waste

legislation, as seen in various countries, often includes restrictions on e-waste import/export, regulations for recycling specific categories of e-waste, and Extended Producer Responsibility (EPR) schemes (Patil and Ramakrishna, 2020). The absence or weak enforcement of such policies in developing countries, including Nigeria, exacerbates the problem of uncontrolled e-waste dumping and processing.

Challenges and Limitations of Present Management Approaches in Nigeria

Key challenges in Nigeria's CRT waste management include weak enforcement of import bans on used CRTs, inadequate collection infrastructure, and the economic appeal of informal recycling which incentivizes unsafe practices (Egwali, 2013; Agu, 2023; Abogunrin-Olafisoye *et al.*, 2025). The widespread presence of unregulated e-waste markets, such as those in Lagos (Alaba International Market) and other urban centers, complicate efforts to systematize CRT waste management (Okorhi *et al.*, 2018). Lack of public awareness on the dangers of CRT waste further inhibits voluntary return and safe handling (Sanjo Kazeem *et al.*, 2021). Limited policy implementation of Extended Producer Responsibility (EPR) and environmental regulations by agencies like NESREA constrains formal sector growth (Agu, 2023; Abogunrin-Olafisoye *et al.*, 2025). Additionally, logistical and financial barriers restrict scaling of technology-intensive recycling solutions (Abogunrin-Olafisoye *et al.*, 2025). Consequently, informal practices continue to prevail, perpetuating environmental pollution and health risks.

While formal CRT recycling initiatives in Nigeria demonstrate promising technology-driven management approaches, overall efforts are hampered by systemic challenges. The predominance of informal sector involvement underscores the urgent need for integrated approaches that improve collection, enhance regulatory enforcement, and facilitate the transition to environmentally sound management of CRT waste.

Ban on the Importation of CRT Devices in Nigeria

The ban on the importation of Cathode Ray Tube (CRT) devices in Nigeria has had significant impacts on various facets of the economy, environment, and local industry development.

Firstly, the ban aims to reduce the influx of obsolete and hazardous electronic waste into the country. Prior to the ban, Nigeria faced serious environmental and health challenges due to the uncontrolled importation and disposal of CRTs, which contain toxic substances like lead. The ban helps protect the environment by limiting further contamination risks from improper CRT disposal and dismantling, which predominantly occurred in informal sectors lacking proper safety measures (Abogunrin-Olafisoye *et al.*, 2025).

Secondly, the import ban has stimulated local manufacturing and recycling industries. By restricting obsolete CRT imports, the government encourages the development of domestic electronic production and formal e-waste recycling infrastructure, fostering

investment in cleaner technologies and waste management practices (Abogunrin-Olafisoye *et al.*, 2025). This aligns with the broader "Nigeria First" policy, which prioritizes local goods and services to boost economic self-reliance and job creation.

However, the implementation of this ban faces persistent challenges. Despite the prohibition, illegal importation of CRTs in concealed shipments reportedly continues, undermining regulatory efforts (Abogunrin-Olafisoye *et al.*, 2025). The informal e-waste sector remains highly active, frequently processing CRTs under unsafe conditions, leading to environmental pollution and health risks (Egwali, 2013; Agu, 2023). Consequently, strengthening enforcement capacity, particularly at border controls and through enhanced inter-agency cooperation, is crucial for the ban's effectiveness.

Economically, the import ban has yielded mixed effects. While it promotes local industries and could potentially foster a circular economy by recovering valuable materials from e-waste (Okorhi *et al.*, 2018; Tsebe and Steenkamp, 2024), it has also drawn criticism from foreign trade partners, notably the United States. These partners argue that the ban restricts market access for their exporters, leading to trade tensions and calls for a review of Nigeria's import restriction policies (Abogunrin-Olafisoye *et al.*, 2025). This highlights a broader issue where developed countries often export e-waste to less developed nations due to the high costs of local processing, creating a complex global challenge (Abalansa *et al.*, 2021).

Nigeria's CRT import ban represents a positive stride towards environmental protection and industrial development. Nevertheless, its maximal benefits depend on robust enforcement mechanisms, public education, and sustained international cooperation to mitigate unintended economic consequences and ensure a comprehensive transition to environmentally sound management practices. The proper management of e-waste, including CRTs, is vital because these materials not only contain hazardous substances like lead and mercury but also valuable rare earth elements (REEs) that can be recovered through appropriate recycling technologies (Qi *et al.*, 2019; Tsebe and Steenkamp, 2024). The complexity of CRT recycling, particularly the separation of leaded glass, necessitates advanced technologies to prevent environmental contamination.

Sustainable Management Strategies for Waste CRTs in Nigeria

Best Practices in Collection and Transportation within Nigeria

In Nigeria, effective collection and transportation of waste Cathode Ray Tube (CRT) devices are critical for mitigating environmental contamination and enabling responsible recycling efforts. Despite the recognition of its importance, systemic CRT waste collection faces significant challenges, including a lack of formal collection networks and insufficient public awareness. The existing dual system of waste management, characterized by both formal and informal sectors, contributes to these complexities (Abogunrin-Olafisoye *et al.*, 2025). However, organizations such as E-Terra Technologies in Lagos are pioneering initiatives to establish grassroots collection systems, targeting both households and corporate facilities

for CRT waste. These efforts aim to ensure the secure evacuation of CRT waste, thereby reducing the prevalence of informal sector involvement and minimizing environmental exposure to toxic substances like lead and mercury present in CRTs (Abogunrin-Olafisoye *et al.*, 2025). The formal sector's approach, as exemplified by E-Terra, involves modern recycling technologies to safely dismantle CRTs, recover valuable materials, and detoxify hazardous components in accordance with international standards.

Collaborations between government agencies, private recyclers, and community groups are crucial for strengthening logistics chains. These partnerships facilitate the introduction of environmentally friendly transportation methods and enhance monitoring to ensure compliance with health and safety standards (Abogunrin-Olafisoye *et al.*, 2025). Such structured approaches are vital given that Nigeria generates approximately 500,000 tons of Waste Electrical and Electronics Equipment (WEEE) annually, much of which includes CRTs imported as used electronic equipment (Sanjo Kazeem *et al.*, 2021). Figure 4 illustrates the typical pathways of e-waste management, highlighting the need for efficient collection and processing to divert materials from informal, unsafe practices.

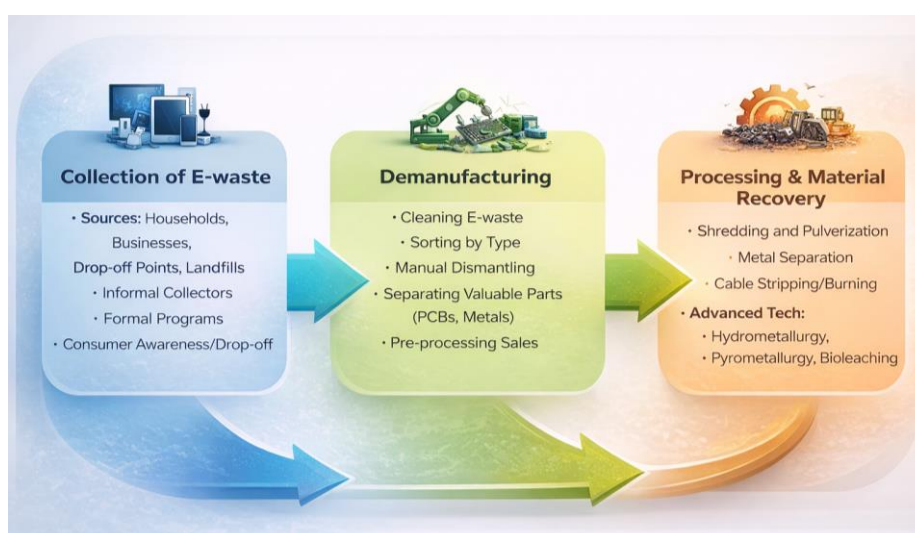


Figure 4: Overview of urban mining processes and key practices in developing countries.

