



## Charting a Resilient Future: Climate Change as a Catalyst for Sustainable National Development

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### INNOVATIVE TECHNOLOGIES AND CIRCULAR ECONOMY STRATEGIES FOR SUSTAINABLE WASTE MANAGEMENT IN NIGERIAN URBAN CENTERS

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#### Abstract

*Rapid urbanization in Nigeria has intensified the challenges of municipal solid waste management, contributing to environmental degradation, public health risks, and greenhouse gas emissions. Traditional linear waste management approaches characterized by 'take-make-dispose' have proven inadequate to address the growing waste volumes and complexities in Nigerian urban centers. 1). This paper examines the potential of emerging technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain, to support circular economy strategies, that aim to reduce waste generation and enhance recycling. 2). Relying on secondary sources and case studies within Nigeria and comparable cities across the world, this study applies thematic analysis to identify technological interventions that foster circularity in waste management systems. 3). Findings reveal that while pilot projects employing smart bins, AI-enabled sorting, and blockchain-based traceability are still in pilot stage. The widespread expectation in its adoption would be hindered by infrastructural deficits, regulatory gaps, and limited stakeholder engagement. The paper argues for integrated policy frameworks that incentivize technological innovation aligned with circular economy principles, supported by capacity building among municipal authorities and communities. In advancing these technologies within a circular economy context, Nigerian urban centers can move towards sustainable waste systems that reduce environmental impact, create economic opportunities, and contribute to climate change mitigation. This research contributes to sustainability transitions literature by elucidating the nexus between cutting-edge technology and circularity in developing urban contexts.*

**Keywords:** Circular Economy, Climate Change, Sustainability, Waste Management

## 1.0 INTRODUCTION

### 1.1 Background

Nigeria's urban centers are undergoing a phase of rapid growth, with cities such as Lagos, Abuja, and Port Harcourt grappling with an expanding solid waste crisis. This urbanization surge, while contributing to economic growth and infrastructure development, presents a significant challenge in the area of waste management. According to Aliyu & Amadu (2017), Binafeigha & Enwin (2017), and Debrah et al. (2021), this exponential urban growth correlates with an alarming increase in waste generation, which outpaces the capacity of existing waste management systems.

The scale of waste generation is evident in the Nigerian Urban Development Report (UN-Habitat, 2020), which forecasts a dramatic rise in solid waste output. In 2019, Nigeria's urban centers generated around 66,826 tonnes per day (TPD), with projections indicating this will nearly double to 125,473 TPD by 2040. This surge reflects a population growth from 106 million to 199 million people. However, while waste generation is rapidly increasing, waste collection infrastructure lags behind, with only 41% to 46% of urban waste being collected, though efforts to improve the system project an increase to 60% by 2025. The low collection rate highlights a critical gap between waste generation and the capacity of urban waste management services to cope effectively.

The prevalence of plastic waste exacerbates this challenge, comprising approximately 10% of the collected waste. Inadequate waste collection in informal settlements and less visible urban areas further compounds the issue, leading to unsightly and hazardous waste accumulation. This often results in blocked water channels, which in turn causes flooding, a recurring issue in major Nigerian cities. As Ezeudu, Tenebe, & Ujah (2024) point out, these environmental challenges are not only a nuisance but also a breeding ground for vector-borne diseases and a catalyst for further environmental degradation. The mismanagement of waste also leads to an increase in greenhouse gas emissions, intensifying the threat of climate change and undermining efforts toward sustainable urban development (World Bank, 2012; Idowu et al., 2020).

Traditional waste management practices in Nigeria follow a linear model, where waste is simply discarded and usually ends up in landfills or open dumpsites, with little regard for recycling or reuse. The linearity of this system, as opposed to a circular one, is directly linked to the rapid rise in waste volumes. Lagos, for instance, generates about 13,000 metric tons of waste daily, but only 30-70% of this waste is effectively managed (World Bank, 2024). Much of the remaining waste is abandoned in public spaces, clogging drainage systems and water bodies, further exacerbating environmental and public health issues. As projections suggest, by 2030, Lagos will produce around 17,300 tons of waste per day, an increase of 33% from the present level, putting immense pressure on the already strained infrastructure.

