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REVIEW

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Climate change implications of electronic waste: strategies for sustainable management

Akeeb Adepoju Fawole[1], Ochuko Felix Orikpete[2,3], Nwakamma Ninduwezuor Ehiobu[4] and Daniel Raphael Ejike Ewim[5,6*]

Abstract

Background This paper addresses the escalating global issue of electronic waste (e-waste), a consequence of the burgeoning demand for electronic products coupled with their transient lifespan. The rapid accumulation of e-waste is a significant concern, especially in the context of climate change, necessitating a detailed analysis of current management strategies and the development of sustainable management practices. The intricate relationship between e-waste and climate change is emphasized, illustrating how improper disposal and recycling practices substantially contribute to greenhouse gas emissions.

Main body of the abstract A meticulous analysis is conducted to critique the prevailing e-waste management strategies, identifying their shortcomings and the urgent need for enhancement and globalization of these protocols. The paper argues for a fortified, universal approach to e-waste management to address the deficiencies in current methodologies. A set of strategic, sustainable solutions for e-waste management is proposed, encompassing comprehensive regulatory frameworks, advanced recycling technologies, the incorporation of eco-design principles, and the enhancement of consumer awareness. These solutions pivot around the circular economy concept, viewing waste as a valuable resource rather than a disposal predicament, thereby promoting sustainability.

Short conclusion The paper concludes that a consolidated, global approach to e-waste management is imperative for addressing the proliferation of discarded electronics and is pivotal in the wider context of mitigating climate change and fostering sustainable development. It underscores the transformative potential of sustainable e-waste management, transforming a formidable challenge into an opportunity for environmental conservation, economic growth, and societal progress, emphasizing the importance of viewing e-waste management as a vehicle for sustainability.

Keywords Circular economy, Climate change, Eco-design, e-waste, Electronic waste management, Recycling technologies, Regulatory frameworks, Sustainable development

*Correspondence:
Daniel Raphael Ejike Ewim
daniel.ewim@yahoo.com
Full list of author information is available at the end of the article

Background

The electronics industry has radically transformed the world in recent decades. Electrical and electronic products have become omnipresent in our daily lives across the globe. Without these innovations, modern existence in developed, developing, and industrializing countries would be unimaginable (Magalini and Kuehr 2011). Electronic waste, commonly known as e-waste, encompasses all discarded electronics or electrical devices that have reached the end of their usable life or become obsolete due to rapid technological advancements (Nguyen et al. 2018). E-waste is a broad term that captures an array of common domestic items. These range from small appliances such as LED lamps, clocks, and irons, to larger household machines like refrigerators, air conditioners, and washing machines. It also includes small information technology hardware like external hard drives, routers, keyboards, and mice, as well as consumer electronics and their accessories, such as smartphones, headphones, remote controls, and audio devices. IT equipment such as computers, laptops, tablets, printers, and hard disks also fall into this category, along with smaller food preparation devices like toasters, food processors, and grills (Gollakota et al. 2020; Wath et al. 2010; WEEE Forum 2022). E-waste presents a double-edged sword as it can be a source of valuable materials like gold, silver, copper, and rare earth metals (Fornalczyk et al. 2013), but can also be a toxic hazard if not handled appropriately due to substances like lead, mercury, and cadmium (Borthakur and Singh 2021).

In recent years, the scale of the global e-waste problem has become increasingly significant. According to the UN's Global E-waste Monitor 2020 report, there was an unprecedented generation of 53.6 million metric tonnes (Mt) of electronic waste worldwide in 2019, reflecting a 21% increase over a span of just five years. The recent report also forecasts that the global volume of electronic waste, which includes discarded items with a battery or plug, is projected to escalate to 74 metric tonnes by 2030. This estimate represents nearly a twofold increase in e-waste within a span of just 16 years (The Global E-Waste Statistics Partnership 2023). Moreover, WEEE Forum (2022) has disclosed that in 2022, around 5.3 billion mobile phones are expected to become waste, being discarded or simply hoarded in our homes. This constitutes a third of the 16 billion mobiles that are globally owned. Staggeringly, if we were to stack these wasted phones, they would ascend 50,000 km, a height that is 120 times the altitude of the International Space Station and about one-eighth of the journey to the moon (WEEE Forum 2022). This upward trend is driven by factors such as higher consumption rates of electronic products, shorter life cycles, and limited repair options (Forti et al. 2020). Most worryingly, only a small fraction of this waste is recycled in an environmentally sound manner, while a considerable portion is dumped or burned informally, thus contributing to environmental pollution and climate change (Ghulam and Abushammala 2023). According to Zhao et al. (2019), only one-fifth of all e-waste is ever successfully recycled. Such wasteful actions do not just clutter our environment, but they also sequester critical minerals like copper, lithium, cobalt, and palladium.