Effective collection practices are a foundational element of the waste management hierarchy, which prioritizes prevention, reuse, and recycling over recovery and disposal. The implementation of robust collection networks, supported by public awareness campaigns and clear regulatory frameworks, is necessary to steer CRT waste towards formal recycling channels (Abogunrin-Olafisoye *et al.*, 2025). This transition not only safeguards the environment and public health but also allows for the recovery of valuable materials, contributing to a circular economy.

Emerging and Innovative Recycling Technologies in the Nigerian Context

Nigeria's e-waste management landscape is progressively shifting towards more sustainable and technologically advanced recycling practices, moving away from informal, crude methods that often pose significant environmental and health risks (Adeyi *et al.*, 2020). A pivotal development in this transition was the establishment of Nigeria's first internationally standardized Cathode Ray Tube (CRT) recycling facility by E-Terra in Lagos in 2017 (E-Terra Technologies Limited, 2017). This facility represents a significant advancement in the country's capacity for environmentally sound e-waste processing.

The E-Terra facility integrates several sophisticated recycling technologies, including mechanical separation, chemical detoxification, and material recovery processes, enabling it to handle approximately 200 CRTs daily (E-Terra Technologies Limited, 2017). The initial stage of CRT recycling involves meticulous dismantling, where components such as plastics, leaded glass, motherboards, and screens are carefully isolated (Xu *et al.*, 2012). This segregation is critical for subsequent processing steps and for ensuring efficient material recovery. Following dismantling, a detoxification step is performed to securely extract hazardous substances, particularly lead from the glass and other toxic elements commonly found in CRTs (Xu *et al.*, 2012). This chemical detoxification is crucial because e-waste, especially older CRT monitors, contains hazardous materials like lead, cadmium, mercury, and brominated flame retardants, which can leach into the environment if not properly managed (Xu *et al.*, 2012; Sindiku *et al.*, 2014; Nandan *et al.*, 2023). For instance, polybrominated diphenyl ethers (PBDEs), classified as persistent organic pollutants (POPs) by the Stockholm Convention, were extensively used in CRT casings (Sindiku *et al.*, 2014). Once detoxified, the treated materials are compacted and prepared for sale, which helps offset manufacturing inputs and supports circular economy principles (Sindiku *et al.*, 2014; Halkos and Aslanidis, 2024). The circular economy model emphasizes reducing waste, reusing materials, and recycling resources to minimize environmental impact and maximize economic value (Halkos and Aslanidis, 2024). By recovering valuable materials such as metals (e.g., copper, gold, silver, palladium, aluminum, nickel, and lead) and plastics, these technologies reduce the reliance on virgin resources and mitigate pollutant release associated with crude informal recycling (Liu *et al.*, 2023).

Mechanical separation techniques are fundamental in modern e-waste recycling, serving as initial steps to reduce the complexity of mixed e-waste streams (Kanta Das *et al.*, 2024). For example, in the recycling of waste printed circuit boards (wPCBs), mechanical size reduction and sieving are often employed to prepare materials for further processing (Fazari *et al.*, 2024).

Mechanical recycling represents a relevant pathway for the management of plastic components recovered from cathode ray tube devices, particularly casings and internal polymer-based parts. Although Figure 5 presents general polymer recycling pathways, its inclusion serves to contextualize the treatment options applicable to plastics generated during CRT dismantling and preprocessing stages. The figure supports the analysis by

clarifying how primary, secondary or mechanical, tertiary or chemical, and quaternary or energy recovery recycling routes relate to the downstream handling of CRT derived plastics following separation from leaded glass and electronic components. This linkage is important because plastic fractions constitute a significant portion of CRT mass and influence the overall environmental performance of CRT recycling systems. By situating CRT plastic management within established polymer recycling frameworks, the figure aids interpretation of material recovery options and highlights where current practices align with or diverge from sustainable CRT waste management objectives.

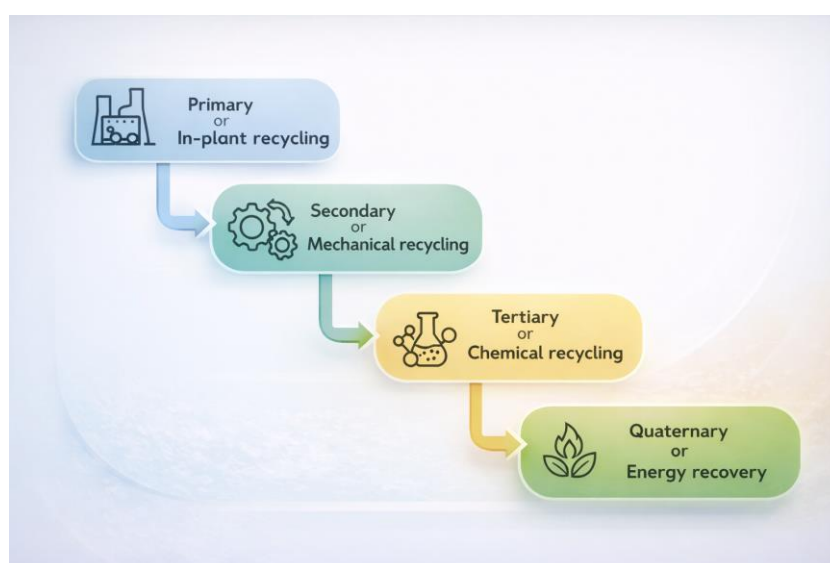


Figure 5: Sequential technique for thermoplastic recycling. Modified from Oladele *et al.*, (2023)

Chemical detoxification methods are equally vital for managing hazardous components. For instance, in the context of LED waste containing gallium arsenide (GaAs), specialized chemical processes are used for detoxification and recovery of gallium while ensuring safe disposal of arsenic (Swain *et al.*, 2020). The E-Terra facility, by adopting these advanced techniques, aims to minimize the environmental footprint of e-waste recycling and maximize resource recovery. This approach significantly reduces the potential for heavy metal contamination and the release of other pollutants that are prevalent in informal recycling sites in Nigeria. Informal e-waste recycling practices, common in areas like Lagos, often involve crude methods like open burning and acid leaching, which release toxic heavy metals such as lead, manganese, iron, zinc, cobalt, cadmium, nickel, silver, copper, arsenic, and chromium into the soil, posing severe risks to human health and the environment (Anselm *et al.*, 2021).

Beyond CRTs, innovative practices at such facilities extend to the safe recycling of fluorescent bulbs, cables, and batteries, integrating them into broader e-waste

management systems. This holistic approach is essential given the diverse nature of e-waste and the rapid proliferation of electronic devices globally. The increasing demand for sustainable energy solutions also highlights the need for advanced recycling of components like photovoltaic (PV) modules and lithium-ion batteries (Das and Sarmah, 2025).