The continued reliance on linear waste systems in Nigerian cities is starkly at odds with the principles of a circular economy, which emphasizes the reduction of waste, recovery of resources, and the establishment of closed-loop material cycles (Velenturf & Purnell, 2021). Instead of discarding materials at the end of their useful life, a circular economy model would advocate for recycling, reuse, and redesigning products to minimize waste production. The failure to adopt such a model in Nigeria results in unsustainable practices, whereby valuable resources are wasted, and environmental harm is intensified. The absence of a robust recycling infrastructure and systemic challenges, such as insufficient funding and limited awareness about circular economy principles, contribute to this persistent issue.

Ultimately, the inability to implement a circular economy framework in Nigerian urban waste management reflects deeper systemic failures, including political will, funding, and policy enforcement. The current waste management model exacerbates public health issues, environmental pollution, and contributes to global warming all challenges that urgently need rethinking and reorientation toward more sustainable, circular, and resource-efficient solutions. The case of plastic waste, which remains a particular challenge, underscores the necessity of systemic change. It calls for a reimagined approach that goes beyond merely collecting waste and encourages recovery, reuse, and sustainable design at every stage of the product lifecycle. The consequences of maintaining the status quo are not just local environmental concerns but are indicative of a broader, unsustainable trajectory that will have long-term implications for Nigeria's urban future.

## **2.0 INNOVATIVE TECHNOLOGIES AND CIRCULAR ECONOMY**

Emerging technologies hold immense potential to revolutionize urban waste management systems, particularly in the context of Nigeria's rapid urbanization and growing waste management challenges. The integration of real-time data processing through Internet of Things (IoT)-based waste management systems offers a promising approach to optimizing waste collection. These systems continuously monitor waste levels in bins and adjust collection schedules accordingly, thus minimizing inefficiencies and operational costs (Lakhouit, 2025). Such smart solutions also reduce the risk of waste overflow, which is a persistent issue in Nigerian urban centers. However, despite the promise of IoT-based technologies, challenges persist, such as sensor inaccuracies and variations in waste packaging, which can lead to inefficiencies and hinder the overall system's effectiveness. These limitations highlight the need for careful calibration and system design to ensure the reliable operation of such technologies (Pardini et al., 2019; Wijaya et al., 2017).

Another critical technological advancement is the application of artificial intelligence (AI) in waste sorting. AI-driven systems are capable of automating the identification and separation of materials, significantly enhancing the efficiency and precision of recycling efforts. By leveraging image recognition, machine learning, and hyperspectral imaging, AI systems can accurately sort waste into distinct categories such as plastics, metals, and organic materials, thereby reducing contamination and improving recycling rates (Olawade et al., 2024; Chen et al., 2021). The application of AI within a circular economy framework aligns well with the need to optimize waste-to-resource transitions in Nigeria. AI-powered systems not only streamline waste management operations but also ensure that valuable resources are effectively recovered, contributing to the broader goals of sustainability and resource efficiency.

Moreover, blockchain technology plays a vital role in enhancing waste traceability, a critical aspect of effective waste management systems. By providing transparent and immutable records of waste movement from collection to recycling, blockchain fosters greater accountability and trust among stakeholders (Olawade et al., 2024). This transparency is essential for ensuring that waste is managed responsibly and in accordance with environmental standards. Blockchain's integration into waste management systems further strengthens the integrity of recycling processes and promotes stakeholder confidence in the sustainability of urban waste systems.

Together, these technologies: IoT, AI, and blockchain, form the backbone of an innovative waste management approach that can propel Nigeria toward more sustainable urbanization. Through incorporating these advanced systems into waste management practices, Nigeria can address the inefficiencies and limitations of traditional systems while significantly improving recycling rates, reducing waste volumes, and mitigating environmental impacts. The seamless integration of these technologies represents a shift toward a circular economy, where waste is not merely discarded but repurposed into valuable resources, thereby advancing Nigeria's climate change mitigation efforts and sustainable urbanization goals (Al Duhayyim, Al-Dosari, & Al-Qarni, 2022).