This paper aims to explore the climate change implications of the growing e-waste crisis and proposes strategies for its sustainable management. The first section will discuss the environmental impacts of e-waste, with a focus on greenhouse gas emissions and the release of toxic substances. We will then evaluate the existing e-waste management strategies and identify their gaps. Finally, we will delve into potential sustainable strategies for managing e-waste, which include adoption of circular economy principles, improvements in recycling technologies, stringent legislation for e-waste disposal, and increased consumer education and awareness. Our goal is to provoke thoughtful discourse around e-waste and its management, a topic of growing importance in the global battle against climate change.

Methods

This research paper follows an explorative and qualitative methodology to investigate the critical issue of e-waste and its impact on climate change, current management strategies, and prospective sustainable solutions. A comprehensive literature review was conducted to inform the analysis.

Literature review

The literature review involved an extensive search of several databases, including Google Scholar, Web of Science, PubMed, and the databases of key international organizations like the United Nations Environment Programme (UNEP), the World Economic Forum (WEF), and the United States Environmental Protection Agency (EPA). The search strategy aimed to find peer-reviewed articles, books, reports, and conference proceedings that deal with the concepts of e-waste, its environmental impact, existing management strategies, and proposals for sustainable practices.

Selection and evaluation of sources

Publications for review were selected based on their relevance to the research questions. The main criteria for inclusion were that the source provides insight into the impacts of e-waste on the environment, especially in terms of climate change, and sheds light on the effectiveness of current e-waste management practices and sustainable strategies. The evaluation of these sources was based on their credibility, their contribution to the field, and the robustness of their methodology.

Data synthesis

The findings from the literature review were synthesized in a narrative manner. This approach allowed for the integration of diverse findings and the provision of a holistic view of the e-waste issue, its impacts, current strategies, and potential solutions. The narrative synthesis also facilitated the discussion and interpretation of the findings within the broader context of environmental sustainability and climate change.

Limitations

While every effort was made to conduct a comprehensive literature review, the results presented in this paper are subject to the inherent limitations of the methodology. These include the potential for omission of relevant studies and the reliance on the available literature, which may not fully capture the complexities of the e-waste issue and its various dimensions across different global contexts. Despite these limitations, the paper provides a valuable overview of the e-waste problem, its implications for climate change, and potential sustainable strategies for its management.

Review of existing research

The emerging problem of e-waste and its impact on environmental health have been a focus of numerous studies. In California, a survey of e-waste processors carried out by Nixon and Saphores (2007) highlighted a gap between processing capacity and projected e-waste volume. Kyere's (2016) comprehensive examination of electronic waste (e-waste) management and related legislation in Ghana revealed several challenges impeding effective handling of e-waste. These included an absence of legislative measures specifically tailored for e-waste management, insufficient infrastructural support, a dearth of expertise and human capacity in this sector, and limited public awareness and education concerning the importance and methods of e-waste management.

Awasthi et al. (2016) examined the environmental impact of rapidly increasing electronic waste (e-waste) in India. The findings revealed excessive levels of harmful pollutants in the environment due to improper e-waste handling methods such as open burning and acid baths. These practices contributed to the release of toxins, negatively impacting the environment, workers, and nearby residents. The study confirmed contaminants' movement through the food chain, threatening human health, and proposed remediation of contaminated sites using plants and microbes. Using Life Cycle Assessment to evaluate five e-waste management strategies in Jordan, Ikhlayel (2017) found that landfilling was the least effective method, whereas an integrated approach involving recycling, energy recovery from incineration, and residue landfilling was particularly effective, especially for managing mobile phone waste.