The implementation of such standardized facilities marks a crucial step towards developing a robust circular economy for e-waste in Nigeria, contributing to a more sustainable future by recovering valuable resources and mitigating environmental degradation (Golpeo *et al.*, 2025). Effective e-waste management requires a comprehensive strategy encompassing collection, transportation, treatment, and disposal, with a strong emphasis on reducing environmental, economic, and social impacts (Nandan *et al.*, 2023). Despite challenges such as inadequate infrastructure, lack of data, and poor planning that are common in developing countries like Nigeria, these innovative recycling technologies offer promising solutions.

Closed-Loop Recycling and Design for Recyclability in Nigeria

The concept of closed-loop recycling, where materials are reprocessed into identical products, faces inherent challenges globally, particularly with older technologies such as CRTs (Smith and Behdad, 2025). However, Nigeria's strategy for e-waste management is evolving to maximize material recovery and integrate design-for-recyclability principles into newer electronic products (Eneh, 2021). This approach aligns with global circular economy trends, which emphasize minimizing waste and maximizing resource utilization through methods like reuse, repair, and recycling (Dragomir and Dumitru, 2024).

A key driver for this shift in Nigeria is the regulatory push towards Extended Producer Responsibility (EPR) (Agu, 2023). EPR schemes hold manufacturers and importers accountable for the entire lifecycle of their products, encouraging them to adopt eco-design principles that facilitate future recovery and recycling. By mandating producers to consider end-of-life management, EPR promotes the creation of products that are easier to dismantle, contain fewer hazardous substances, and are made with recyclable or reusable materials. This is crucial for developing countries like Nigeria, which often face the burden of e-waste imports, necessitating robust national standards and enforcement.

Nigeria's recycling sector is increasingly emphasizing the upcycling of CRT components, transforming them into secondary raw materials for applications in construction and manufacturing (Eneh, 2021). This strategy mitigates environmental impact by diverting hazardous CRT materials from landfills and informal disposal sites, where they could release toxic substances such as lead, cadmium, and mercury into the environment. Simultaneously, it fosters sustainable industrial growth by providing locally sourced raw materials, reducing reliance on virgin resources, and supporting the development of local industries (Elgarahy *et al.*, 2024). The recovery of valuable materials from e-waste, such as copper, gold, silver, palladium, aluminum, nickel, and lead, is a significant economic opportunity, particularly for developing nations.

Promoting product stewardship and encouraging consumer participation are essential components that complement systematic collection and recycling efforts in Nigeria (Eneh, 2021). Product stewardship involves responsible management of products throughout their lifecycle, encouraging consumers to properly dispose of e-waste and participate in collection programs. Consumer engagement is critical because informal collection practices, while widespread, often involve environmentally unsound methods such as open burning and acid leaching, which release heavy metals and persistent organic pollutants into the environment (Erdiaw-Kwasie *et al.*, 2024). Formal collection points and regulated recycling facilities are vital to address the challenges posed by the rapid increase in e-waste generation.

The shift towards formal and innovative recycling technologies, as exemplified by facilities capable of processing CRTs using mechanical separation, chemical detoxification, and material recovery, signifies a significant improvement in Nigeria's e-waste management capabilities (Egwali, 2013). Such advanced methods reduce dependence on crude informal practices, minimize the release of pollutants, and efficiently recover valuable materials for reuse and upcycling. Beyond CRTs, the integration of safe recycling practices for other e-waste components, including fluorescent bulbs, cables, and batteries, into broader management systems further strengthens this sustainable pathway. The increasing complexity of e-waste, including emerging streams like lithium-ion batteries from electric vehicles and solar photovoltaic panels, necessitates continuous innovation in recycling technologies to recover critical elements and prevent environmental contamination. This holistic approach is fundamental to forging a sustainable management pathway aligned with global circular economy trends.

Comparative Analysis of Available Management Options

Presented in Table 1 is a comparison of three practical CRT recycling methods including their advantages and disadvantages:

Table 1: Comparison of three practical CRT recycling methods

Recycling Method	Description	Advantages	Disadvantages	Suitable Applications
Manual Dismantling and Separation	Hand disassembly to sort CRT components: glass, metals, plastics, circuit boards	- Enables high recovery rates of valuable components (metals, plastics). - Low capital costs, suitable where labor is abundant. - Supports local employment.	- Labor intensive and time-consuming. - Informal practices may expose workers to toxic substances without adequate protection. - Risk of environmental contamination if safety protocols are neglected.	Informal and formal recycling centers focusing on material recovery and sorting stages.

Recycling Method	Description	Advantages	Disadvantages	Suitable Applications
		Allows targeted hazardous material handling when done safely.	Variable efficiency depending on worker skill.	
Thermal Processing (Smelting and Lead Recovery)	High-temperature melting to separate metals (especially lead) and reduce CRT volume	- High lead recovery efficiency producing reusable metals. - Significant waste volume reduction. - Produces high-purity materials for industrial use.	- High energy and operational costs. - Potential release of hazardous emissions without advanced pollution control. - Expensive initial capital investment. - Generates secondary pollutants requiring treatment.	Large-scale formal recyclers with pollution control systems, mainly in developed regions.
Incorporation into Cementitious Materials (Concrete/Mortar)	Using CRT glass as a raw material substitute in concrete, immobilizing toxic components	- Environmentally friendly with minimal leaching risk. - Economically viable and scalable. - Supports circular economy by converting waste to building materials. - Requires less specialized technology and infrastructure.	- Downcycling: does not return glass to original CRT manufacturing. - Quality standards may limit use in some construction applications. - Regulatory approval may be needed. - Limited information on long-term performance.	Construction industry for producing mortars, concretes, and blocks with recycled CRT glass content.

Expanded Explanation of Methods

Manual Dismantling and Separation:

This process involves taking apart CRT devices by hand to remove various components before further processing. Skilled workers separate leaded funnel glass from flat panel glass, recycle circuit boards, remove copper wiring, and segregate different plastics. This method allows for targeted recovery and prevents mixing of hazardous and non-hazardous materials, which is critical for effective recycling (Erdiaw-Kwasie *et al.*, 2024). While being cost-effective in labour-rich environments, it requires strict occupational safety controls to protect workers from lead dust and chemical exposure (Liu *et al.*, 2023). Informal practices lacking safety can cause severe health risks and environmental pollution (Agu, 2023).

Thermal Processing (Smelting and Lead Recovery):

Smelting melts CRT glass at very high temperatures, separating and recovering lead in metallic form, which can be resold to industries requiring lead inputs, such as battery

manufacturers or glass producers (Alam *et al.*, 2022). This method significantly reduces the volume of CRT waste and recovers high-purity materials. It requires substantial energy and investment in pollution control technology to mitigate air emissions like lead fumes and dioxins (Alam *et al.*, 2022). Mainly employed by large-scale formal recyclers, this method is less accessible in regions with limited financial or technical capacity but offers excellent environmental control if well managed (Alam *et al.*, 2022).

Incorporation into Cementitious Materials:

CRT glass can be crushed and mixed into cement, mortar, or concrete products. This immobilizes hazardous metals like lead within the hardened cement matrix, preventing leaching into the environment (Eneh, 2021). This approach circumvents the technical and financial barriers of smelting and allows large volumes of CRT glass to be safely reused. It aligns well with sustainability goals, enabling circular economy models within the construction sector (Eneh, 2021). The primary limitations include downcycling since this glass is not returned to CRT production and the need for regulatory approval to ensure construction product safety and performance.

It is important to note that no single CRT recycling method satisfies all environmental, economic, and technical requirements universally. Mixed strategies often prevail, adapted to local conditions. Manual dismantling paired with safe downstream treatment balances resource recovery and worker safety. Smelting remains the gold standard for lead recovery but requires advanced infrastructure. Cementitious incorporation offers scalable, cost-effective pollution containment where smelting is infeasible. Policymakers and industry should support formalization, technological innovation, and regulatory frameworks to maximize CRT recycling effectiveness and minimize health and environmental risks globally.