### **2.1 Problem Statement**

Despite the promising potential of technological innovations and circular economy principles in transforming waste management, Nigerian urban centers face substantial barriers that hinder their full implementation. Onungwe et al. (2023) highlight that, while pilot projects have shown success, challenges persist in integrating these technologies within existing urban waste systems. These challenges stem from limited funding, which restricts the scale-up of these innovative solutions, and the lack of technical expertise required to operate and maintain advanced systems. Additionally, regulatory frameworks remain weak, with inadequate enforcement mechanisms, allowing outdated waste management practices to persist (Obani et al., 2025).

Socio-cultural resistance further complicates the adoption of circular economy practices, as communities are often reluctant to embrace new methods that disrupt traditional waste disposal habits (Suleman et al., 2023). This resistance, combined with the absence of a comprehensive policy framework, exacerbates the difficulty in transitioning towards a more sustainable and resource-efficient waste management model. The resulting gap prevents Nigeria from effectively reducing waste-related emissions and optimizing resource recovery. The need for a holistic analysis that addresses the intersection of technology, circular economy strategies, and robust policy enforcement is critical to overcoming these challenges and realizing the potential benefits of innovative waste management in Nigeria's urban centers.

### **3.0 LITERATURE REVIEW**

#### **3.1 Waste Management Challenges in Nigerian Cities**

Nigerian urban waste management systems are plagued by significant fragmentation and inefficiencies, which hinder effective waste disposal and resource recovery. Research indicates that waste collection coverage remains low, with many areas in cities lacking proper waste management infrastructure (World Bank, 2024). A large portion of waste is still disposed of in open dumpsites, contributing to environmental pollution and health risks. This underlines the inefficiency of the current system, where waste is either left uncollected or improperly managed. Recycling efforts in Nigeria are also minimal, with a clear lack of formal infrastructure to support recycling operations, making it difficult to close the loop on waste and resource management (Idowu et al., 2024). Despite this, informal recycling sectors play a crucial role in mitigating waste accumulation, handling a significant portion of recyclable materials. However, these efforts remain largely unrecognized and unsupported by formal regulatory frameworks (Ogwueleka & B P, N, 2021). Informal recyclers, while contributing to waste reduction, face challenges such as inadequate technology, unsafe working conditions, and lack of integration into formal waste management systems. This gap further entrenches inefficiency, as the informal sector operates in isolation, without coordination or adequate support from government or formal waste management services.

#### **3.2 Emerging Technologies in Waste Management**

Emerging technologies are playing an increasingly significant role in transforming waste management practices, both globally and within Nigeria. Research on smart waste management systems shows promising advancements in the use of the Internet of Things (IoT), artificial intelligence (AI), and blockchain to optimize waste collection, improve recycling, and increase transparency. Ahmed et al. (2023) document the successful use of IoT in smart waste bins that monitor fill levels, allowing for optimized collection logistics. These systems use real-time data to adjust collection schedules, reducing unnecessary pickups and improving operational efficiency. Similarly, AI-driven sorting systems, using computer vision, have revolutionized material recovery by accurately identifying and separating recyclables. This increases the efficiency of recycling processes, reduces contamination, and ensures that more materials are diverted from landfills (Chattaraj et al., 2025; Chertow et al., 2024). Blockchain technology further enhances transparency in waste management systems by providing immutable records of waste tracking, which helps to prevent illegal dumping and promotes the establishment of circular supply chains (Bułkowska et al., 2023).