The study conducted by Sajid et al. (2019) aimed to quantify the e-waste inventory in Pakistan and evaluate its generation (both domestic and imported) as well as recycling practices. The focus was on the most imported e-waste items like desktop computers, laptops, monitors, and LCD units. Their findings revealed that an estimated 50 kilotons of e-waste were being imported as scrap annually, in addition to the approximately 38 kilotons generated domestically. The study also uncovered that e-waste processing in the country was conducted in a crude and unsafe manner. Based on these findings, the authors strongly recommended immediate and effective oversight and regulation of informal e-waste management in Pakistan.

Duman et al. (2019) introduced a novel method for predicting e-waste accumulation, which is rapidly increasing in the U.S. They used a nonlinear grey Bernoulli model with convolution integral enhanced by Particle Swarm Optimization (PSO), to forecast e-waste. They found this model to be more accurate than other methods, particularly when the available historical data is limited. The study revealed that population density significantly affects e-waste generation, followed by household income level. The researchers also found that e-waste distribution in Washington State appears to be reaching saturation.

Shaikh et al. (2020) investigated e-waste production and disposal in Pakistan, one of the top global producers. They identified consumer behaviour, such as a preference for cheap, low-quality goods, and the lack of proper disposal options as significant contributors to the problem. The study suggested implementing a formal e-waste collection and recycling system to help manage this growing issue.

Arya and Kumar (2020) investigated the challenges and potential solutions related to e-waste management, with a focus on the situation in developing countries like India. They found that while developed countries have robust e-waste management systems, developing nations struggle due to issues like inadequate data, illegal dumping, and lack of treatment options. The authors proposed strategies for India, including eco-product design, circular resource management, extended producer responsibility, and bioleaching, among others. They emphasized the importance of formalizing the informal recycling sector.

Adanu et al. (2020) advocated for a holistic approach that encompasses a broad understanding of peripheral technologies, an assessment of economic and societal implications, a strong focus on environmental sustainability, and a comprehensive effort to raise and maintain consumer awareness. Gollakota et al. (2020) investigated the global implications of waste from electronic and electrical equipment (WEEE) and suggested adopting more environmentally friendly and innovative technologies and practices. Examples include chelation, ionic liquids, hybrid technologies, micro factories, photocatalysis, and green adsorption. Ismail and Hanafiah (2020) carried out a comprehensive review and analysis of existing research on sustainable e-waste management. They found a significant increase in research but identified limitations including a lack of studies based on countries of origin, inconsistencies in research subjects and levels of analysis, and a dearth of comprehensive, up-to-date reviews of methodologies. They also noted that evaluations of emerging or older technologies in electronic appliances were often overlooked. Based on these findings, they made recommendations for future research.

Amalia et al. (2021) carried out a detailed analysis of the growth and public perception of e-waste in Indonesia. Through forecasting and surveys, the researchers found that e-waste in Indonesia is consistently increasing annually, with public awareness of the dangers of e-waste concurrently growing. Sahle-Demessie et al. (2021) investigated the use of pyrolysis for the sustainable management of e-waste. Their findings indicated that this technique successfully recovered valuable materials, including critical metals, from e-waste. However, the process also resulted in environmental concerns due to the release of particulate matter and pollutants. Notably, a high level of lead was found in the PCBs leachate, significantly exceeding toxicity limits. This research underscores the importance of developing sustainable e-waste recycling alternatives that effectively recover materials while mitigating environmental health risks.

Rautela et al. (2021) thoroughly assessed the issues related to electronic waste (e-waste) management. The authors identified key challenges such as insufficient technical skills, inadequate infrastructure, limited financial support, and minimal community engagement. The authors found that these problems often led to improper e-waste recycling, potentially harming human health and the environment. To tackle these issues, they proposed an inventory of end-of-life electronic products within an eco-friendly recycling regime. This approach was designed for both developed and developing countries to better manage their e-waste.

Alaskar et al. (2022) examined the global problem of electronic waste (e-waste) generated primarily by the Information and Communication Technology (ICT) sector. The researchers identified significant challenges in the current e-waste management, including poorly defined regulations, untrained waste handlers, high costs, inadequate coordination among key stakeholders, and dominance of the informal sector. The study provided insight into existing management strategies and suggested sustainable solutions for the ICT sector's e-waste problem.