Policy and Regulatory Framework for CRT Waste in Nigeria

Nigerian and International Policies Governing E-Waste and CRT Management

Nigeria's comprehensive regulatory framework for managing waste CRTs and broader e-waste is anchored by both national policies and adherence to international commitments. A pivotal national instrument is the National Environmental (Electrical/Electronic Sector) Regulation of 2011, enacted by the National Environmental Standards and Regulations Enforcement Agency (NESREA) (Ahanor *et al.*, 2025). This regulation explicitly bans the importation of waste CRTs into Nigeria, thereby mitigating the inflow of hazardous materials. It further mandates the implementation of Environmentally Sound Management (ESM) practices, which are crucial for minimizing the adverse ecological and health impacts associated with e-waste (Ahanor *et al.*, 2025).

The ESM framework outlined in this regulation delineates clear responsibilities for the entire lifecycle of e-waste management, encompassing collection, transportation,

recycling, and final disposal. A core tenet of this policy is the stringent prohibition of environmentally harmful practices such as open burning, indiscriminate landfill disposal, and unauthorized dumping of e-waste (Ahanor *et al.*, 2025). These measures are critical given that informal recycling practices, prevalent in many developing countries including Nigeria, often involve such methods, leading to severe environmental pollution and significant health risks to workers and surrounding communities (Zunguka, 2025; Okolo *et al.*, 2025).

To safeguard the health of individuals involved in e-waste handling, the regulation strictly enforces the use of personal protective equipment (PPE) for workers. This is particularly important because e-waste contains numerous toxic substances, including heavy metals like lead, mercury, and cadmium, as well as brominated flame retardants, which can cause neurological damage, developmental problems, and various cancers upon exposure (Udousoro *et al.*, 2025; Okolo *et al.*, 2025). Furthermore, to ensure transparency and accountability in the movement of e-waste, the regulation mandates detailed manifest systems to track waste from its point of generation to its final processing (Ahanor *et al.*, 2025). This tracking mechanism is vital for preventing diversion to illegal or environmentally unsound processing channels.

On the international front, Nigeria is a signatory to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (McBrewster *et al.*, 2009; Ahanor *et al.*, 2025). This convention is an international treaty designed to prevent the uncontrolled transfer of hazardous wastes, including CRTs, between nations, particularly from developed to developing countries (Thapa *et al.*, 2022). By adhering to the Basel Convention, Nigeria reinforces its national prohibition on illegal e-waste imports, aligning its domestic policies with global efforts to manage hazardous waste responsibly. This commitment is essential, as previous research indicates that a substantial amount of used European electric and electronic equipment (UEEE) exported to Nigeria is often unfit for reuse and is effectively e-waste, despite legal prohibitions (Bimir, 2020; Thapa *et al.*, 2022). The short lifespan of such imported equipment has significant sustainability and circularity implications, highlighting the ongoing challenge of illegal transboundary e-waste trade (Thapa *et al.*, 2022).

Implementation of Extended Producer Responsibility (EPR)

Extended Producer Responsibility (EPR) frameworks are increasingly being integrated into Nigeria's e-waste management policies, encouraging producers, importers, and manufacturers to take accountability for the entire lifecycle of their products (Ahanor *et al.*, 2025). The Nigerian Communications Commission (NCC) issued E-Waste Regulations in 2018 that provide guidance on EPR implementation within the telecommunications sector, including requirements for take-back schemes and authorizations for recyclers and transporters (Ahanor *et al.*, 2025). NESREA supports these initiatives by regulating the importation and disposal of electrical and electronic equipment (EEE) and enforcing

compliance from producers to reduce environmental impacts (Zunguka, 2025). While formal EPR adoption is at an early stage and faces enforcement challenges, these policy frameworks aim to incentivize equitable responsibility sharing and drive market-based sustainable waste management solutions (Abogunrin-Olafisoye *et al.*, 2025).

This commitment to EPR is crucial given the substantial environmental and health challenges posed by e-waste. For instance, the demand for electronic equipment drives increased production, leading to significant volumes of Waste Electrical and Electronic Equipment (WEEE) (Okolo *et al.*, 2025). This results in pressures from growing WEEE volumes and low global collection and recycling rates, which contribute to high concentrations of e-waste pollutants in the environment, including hazardous contaminants like plastic additives and metals. The impact manifests as pollutants found in organisms and adverse effects on human health and ecosystems (Okolo *et al.*, 2025). Responses involve sustainable design, improved waste management, and environmental remediation.

Policy Gaps and Areas for Improvement

Despite the existence of foundational policy frameworks, significant gaps persist in the effective management of CRT waste in Nigeria, contributing to environmental and public health concerns. Enforcement mechanisms are often inconsistent, exacerbated by weak border controls that facilitate the illicit import of obsolete CRTs (Dada *et al.*, 2024). Public awareness regarding e-waste hazards and legal requirements remains low, impeding voluntary compliance and source segregation. A lack of streamlined coordination among regulatory bodies such as the National Environmental Standards and Regulations Enforcement Agency (NESREA), the Nigerian Communications Commission (NCC), and customs agencies further complicates monitoring and reporting efforts (Dada *et al.*, 2024). Financial and technical support for formal recycling infrastructure is insufficient, and there are inadequate incentives to integrate and formalize the informal waste sector. Key opportunities for legislative and institutional improvements include the nationwide implementation of comprehensive Extended Producer Responsibility (EPR) schemes, enhanced data collection on CRT waste flows, and the promotion of green procurement policies (Dada *et al.*, 2024).

Nigeria's policy and regulatory environment, while consistent with international standards, requires strengthened implementation, enhanced enforcement, and improved stakeholder collaboration to translate regulations into tangible environmental and public health benefits (Dada *et al.*, 2024). Relevant legal and policy instruments include:

1. **Constitution of the Federal Republic of Nigeria (1999):** Provides the fundamental legal basis for environmental regulations and the adoption of international law (Dada *et al.*, 2024).

2. **National Environmental Standards and Regulations Enforcement Agency (NESREA) Act:** Establishes the agency responsible for enforcing environmental laws, including waste management and pollution control (Dada *et al.*, 2024).
3. **Environmental Impact Assessment Act:** Governs environmental impact assessments for projects such as waste processing facilities, ensuring sustainable practices (Dada *et al.*, 2024).
4. **Harmful Waste (Special Criminal Provisions) Act:** Addresses the handling, disposal, and penalties for harmful waste, applicable to hazardous e-waste components like CRTs (Dada *et al.*, 2024).
5. **Extended Producer Responsibility (EPR) Framework under NESREA:** Encourages producers to take responsibility for end-of-life electronic products (Dada *et al.*, 2024).
6. **Quarantine Act:** Relevant for international shipments of e-waste, including CRTs, enforcing health and environmental safety at borders (Dada *et al.*, 2024).
7. **Relevant International Conventions:** Nigeria has ratified conventions such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, which impacts e-waste import/export regulations (Dada *et al.*, 2024).

These regulations collectively provide a robust legal foundation for CRT waste management in Nigeria, encompassing environmental protection, waste handling, producer responsibility, and international compliance obligations.

Current recycling technologies for CRTs, such as glass smelting and lead extraction, show environmental promise but face significant challenges, including high operational costs, limited scalability beyond laboratory settings, and the potential generation of secondary pollutants. Traditional closed-loop recycling methods have become outdated and economically unviable (Dada *et al.*, 2024).