In Nigeria, emerging technologies have made notable strides, demonstrating their potential for advancing waste management within the context of the country's unique challenges. Lagos, the country's largest city, has led the way with its Cleaner Lagos Initiative, which integrates modern waste collection technologies alongside community participation programs. The initiative's dual approach combines technological innovations such as IoT-based smart bins with efforts to educate and engage the public about the

importance of waste segregation and recycling. According to Novatia Consulting (2024), this initiative has already yielded positive outcomes, improving urban cleanliness and fostering growing awareness among residents about sustainable waste management practices. The integration of technology has enhanced waste collection efficiency, and community engagement has promoted active participation, signaling the potential for these strategies to scale across other urban centers in Nigeria.

Lagos' efforts are complemented by smaller-scale but equally significant pilot projects in cities like Abuja. The introduction of smart waste bins in Lagos and blockchain waste tracking experiments in Abuja demonstrate the transformative potential of technology in managing urban waste. However, these initiatives also reveal significant infrastructural and institutional challenges that must be addressed to ensure long-term success. Nwokoro (2024) points out that while these projects showcase innovation, inadequate funding, inconsistent policy enforcement, and limited technological infrastructure present barriers to their sustainability. Despite these obstacles, they raised the importance of leveraging technology to address Nigeria's growing waste crisis.

Another promising initiative is occurring in Enugu, where local NGOs are driving a composting program aimed at diverting organic waste from landfills. Through partnerships with farmers and local households, these organizations have created a system that transforms food scraps into compost, benefiting both the environment and local agricultural productivity (Didigwu, 2023; Novatia Consulting, 2024). This initiative embodies a circular economy model, where waste is repurposed to create valuable resources, rather than being discarded. The composting project not only reduces the amount of organic waste in landfills but also improves soil fertility, thus supporting sustainable agriculture. This example highlights the potential for circular economy principles to be integrated into waste management systems in Nigeria, ensuring that waste reduction and resource recovery are prioritized.

In Port Harcourt, a recycling program focusing on plastic waste has achieved significant success through community participation. Local businesses and schools have partnered to incentivize the collection and recycling of plastic waste, with residents being rewarded for their participation. Novatia Consulting (2024) reports that this project has reduced plastic waste in the city, created employment opportunities for young people, and fostered local economic growth. The initiative has demonstrated that recycling can go beyond environmental benefits to create economic value, while also addressing the critical issue of plastic pollution. By involving local stakeholders in the recycling process, this program not only helps clean up the environment but also promotes community empowerment and job creation.

While these initiatives represent encouraging progress, they also highlight the obstacles that must be overcome for widespread implementation. Nigeria's waste management systems remain fragmented, with low levels of waste collection coverage, especially in informal settlements, and limited infrastructure to support recycling (World Bank, 2024; Idowu et al., 2024). Additionally, informal recycling sectors, which play a critical role in waste recovery, often operate without formal recognition or support (Ogwueleka & B P, N, 2021). These sectors lack the technology, infrastructure, and regulation that would allow them to operate more efficiently and safely. As Nwokoro (2024) emphasizes, successful integration of emerging technologies requires not only technological investment but also improvements in the policy framework, regulatory enforcement, and public awareness.

Thus, while Nigeria is making strides in integrating emerging technologies into its waste management systems, challenges related to infrastructure, regulation, and funding persist. Nevertheless, the examples from Lagos, Enugu, Port Harcourt, and Abuja demonstrate that technology, when paired with community involvement and a circular economy approach, holds great promise for addressing Nigeria's urban waste challenges. The key to advancing these initiatives lies in overcoming institutional and infrastructural barriers while ensuring that innovations are appropriately scaled to benefit the entire nation. By fostering

collaboration between technology developers, local governments, and communities, Nigeria can pave the way for more sustainable waste management practices that reduce pollution, promote recycling, and generate economic opportunities for its citizens.

### **3.3 Circular Economy Strategies**

Circular economy strategies focus on transforming traditional linear systems of production and consumption by emphasizing waste elimination through reuse, repair, and recycling. Awan & Sroufe (2023) and Ezeudu et al. (2023) highlight that a core principle of the circular economy is to create closed-loop systems where materials are continually reused, reducing reliance on raw resources and minimizing environmental impacts. These strategies not only improve waste management practices but also promote sustainability by encouraging the recovery of resources from waste streams.