More recently, Ghulam and Abushammala (2023) extensively investigated the burgeoning issue of electronic waste (e-waste), its harmful impacts on human health and the environment, and the significance of its proper management. They explored the lifecycle of electronics, from production to disposal, underscoring the environmental repercussions of mining and disposal practices. The researchers highlighted practical, sustainable solutions for e-waste management, emphasizing the importance of governmental regulations to ensure compliance.

Despite the considerable body of research addressing the environmental ramifications of electronic waste (e-waste), there is a notable dearth of investigations explicitly elucidating the relationship between the increasing accumulation of e-waste and climate change. Consequently, this study engages in a comprehensive examination of the potential climate change implications inherent in e-waste proliferation, along with strategizing sustainable management approaches for this escalating issue.

Results and discussion

The climate change implications of E-waste

Climate change, the long-term alteration in average weather patterns, poses a profound and complex challenge that continues to shape our planet (Abbass et al. 2022). E-waste, one of the fastest-growing waste streams worldwide, surprisingly has significant yet under-appreciated impacts on climate change, through various direct and indirect mechanisms (Singh and Ogunseitan 2022). This section aims to elaborate on the multifaceted ways in which e-waste contributes to climate change.

To begin with, the direct contribution of e-waste to climate change is associated with the generation of potent greenhouse gases (GHGs) during the improper management of e-waste. In many regions, inappropriate handling methods such as unregulated landfill disposal and open burning of e-waste are prevalent (Maes and Preston-Whyte 2022). These practices accelerate the release of greenhouse gases into the atmosphere, thereby directly contributing to global warming.

When electronic waste is openly incinerated, which unfortunately is a common practice in many developing countries due to a lack of resources for proper disposal methods, it releases harmful gases into the atmosphere (Abalansa et al. 2021; Ghulam and Abushammala 2023; Moyen Massa and Archodoulaki 2023). This includes carbon dioxide (CO_2) and methane (CH_4), both potent GHGs. It is estimated that one metric tonne of circuit boards can contain up to 40 to 800 times the concentration of gold ores mined in the United States (Cho 2018). This density of precious metal combined with the burning process can generate significant volumes of GHGs. Furthermore, refrigerants and insulating foams from waste electronic and electrical equipment (WEEE) contain hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which are potent GHGs. If not properly managed, they are released into the atmosphere during the disposal phase (Castro et al. 2021).

Moreover, the leachate from the landfill sites where e-waste is commonly dumped often contains high levels of organic matter (Saha et al. 2021). The decomposition of this organic matter by microbes in the absence of oxygen (anaerobic decomposition) results in the generation of methane, a greenhouse gas 28 times more potent than carbon dioxide in terms of its heat-trapping capacity (United States Environmental Protection Agency 2023). Landfills contribute about 14% of human-induced methane emissions globally (Global Methane Initiative 2011). Thus, the landfilling of e-waste represents a significant source of GHG emissions, directly linking e-waste management with climate change.

Beyond these direct emissions, e-waste indirectly contributes to climate change through its influence on the demand for energy and natural resources. The extraction and refining of metals for electronic goods is a highly energy-intensive process, primarily reliant on the combustion of fossil fuels. According to the United States Environmental Protection Agency (2016), the recycling of metals is generally far less energy-intensive, with recycled aluminium, copper, and steel requiring 90%, 85%, and 74% less energy than their virgin counterparts, respectively.

With a burgeoning demand for electronic goods and the average lifespan of these devices becoming shorter, the constant need for new devices drives the extraction of virgin metals, thus indirectly contributing to higher energy consumption and associated GHG emissions. It's estimated that approximately 80% of the emissions over the life-cycle of a computer, for example, are incurred during the manufacturing stage (TCO Certified 2022), highlighting the significant carbon footprint associated with the production of new electronic goods.

However, a significant proportion of e-waste consists of these valuable and rare metals. The Urban Mine Platform estimates that the existing e-waste stockpile contains approximately 7% of the world's gold (Kumar et al. 2017). Despite this potential gold mine, the global rate of e-waste recycling is dismally low. The Global E-waste Monitor 2020 estimates that only 17.4% of e-waste generated in 2019 was officially documented as properly collected and recycled (Forti et al. 2020). This poor recycling rate means that most of these valuable metals are lost, which not only represents a significant economic opportunity cost but also drives further demand for the energy-intensive extraction of virgin metals.