Promising advancements include the incorporation of CRT glass into cementitious materials like concrete and mortar, offering an effective, economical, and environmentally sound method for recycling large volumes of CRT waste while minimizing pollution risks. This approach aligns with circular economy principles by safely recovering valuable materials (Júnior *et al.*, 2024). To ease the management of waste CRTs, several policy recommendations are crucial:

- Strengthen regulatory frameworks to ensure safe collection, transportation, and processing of CRT waste, reducing informal and unsafe practices.
- Support research and development to scale environmentally friendly recycling methods tailored to local contexts.
- Promote and incentivize innovative recycling pathways, such as CRT glass utilization in construction materials.
- Enhance public awareness campaigns to encourage proper disposal and participation in formal recycling programs.

- Foster multi-stakeholder collaborations engaging government agencies, industry, and communities for sustainable CRT waste management.

Implementing these measures is vital for mitigating the environmental and health risks associated with CRT waste, aligning with broader goals of sustainable resource use and pollution control (Dada *et al.*, 2024). The World Bank estimates that total waste generation will triple in Sub-Saharan Africa and double in South Asia by 2050, highlighting the urgency for improved waste management strategies (Khan *et al.*, 2022). Digitalization, including the Internet of Things (IoT), cloud computing, and artificial intelligence, offers tools to enhance waste management and recycling efficiency (Onur *et al.*, 2024). However, these technological advancements require robust policy support to be fully effective.

Recommendations and Conclusion

Recommendations

This review has highlighted the significant environmental and human health impacts associated with waste CRT devices in Nigeria. Toxic elements such as lead oxide, mercury, and cadmium within these devices present long-term pollution risks, particularly when processed through informal recycling channels. Nigeria's CRT waste management landscape is dominated by informal recyclers who use rudimentary techniques that contribute to widespread contamination and pose significant health risks. Although formal recycling initiatives such as those led by E-Terra Technologies, show strong potential through technological advancements, they remain limited by scale, funding, and regulatory enforcement challenges. The existing policy and regulatory framework, guided by NESREA regulations and Nigeria's international commitments under the Basel Convention, has built a foundation for effective CRT waste management. However, enforcement gaps, low public awareness, insufficient infrastructure, and weak institutional coordination continue to hinder progress. Addressing these challenges requires a coordinated, multi-stakeholder approach:

- Government should strengthen enforcement of import bans, expand formal collection infrastructure, and incentivize safe recycling technologies through funding and capacity building. Enhancing coordination among NESREA, customs, and local governments will improve regulatory compliance.
- Manufacturers and importers must embrace Extended Producer Responsibility (EPR) frameworks by developing take-back programs, designing for recyclability, and supporting local recycling industries financially and technically.
- Consumers and communities should be educated on the hazards of informal recycling and encouraged to participate in formal collection schemes. Public awareness campaigns and community engagement will facilitate safer waste segregation and disposal.

Future research should focus on developing context-specific solutions to the technological, economic, and social barriers facing CRT waste recycling in Nigeria. Evaluating the performance of existing formal recycling facilities and testing innovative recycling technologies can provide guidance for scaling successful models. Additionally, studies examining the socio-economic dynamics of informal recycling, public health risks, and behavioural drivers can inform more precise policy responses and community-based initiatives. Integrating CRT recycling into Nigeria's broader circular economy and green industrial development strategies will further enhance sustainability outcomes. Continuous data collection, monitoring, and transparent reporting on CRT waste flows will be crucial for adaptive governance and evidence-based policymaking.

Conclusion

The management and recycling of waste CRT present a multifaceted challenge that lies at the intersection of environmental protection and technological innovation. The toxic compounds embedded in CRT glass particularly lead, highlight the urgency of this issue. With the global shift toward modern display technologies, CRTs have become obsolete, leading to an ever-increasing accumulation of waste that demands efficient and sustainable recycling solutions. This paper has emphasized the significant environmental hazards posed by improper disposal of CRT waste, such as soil and water contamination from toxic metals and the severe health risks linked to informal and unregulated recycling activities. Several recycling approaches ranging from manual dismantling to thermal processing and material incorporation, offer varying degrees of effectiveness. Manual dismantling yields high material recovery rates and creates employment but requires rigorous safety standards to safeguard workers. Thermal smelting facilitates efficient lead recovery yet depends on substantial energy inputs and advanced pollution control systems. Incorporating CRT glass into cementitious materials represents a promising and scalable solution that stabilizes hazardous substances and aligns with circular economy principles, even though it constitutes a form of downcycling.

In Nigeria, policies such as the ban on CRT imports are vital steps toward reducing hazardous e-waste inflows and fostering the growth of a domestic recycling industry. However, meaningful progress depends on stronger enforcement, improved formal recycling capacity, and the gradual integration of informal recyclers into regulated systems. Sustainable CRT waste management requires a holistic approach that integrates technological innovation, strict regulatory oversight, public awareness, and targeted capacity building. Policymakers should prioritize investments in environmentally sound recycling infrastructure, promote formalization of the informal sector, and encourage research into advanced detoxification and reuse methods to broaden management options.

However, the analysis addressed the first objective by demonstrating that CRT waste remains a significant source of lead and other toxic metals, with clear links to soil, water,

and occupational exposure in informal recycling environments. The second objective was met through a critical assessment of current management systems, showing persistent reliance on informal practices, limited formal recycling capacity, and weak regulatory enforcement. In relation to the third objective, the review examined available recycling and management options, comparing manual dismantling, thermal recovery, and material incorporation pathways, and identified approaches with potential relevance under Nigerian technical and economic conditions. The fourth objective was addressed through a synthesis of national policies and international regulatory frameworks shaping CRT waste control, highlighting gaps between policy intent and implementation. Finally, the review fulfilled the fifth objective by proposing targeted recommendations for policymakers, industry actors, and communities, with emphasis on enforcement, infrastructure development, and inclusion of informal recyclers within regulated systems. Overall, the findings show that CRT waste requires distinct consideration within electronic waste governance due to its hazardous composition and long legacy. Sustainable management depends on coordinated policy execution, technological development, and stakeholder engagement rather than isolated interventions.

This review has limitations. It focuses primarily on Nigeria, which may limit direct transferability to other contexts. The analysis relies largely on English language literature and secondary data sources, reflecting limited availability of primary data on informal CRT recycling activities. These constraints highlight the need for future empirical studies on exposure pathways, material flows, and locally appropriate recycling innovations to strengthen evidence-based CRT waste management strategies.

Ultimately, addressing the legacy of CRT obsolescence in Nigeria demands coordinated policy execution, technological progression, and inclusive stakeholder participation. Transitioning from hazardous informal practices to a sustainable, well-regulated CRT management system is essential for safeguarding environmental quality, protecting public health, and advancing Nigeria's pursuit of sustainable development goals.