Furthermore, the informal processing of e-waste, prevalent in developing countries, often involves rudimentary techniques (Ikhlayel 2018). These practices not only pose significant health risks to the workers involved but are also inefficient at extracting the valuable metals contained within e-waste. This inefficiency means that the potential for e-waste recycling to offset the demand for virgin metal extraction, and the associated energy consumption and emissions, is not fully realized.

In addition to these lost opportunities for energy savings, the inadequate management of e-waste also means that other harmful substances contained within e-waste, such as heavy metals and brominated flame retardants, are often released into the environment. Although these substances do not directly contribute to climate change, they pose significant environmental and health risks (Maia et al. 2020). Moreover, the release of these substances can disrupt ecosystems and biodiversity, which can indirectly exacerbate climate change impacts by compromising the resilience of these systems to climate change and their capacity to act as carbon sinks.

Categorically speaking, the improper management of e-waste represents a significant and growing source of GHG emissions, thereby directly contributing to climate change. In addition, the inadequate recycling of e-waste indirectly contributes to climate change by driving higher energy consumption and associated emissions from the production of new electronic goods. The comprehensive management of e-waste, therefore, represents a significant opportunity for climate change mitigation, by reducing direct emissions from e-waste disposal and indirectly through energy savings from the recycling of valuable metals.

Current management strategies of e-waste

As the mounting tide of e-waste becomes an increasingly pressing global environmental issue, understanding and refining the strategies we utilize to manage this waste is essential. These strategies, vastly differing in their approach and efficiency, can be largely divided into three categories: formal recycling, informal recycling, and disposal methods such as landfilling and incineration. Each presents its own unique benefits and drawbacks, and while they all play a role in our global management of e-waste, each also reveals critical gaps that hinder their ability to completely address the escalating issue of e-waste.

Formal recycling

At the apex of environmentally friendly e-waste management lies formal recycling. Governed and regulated by institutional or governmental bodies, formal recycling involves a systematic approach to e-waste management. E-waste is methodically collected, then processed to recover valuable materials, all within an environmentally safe and friendly context (Rautela et al. 2021).

Not only does this approach aim to extract and recycle materials from the waste stream, but it also aims to minimize the disposal of hazardous waste, promoting a more sustainable usage of electronics. However, this practice faces significant challenges. The high cost and technical complexity associated with the recycling of certain types of e-waste, such as photovoltaic panels and flat-panel displays, can make it a less viable option.

Moreover, despite the strong regulatory framework in place for formal recycling, it suffers from low efficiency in e-waste collection. It is estimated that only about 20% of the world's e-waste is collected formally (Jain et al. 2023), leaving a substantial amount of e-waste to either land in landfills or be processed through informal recycling, which carries its own environmental implications.

Informal recycling

In stark contrast to formal recycling stands the informal sector. Predominantly found in developing countries, this type of recycling, outside the bounds of formal regulation, often employs rudimentary methods to extract valuable materials from e-waste. While this sector provides an income for many individuals, its methods are far from environmentally friendly or safe.

Informal recycling often involves hazardous practices such as acid leaching and open burning (Cesaro et al. 2019; Okwu et al. 2022). These practices result in the release of harmful pollutants into the environment, including persistent organic pollutants and heavy metals (Ghulam and Abushammala 2023). Furthermore, the methods used in informal recycling often fail to recover valuable materials efficiently, leading to significant resource loss (Abalansa et al. 2021).

Disposal

Where recycling—formal or informal—is not an option, e-waste often ends up being discarded in landfills or incinerated. Landfills, although cost-effective and straightforward, pose a significant environmental risk (Siddiqua et al. 2022). Hazardous substances from e-waste can leach into the environment, contaminating the soil and groundwater (Gupta and Nath 2020). Incineration can lead to toxic emissions being released into the atmosphere, contributing to air pollution and exacerbating climate change (National Research Council Committee on Health Effects of Waste Incineration 2000).

Critical gaps in current practices

E-waste management, as it currently stands, reveals several critical gaps. The lack of a comprehensive global regulation leads to the frequent movement of e-waste across borders. This is often from developed to developing countries, contributing to the environmental burden in these developing nations (Abalansa et al. 2021). In the process, it undermines the development of effective e-waste management strategies in the countries that are the source of the e-waste.

Current e-waste management practices also often fail to incorporate the principles of circular economy. The ideal is to design products for longevity, ease of repair, and recyclability. Instead, the current approach leads to a 'take-make-dispose' pattern, which only further drives the generation of e-waste (Morseletto 2020).

Another significant gap lies in the lack of public awareness and participation in e-waste management. Consumers often lack the necessary information for proper e-waste disposal, which hinders the effectiveness of recycling and collection efforts (Almulhim 2022).

It is therefore our stand that, while the current strategies for e-waste management have made some strides in addressing this growing issue, they fall significantly short of providing a comprehensive solution. The existing gaps in our approach, from regulatory shortcomings to a lack of circularity and public engagement, underscore the urgent need for a reimagining of how we manage e-waste. As we move forward, it is crucial that we consider these gaps in our strategies and work towards more sustainable and effective e-waste management solutions.

Strategies for sustainable management of E-waste

Addressing the challenges posed by e-waste requires an integrated approach encompassing multiple strategies that includes legislative measures, green design, sustainable recycling, consumer awareness, and international cooperation.

Regulatory and legislative measures

A strong and well-enforced legislative framework is crucial to ensure that e-waste is dealt with appropriately. This includes regulations that enforce proper disposal of e-waste and prevent its illegal export. E-waste management policies should provide incentives for recycling and reuse, enforce producer responsibility, and set standards for environmentally sound management practices. Legislation should also encourage the formalization of the informal recycling sector, which often employs hazardous recycling practices. The European Union's WEEE Directive 2012, which holds producers responsible for the disposal of their electronic products (European Parliament and Council 2012), is an example of such regulation. However, implementing such regulations globally is a challenge due to differences in economic development, technological capacity, and legal frameworks among countries.

Eco-design and reduction of hazardous substances

Eco-design involves designing electronic products in a way that they have a minimal environmental impact throughout their life cycle (Navajas et al. 2017). This includes using less energy, reducing the use of hazardous substances, designing for durability, reparability and upgradability, and ease of disassembly for recycling (Envirowise 2001). The reduction of hazardous substances in electronic equipment would not only make recycling safer but also more profitable. The European Union's Restriction of Hazardous Substances (RoHS) Directive 2012, which restricts the use of certain hazardous substances in electrical and electronic equipment (European Commission 2012), is a step in this direction.

Sustainable recycling and recovery of precious metals

Improving e-waste recycling technologies and infrastructure is critical for efficient resource recovery and reduction of environmental pollution. Currently, only a small fraction of e-waste is recycled in an environmentally sound manner. More investment and research are needed to develop technologies that can economically recover valuable and critical metals from e-waste. Moreover, creating safe recycling facilities globally could provide job opportunities, contributing to sustainable economic development.

Consumer awareness and education

Public awareness campaigns and education are crucial to change consumer behaviour regarding e-waste. Consumers should be educated about the environmental and health impacts of improper e-waste disposal, the importance of recycling, and how to properly dispose of their electronic waste. E-waste collection events and take-back programmes can also encourage consumers to recycle their e-waste.

International cooperation

Given the trans-boundary nature of e-waste, international cooperation is essential to address this challenge. This includes sharing best practices, harmonizing legislation, providing technical assistance to developing countries, and monitoring international e-waste flows to prevent illegal trade. The Basel Convention on the Control of Trans-boundary Movements of Hazardous Wastes and Their Disposal 1989 (United Nations Environment Programme 1992) is an example of an international treaty aimed at reducing the movement of hazardous waste between nations.

While these strategies provide a comprehensive approach to e-waste management, their successful implementation will require overcoming significant challenges. These include the fast pace of technological change, lack of financial resources and technical capacity in many countries, and difficulties in changing consumer behavior. However, the benefits of sustainable e-waste management—including climate change mitigation, resource conservation, economic development, and improved health outcomes—make it a goal worth pursuing.

Moving forward, it is critical to recognize e-waste not just as a waste management issue, but as a significant facet of the broader sustainability challenge. This means treating e-waste management not as an end-of-pipe solution, but integrating it into our strategies for sustainable consumption and production. As we move towards a circular economy, where the value of products and materials is maintained for as long as possible, sustainable e-waste management will play an increasingly important role.

In a nutshell, addressing the e-waste challenge requires a holistic approach, combining strong policy measures, technological innovation, consumer awareness, and international cooperation. Only by doing so can we hope to turn the tide on the rising tide of e-waste, and its detrimental impact on our climate and our health.