Credit Authorship Contribution Statement

Innocent Chidi Nnorom: Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Faluyi Ibukun:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Solomon Chiemela Onuchukwu:** Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Abalansa, S., El Mahrad, B., Icely, J., and Newton, A. (2021). Electronic Waste, an Environmental Problem Exported to Developing Countries: The GOOD, the BAD and the UGLY. *Sustainability*, 13(9), 5302. <https://doi.org/10.3390/su13095302>
- Abogunrin-Olafisoye, O. B., Adeyi, O., Adeyi, A. J., Oke, E. O., and Ojediran, G. O. (2025). Sustainable Waste Electrical and Electronics Equipment Recycling in Nigeria, Policies and Emerging Technologies. *Environmental Quality Management*, 34(3). <https://doi.org/10.1002/tqem.70020>
- Adesokan, M. D., Adie, G. U., and Osibanjo, O. (2016). Soil pollution by toxic metals near E-waste recycling operations in Ibadan, Nigeria. *Journal of health and pollution*, 6(11), 26-33. <https://doi.org/10.5696/2156-9614-6-11.26>
- Adeyi, A. A., and Oyeleke, P. (2017). Heavy metals and polycyclic aromatic hydrocarbons in soil from e-waste dumpsites in Lagos and Ibadan, Nigeria. *Journal of health and pollution*, 7(15), 71-84. <https://doi.org/10.5696/2156-9614-7.15.71>
- Adeyi, A. A., Olayanju, B., and Fatade, Y. (2020). Distribution and potential risk of metals and metalloids in soil of informal E-waste recycling sites in Lagos, Nigeria. *Ife Journal of Science*, 21(3), 213. <https://doi.org/10.4314/ijfs.v21i3.17>
- Agu, B. O. (2023). Electronic Waste Management and Institutional Theory: Any Lessons for Nigeria? *European Modern Studies Journal*, 7(1), 254–266. [https://doi.org/10.59573/emsj.7\(1\).2023.23](https://doi.org/10.59573/emsj.7(1).2023.23)
- Ahanor, E., Obahor, G., and Isangadighi, G. E. (2025). Informal Sector Dynamics in Nigeria's E-Waste Chain: Legal Recognition and Environmental Risk. *Journal of Built Environment and Geological Research*. <https://doi.org/10.70382/ajbegr.v9i4.027>
- Akeju, K. F., and Omotoso, F. (2023). Exploring women's interests in household waste disposal and management. *Journal Of Environmental Science and Sustainable Development*, 6(1), 1-18. <https://doi.org/10.7454/jessd.v6i1.1152>
- Alam, T., Golmohammadzadeh, R., Faraji, F., and Shahabuddin, M. (2022). E-Waste Recycling Technologies. In *Paradigm Shift in E-waste Management* (pp. 143–176). CRC Press. <https://doi.org/10.1201/9781003095972-10>
- Anselm, O. H., Cavoura, O., Davidson, C. M., Oluseyi, T. O., Oyeyiola, A. O., and Togias, K. (2021). Mobility, spatial variation and human health risk assessment of mercury in soil from an informal e-waste recycling site, Lagos, Nigeria. *Environmental Monitoring and Assessment*, 193(7). <https://doi.org/10.1007/s10661-021-09165-0>
- ASTSWMO (2025). Cathode Ray Tubes (CRT) Management Position Paper. *Association of State and Territorial Solid Waste Management Officials (ASTSWMO) Publications* <https://astswmo.org/cathode-ray-tubes-crt-management-position-paper/>
- Babayemi, J. O., Nnorom, I. C., and Weber, R. (2025). Comprehensive inventory of imports of electrical and electronic equipment and related plastics and POPs plastic additives into Nigeria in the past 32 years (1990–2022). *Emerging Contaminants*, 11(1), 100423. <https://doi.org/10.1016/j.emcon.2024.100423>
- Bankole, A., Ogunkeyede, A., Ngo, H., Liang, L., Agboro, H., Isimekhai, K., Fadairo, E., Isangadighi, G., Isukuru, E., and Ogbodhu, C. (2024). Ecological Risks of Heavy Metals Found in Soils at Informal E-Waste Processing Sites in Nigeria. *European Journal of Science, Innovation and Technology*, 4(2), 417-434. Retrieved from <https://ejsit-journal.com/index.php/ejsit/article/view/428>
- Bimir, M. N. (2020). Revisiting e-waste management practices in selected African countries. *Journal of the Air & Waste Management Association*, 70(7), 659–669. <https://doi.org/10.1080/10962247.2020.1769769>

- Dada, M. A., Obaigbena, A., Majemite, M. T., Oliha, J. S., and Biu, P. W. (2024). Innovative approaches to waste resource management: implications for environmental sustainability and policy. *Engineering Science and Technology Journal*, 5(1), 115-127. <https://doi.org/10.51594/estj.v5i1.731>
- Das, H. J., and Sarmah, N. (2025). Photovoltaic module Recycling: A review on material recovery methods and waste management approach. *Solar Energy*, 299, 113708. <https://doi.org/10.1016/j.solener.2025.113708>
- Dragomir, V. D., and Dumitru, M. (2024). The state of the research on circular economy in the European Union: A bibliometric review. *Cleaner Waste Systems*, 7, 100127. <https://doi.org/10.1016/j.clwas.2023.100127>
- Egwali, A. (2013). Challenges of e-waste recycling in Nigeria. *Nigerian Journal of Life Sciences*, 3(2), 77-83. <https://doi.org/10.52417/njls.v3i2.134>
- Elgarahy, A. M., Eloffy, M. G., Priya, A. K., Hammad, A., Zahran, M., Maged, A., and Elwakeel, K. Z. (2024). Revitalizing the circular economy: An exploration of e-waste recycling approaches in a technological epoch. *Sustainable Chemistry for the Environment*, 7, 100124. <https://doi.org/10.1016/j.scenv.2024.100124>
- Eneh, O. C. (2021). Green chemistry models for municipal electronic waste treatment for resource recovery, repair, recycling and reuse in Nigeria. *Clean Technologies and Environmental Policy*, 23(4), 1169–1178. <https://doi.org/10.1007/s10098-021-02027-w>
- Erdiaw-Kwasie, M. O., Abunyewah, M., and Baah, C. (2024). A systematic review of the factors – Barriers, drivers, and technologies – Affecting e-waste urban mining: On the circular economy future of developing countries. *Journal of Cleaner Production*, 436, 140645. <https://doi.org/10.1016/j.jclepro.2024.140645>
- E-Terra Technologies Limited (2017). CRT recycling. <https://www.eterra.com.ng/system/services/crt-recycling/>
- E-Terra Technologies Limited (2017). *Electronic waste recycling finally in West Africa*. <https://www.eterra.com.ng/system/articles/electronic-waste-recycling-finally-west-africa/>
- Fazari, J., Hossain, M. Z., and Charpentier, P. (2024). A review on metal extraction from waste printed circuit boards (wPCBs). *Journal of Materials Science*, 59(27), 12257–12284. <https://doi.org/10.1007/s10853-024-09941-6>
- Golpeo, J. M., Andres, G. L., Faronal, I. N., and Casuat, C. D. (2025). Sustainable E-Waste Management Through a Circular Economy Framework: Integrating Smart Technologies for Resource Recovery in Urban Environments. *E3S Web of Conferences*, 643, 01005. <https://doi.org/10.1051/e3sconf/202564301005>
- Halkos, G. E., and Aslanidis, P.-S. C. (2024). How Waste Crisis Altered the Common Understanding: From Fordism to Circular Economy and Sustainable Development. *Circular Economy and Sustainability*, 4(2), 1513–1537. <https://doi.org/10.1007/s43615-023-00337-3>
- Hjul-Nielsen, J., Santos, A., Christensen, D., and Andrade, B. (2023). Factors influencing changes in island waste systems: The case of Bornholm, Denmark. *Cleaner Waste Systems*, 4, 100080. <https://doi.org/10.1016/j.clwas.2023.100080>
- Hung, M.-J., Lin, Y.-W., Lin, W.-T., Lee, W.-H., Kuo, B.-Y., and Lin, K.-L. (2024). Functionalization of mesoporous Al-MCM-41 for indoor humidity control as building humidity conditioning material. *Journal of Molecular Structure*, 1299, 137024. <https://doi.org/10.1016/j.molstruc.2023.137024>
- Ike, F. (2025). Informal Sector E-waste Management in Aba Urban, South-eastern Nigeria: Assessment of Quantities Handled and Environmental-health Impacts. *International Journal*, 13(5), 254-262. <https://doi.org/10.11648/j.ijema.20251305.12>

- Iniaghe, P. O., and Adie, G. U. (2015). Management practices for end-of-life cathode ray tube glass: Review of advances in recycling and best available technologies. *Waste Management andamp; Research: The Journal for a Sustainable Circular Economy*, 33(11), 947–961. <https://doi.org/10.1177/0734242x15604212>
- Iniaghe, P. O., and Adie, G. U. (2018). Examining toxic metals contamination, speciation and geochemistry of soil impacted by open disposal of waste cathode ray tubes in Nigeria. *Ovidius University Annals of Chemistry*, 29(2), 77-84. <https://doi.org/10.2478/auoc-2018-0011>
- Iniaghe, P. O., Adie, G. U., and Osibanjo, O. (2013). Metal levels in computer monitor components discarded in the vicinities of electronic workshops. *Toxicological and Environmental Chemistry*, 95(7), 1108-1115. <https://doi.org/10.1080/02772248.2013.863890>
- Issah, I., Arko-Mensah, J., Agyekum, T. P., Dwomoh, D., and Fobil, J. N. (2022). Health risks associated with informal electronic waste recycling in Africa: a systematic review. *International journal of environmental research and public health*, 19(21), 14278. <https://doi.org/10.3390/ijerph192114278>
- Júnior, C. G., Saraiva, J. S., and Aylon, L. L. (2024). Sustainable Public Policy Approaches to Overcome Planned Obsolescence: Models of Circular Economy Innovations. *Beijing Law Review*, 15(03), 1430–1445. <https://doi.org/10.4236/blr.2024.153084>
- Kanta Das, S., Ellamparuthy, G., Kundu, T., Angadi, S. I., and Rath, S. S. (2024). A comprehensive review of the mechanical separation of waste printed circuit boards. *Process Safety and Environmental Protection*, 187, 221–239. <https://doi.org/10.1016/j.psep.2024.04.090>
- Khan, I., Chowdhury, S., and Techato, K. (2022). Waste to Energy in Developing Countries—A Rapid Review: Opportunities, Challenges, and Policies in Selected Countries of Sub-Saharan Africa and South Asia towards Sustainability. *Sustainability*, 14(7), 3740. <https://doi.org/10.3390/su14073740>
- Lima, N. M. O., Morais, C. R. da S., Lima, L. M. R., and Albuquerque, A. V. (2012). Characterization of the glass of cathode ray tube computer for making decorative pieces by recycling. *Materials Science Forum*, 727, 1525-1529. <https://doi.org/10.4028/www.scientific.net/MSF.727-728.1525>
- Liu, K., Tan, Q., Yu, J., and Wang, M. (2023). A global perspective on e-waste recycling. *Circular Economy*, 2(1), 100028. <https://doi.org/10.1016/j.cec.2023.100028>
- Manhart, A., Osibanjo, O., Aderinto, A., and Prakash, S. (2011). *Informal e-waste management in Lagos, Nigeria: Socio-economic impacts and feasibility of international recycling co-operations* (Final report, Component 3, UNEP E-Waste Africa Project). Öko-Institut and Basel Convention Secretariat. [https://www.basel.int/Portals/4/Basel%20Convention/docs/eWaste/E-waste Africa Project Nigeria.pdf](https://www.basel.int/Portals/4/Basel%20Convention/docs/eWaste/E-waste%20Africa%20Project%20Nigeria.pdf)
- McBrewster, J., Miller, F. P., and Vandome, A. F. (2009). Electronic Waste: Waste Legislation, Computer Recycling, Digger Gold, Green Computing, Polychlorinated Biphenyl, Retail Hazardous Waste, Basel Convention. In *Electronic waste Waste legislation, Computer recycling, Digger gold, Green computing, Polychlorinated biphenyl, Retail hazardous waste, Basel Convention*. <https://dl.acm.org/doi/abs/10.5555/1795525>
- Meng, W., Wang, X., Yuan, W., Wang, J., and Song, G. (2016). The recycling of leaded glass in cathode ray tube (CRT). *Procedia Environmental Sciences*, 31, 954-960. <https://doi.org/10.1016/j.proenv.2016.02.120>
- Nandan, A., Suresh, A., Saole, P., Jeevanasai, S., Chandrasekaran, R., Meili, L., Wan Azelee, N., and Selvasembian, R. (2023). An Integrated Approach for Electronic Waste Management—Overview of Sources of Generation, Toxicological Effects, Assessment, Governance, and Mitigation Approaches. *Sustainability*, 15(24), 16946. <https://doi.org/10.3390/su152416946>

- Nnorom, I. C., Osibanjo, O., and Ogwuegbu, M. O. C. (2011). Global disposal strategies for waste cathode ray tubes. *Resources, Conservation and Recycling*, 55(3), 275-290. <https://doi.org/10.1016/j.resconrec.2010.10.007>
- Nwazue, S. C., Iyi, E. A., and Ogochuwu, C. E. (2025). E-waste generation and management practices in Aba Metropolis, Abia State: Implications for sustainable environmental management. *IIARD International Journal of Geography and Environmental Management*, 11(4): 1-11. <https://iiardjournals.org/get/IJGEM/VOL.%2011%20NO.%204%202025/E-Waste%20Generation%20and%20Management%201-11.pdf>
- Ohajinwa, C. M., Van Bodegom, P. M., Vijver, M. G., and Peijnenburg, W. J. (2017). Health risks awareness of electronic waste workers in the informal sector in Nigeria. *International journal of environmental research and public health*, 14(8), 911. <https://doi.org/10.3390/ijerph14080911>
- Ohajinwa, C. M., Van Bodegom, P. M., Xie, Q., Chen, J., Vijver, M. G., Osibanjo, O. O., and Peijnenburg, W. J. G. M. (2019). Hydrophobic Organic Pollutants in Soils and Dusts at Electronic Waste Recycling Sites: Occurrence and Possible Impacts of Polybrominated Diphenyl Ethers. *International Journal of Environmental Research and Public Health*, 16(3), 360. <https://doi.org/10.3390/ijerph16030360>
- Okolo, C. M., Ahaneku, C. V., Ugwu, F. O., Muogbo, C. D., and Odoh, B. I. (2025). A Review of the Environmental and Health Impacts of Electronic Waste: Global Challenges and Sustainable Management Solutions. *International Journal of Environment and Climate Change*, 15(5), 220-237. <https://doi.org/10.9734/ijecc/2025/v15i54847>
- Okorhi, O. J., Okereka, E. E., Akhimie, C. O., and Enekwenchi, K. K. (2018). Frontiers and prospects for recycling Waste Electrical and Electronic Equipment (WEEE) in Nigeria. *Journal of Applied Sciences and Environmental Management*, 21(7), 1382. <https://doi.org/10.4314/jasem.v21i7.30>
- Oladele, I. O., Okoro, C. J., Taiwo, A. S., Onuh, L. N., Agbeboh, N. I., Balogun, O. P., Olubambi, P. A., and Lephuthing, S. S. (2023). Modern Trends in Recycling Waste Thermoplastics and Their Prospective Applications: A Review. *Journal of Composites Science*, 7(5), 198. <https://doi.org/10.3390/jcs7050198>
- Onuchukwu, S. C., Udousoro, I. I., and Umoren, I. U. (2024). Characterization of toxic metals and flame retardants in printed circuit boards from electronic waste. *World Journal of Applied Science and Technology*, 16(1), 10-17. <https://doi.org/10.4314/wojast.v16i1.10>
- Onur, N., Alan, H., Demirel, H., and Köker, A. R. (2024). Digitalization and Digital Applications in Waste Recycling: An Integrative Review. *Sustainability*, 16(17), 7379. <https://doi.org/10.3390/su16177379>
- Osibanjo, O., and Nnorom, I. C. (2007). The challenge of electronic waste (e-waste) management in developing countries. *Waste management and research*, 25(6), 489-501. <https://doi.org/10.1177/0734242x07082028>
- Owen, C., and Scougall, B. (2025, May). *Environmental injustice: How informal e-waste recycling impacts human rights*. Norton Rose Fulbright. <https://www.nortonrosefulbright.com/en-us/knowledge/publications/f54afc62/environmental-injustice-how-informal-e-waste-recycling-impacts-human-rights>
- Owusu-Sekyere, K., Aladago, D. A., Leverenz, D., Oteng-Ababio, M., and Kranert, M. (2024). Environmental impacts on soil and groundwater of informal E-waste recycling processes in Ghana. *Sustainability*, 16(11), 4347. <https://doi.org/10.3390/su16114347>
- Patil, R. A., and Ramakrishna, S. (2020). A comprehensive analysis of e-waste legislation worldwide. *Environmental Science and Pollution Research*, 27(13), 14412-14431. <https://doi.org/10.1007/s11356-020-07992-1>