Conclusions

In conclusion, the escalating challenge of e-waste management is intricately linked with the broader sustainability and climate change crisis that our planet is grappling with today. The environmental and health impacts, coupled with the lost economic opportunities from mishandling e-waste, underscore the pressing need for comprehensive and innovative approaches towards its management. This multifaceted issue demands strategies that go beyond the confines of traditional waste management. Regulatory and legislative measures, eco-design, enhanced recycling technologies, heightened consumer awareness, and robust international cooperation must work in synergy to alleviate the e-waste problem. Recognizing e-waste as not merely a waste management issue, but as an opportunity for resource conservation, climate change mitigation, and sustainable economic development, is crucial in this respect. The transformation towards a circular economy, where waste is minimized and the value of products and materials is maintained for as long as possible, necessitates the integration of sustainable e-waste management practices. By viewing and treating e-waste through the lens of sustainability, we can hope to mitigate its negative impacts while harnessing its potential benefits for a more sustainable and resilient world. This comprehensive approach to the e-waste problem will indeed present its own challenges, ranging from the pace of technological change and financial constraints, to the modification of consumer behavior. However, the multifaceted benefits that sustainable e-waste management can bring—climate change mitigation, resource conservation, economic development, and improved health and environmental outcomes—are compelling reasons for overcoming these obstacles. By taking decisive action on e-waste, we can contribute significantly to the broader fight against climate change, further underscoring the interconnectedness of global environmental issues and the need for integrated solutions.

Abbreviations

CC	Climate change
CE	Circular economy
CH4	Methane
CCI	Climate change implications
CMS	Current management strategies
CO_2	Carbon dioxide
EPA	Environmental protection agency
EWD	E-waste disposal
EWG	E-waste generation
EWI	E-waste inventory
EWM	E-waste management
EWP	E-waste processing
EWR	E-waste recycling
EWS	E-waste stockpile
e-waste	Electronic waste
EU	European union
GE	Global estimate
GEM	Global e-waste monitor
GESP	The global E-waste statistics partnership
GHG	Greenhouse gases
GHGs	Greenhouse gases
GMI	Global methane initiative
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
ICT	Information and communication technology
ISS	International space station
IT	Information technology
LCA	Life cycle assessment
LCD	Liquid crystal display
LED	Light emitting diode
PCBs	Printed circuit boards
PSO	Particle swarm optimization
RT	Recycling technologies
TCO	Total cost of ownership
U.S.	United states
U.S. EPA	United states environmental protection agency
UN	United nations
UNEP	United nations environment programme
UMP	Urban mine platform
WEEE	Waste electrical and electronic equipment
WEF	World economic forum

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Author contributions
AAF: Played a pivotal role in the study design and conceptualization. AAF led the analysis of existing literature regarding the e-waste problem in the context of climate change and had a significant role in writing the initial draft of the manuscript. OFO: Conducted a critical review of current e-waste management strategies within existing literature, identified their gaps, and participated actively in manuscript writing and revision. OFO also led the synthesis of proposed solutions, focusing particularly on literature regarding innovative recycling technologies. NNE: Was responsible for significant research and compilation of relevant literature. NNE also contributed to the manuscript writing and proposed solutions, with a special focus on regulatory actions documented in previous studies. DREE: Provided project leadership and oversight, contributed to the review's conceptualization, design, and interpretation of existing literature, and played a substantial role in manuscript writing and revision. DREE led the discussion on the broader implications of the findings, connecting them to the larger fight against climate change and pursuit of sustainable development. All authors have read and approved the manuscript.

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Author details
[1]Eko City College of Management and Technology, Lagos, Nigeria. [2]Bristow Helicopters Nigeria Limited, ExxonMobil Qua Iboe Terminal, Eket, Akwa Ibom State, Nigeria. [3]Centre for Occupational Health, Safety and Environment (COHSE), Faculty of Engineering, University of Port Harcourt, Choba, Rivers State, Nigeria. [4]FieldCore Canada, Part of GE Vernova, Edmonton, Canada. [5]Department of Mechanical and Aerospace Engineering, The Ohio State University, Columbus, OH, USA. [6]Department of Mechanical Engineering, Durban University of Technology, Durban, South Africa.

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