- Pauzi, N. N. M., Hamid, R., Jamil, M., and Zain, M. F. M. (2021). The effect of melted-spherical and crushed CRT funnel glass waste as coarse aggregates on concrete performance. *Journal of Building Engineering*, 35, 102035. <https://doi.org/10.1016/j.jobbe.2020.102035>
- Prata, J. C. (2024). The environmental impact of e-waste microplastics: a systematic review and analysis based on the Driver–Pressure–State–Impact–Response (DPSIR) Framework. *Environments*, 11(2), 30. <https://doi.org/10.3390/environments11020030>
- Qi, Y., Xiao, X., Lu, Y., Shu, J., Wang, J., and Chen, M. (2019). Cathode ray tubes glass recycling: A review. *Science of The Total Environment*, 650, 2842–2849. <https://doi.org/10.1016/j.scitotenv.2018.09.383>
- Ramadan, A. M., Abdu, N., Yusuf, A. A., Abdullahi, S. A., and Alhassan, A. B. (2024). Assessment of the concentration of heavy metals in electronic waste dump site in Alaba international market, Lagos State. *FUDMA Journal of Sciences*, 8(5), 321–325. <https://doi.org/10.33003/fjs-2024-0805-2328>
- Rao, J. N., and Parsai, T. (2023). A comprehensive review on the decentralized composting systems for household biodegradable waste management. *Journal of Environmental Management*, 345, 118824. <https://doi.org/10.1016/j.jenvman.2023.118824>
- Salim, H., Jackson, M., Stewart, R. A., and Beal, C. D. (2023). Drivers–pressures–state–impact–response of solid waste management in remote communities: A systematic and critical review. *Cleaner Waste Systems*, 4, 100078. <https://doi.org/10.1016/j.clwas.2023.100078>
- Sanjo Kazeem, A., Mohammed, I., Abba Gana, B., and Mam Ago, M. (2021). Households practice and awareness dimension on the recycling of electronic waste in Kano metropolis, Nigeria. *International Journal of Engineering Applied Sciences and Technology*, 6(4). <https://doi.org/10.33564/ijeast.2021.v06i04.003>
- Sawyerr, H. O., and Oladeji, F. O. (2020). Evaluation of the distribution of heavy metals in soil around electronic dumpsite in Owutu, Ikorodu, Lagos State, Nigeria. *Asian Journal of Chemical Sciences*, 8(3), 24–31. <https://doi.org/10.9734/ajocs/2020/v8i319045>
- Sindik, O., Babayemi, J., Osibanjo, O., Schlummer, M., Schluep, M., Watson, A., and Weber, R. (2014). Polybrominated diphenyl ethers listed as Stockholm Convention POPs, other brominated flame retardants and heavy metals in e-waste polymers in Nigeria. *Environmental Science and Pollution Research*, 22(19), 14489–14501. <https://doi.org/10.1007/s11356-014-3266-0>
- Smith, R. L., and Behdad, S. (2025). From present to future: A review of e-waste recycling processes. *Waste Management*, 204, 114863. <https://doi.org/10.1016/j.wasman.2025.114863>
- Swain, B., Lee, D.-H., Lee, C. G., and Park, K.-S. (2020). Detoxification of GaAs Bearing Waste LED and Recovery of Metal Values Through Understanding the Thermodynamics and Chemistry: A Perspective. *Waste and Biomass Valorization*, 12(5), 2769–2778. <https://doi.org/10.1007/s12649-020-01196-x>
- Thapa, K., Vermeulen, W. J. V., Deutz, P., and Olayide, O. (2022). Ultimate producer responsibility for e-waste management—A proposal for just transition in the circular economy based on the case of used European electronic equipment exported to Nigeria. *Business Strategy andamp; Development*, 6(1), 33–52. <https://doi.org/10.1002/bsd2.222>
- Tsebe, S. P., and Steenkamp, J. D. (2024). Development of an Integrated Process Flowsheet to Recover Valuable Metals from Waste Cathode Ray Tubes and Printed Circuit Boards. *Journal of Sustainable Metallurgy*, 10(1), 224–240. <https://doi.org/10.1007/s40831-023-00775-1>
- U.S. Environmental Protection Agency (USEPA) (2024, November 7). *Cathode ray tubes (CRTs)*. <https://www.epa.gov/hw/cathode-ray-tubes-crts>
- Udousoro, I. I., Onuchukwu, S. C., and Umoren, I. U. (2025). Assessment of Electronic Waste for Heavy Metal Contamination and Its Impacts on Ecosystem Health. *Environmental Pollution and Management*, 3, 1–10. <https://doi.org/10.1016/j.epm.2025.09.003>

- Ukem, E. (2008). Electronic Waste: A Growing Challenge In Nigeria. *Global Journal of Pure and Applied Sciences*, 14(4). <https://doi.org/10.4314/gjpas.v14i4.16836>
- Verma, A. K., and Prakash, S. (2020). E-wastes and their impact on environment and public health. *International Journal of Applied Research*, 6(9): 164-168. <https://doi.org/10.22271/allresearch.2020.v6.i9c.7111>
- Wielgus, N., Górski, M., and Kubica, J. (2021). Discarded Cathode Ray Tube glass as an alternative for aggregate in a metakaolin-based geopolymer. *Sustainability*, 13(2), 479. <https://doi.org/10.3390/su13020479>
- Xu, Q., Li, G., He, W., Huang, J., and Shi, X. (2012). Cathode ray tube (CRT) recycling: current capabilities in China and research progress. *Waste management*, 32(8), 1566-1574. <https://doi.org/10.1016/j.wasman.2012.03.009>
- Zunguka J., M. (2025). E-Waste Management: Strategies for Sustainable Practices. *Newport International Journal of Engineering and Physical Sciences*, 5(1), 13–16. <https://doi.org/10.59298/nijep/2025/511316>