In Nigeria, there is growing recognition of the need for circular economy principles, with policy frameworks beginning to reflect this shift. However, Bello et al. (2023) point out, significant implementation gaps persist, largely due to weak regulatory enforcement and a lack of effective coordination among key stakeholders. Despite the recognition of circular economy concepts in national and local policies, the transition from theory to practice remains slow. The absence of robust enforcement mechanisms and fragmented efforts across different levels of government hinder the widespread adoption of circular practices. This lack of coordinated action limits the potential of circular economy strategies to meaningfully address Nigeria's waste management and sustainability challenges.

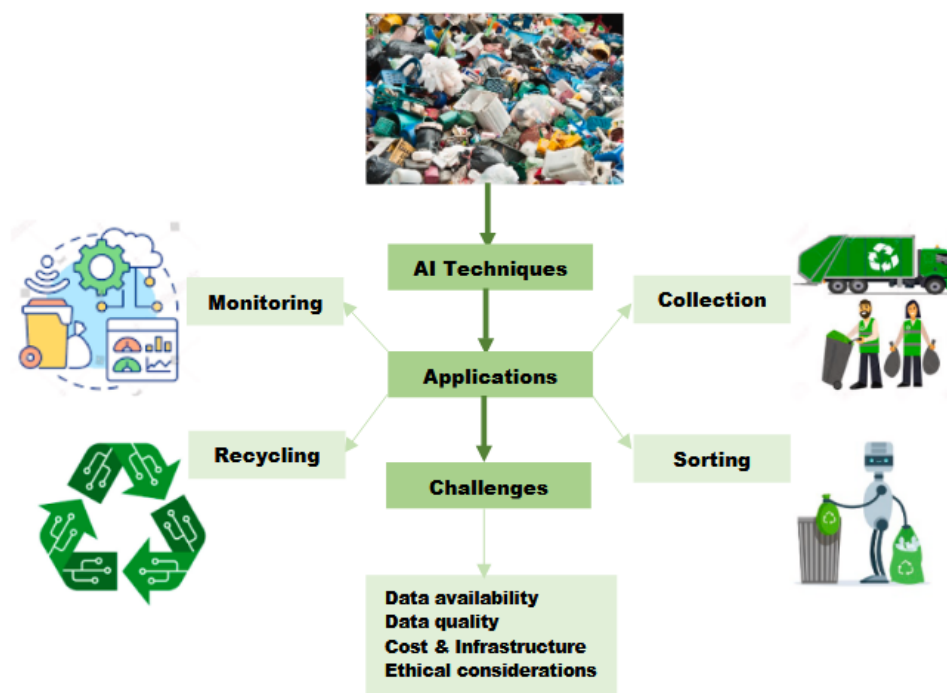
## **4.0 METHODOLOGY**

This study employs a qualitative thematic analysis of secondary data to explore waste management and circular economy practices in Nigerian urban centers. The data sources include Nigerian government policy documents and urban waste management reports, which provide insights into the formal regulatory framework and ongoing initiatives. Additionally, academic research articles sourced from Scopus and Web of Science databases focus on waste management technologies and circular economy approaches, offering a comparative perspective based on similar global contexts. Reports from international agencies such as UN-Habitat and the World Bank, along with input from Nigerian NGOs involved in urban sustainability, further enrich the analysis by offering an external view on the challenges and opportunities in the Nigerian context. Thematic coding involves systematically identifying key themes such as the application of emerging technologies, integration of circular economy principles, barriers to successful implementation, and factors that enable or hinder policy execution. In examining case studies of pilot technology applications in Nigerian cities, the study aims to understand both the practical challenges and the potential of innovative waste management solutions in real-world urban settings. The approach provides a comprehensive framework to assess how circular economy principles can be effectively integrated into Nigeria's urban waste systems

## **5.0 FINDINGS AND DISCUSSION**

- i. Technological Innovations:** The findings from the study highlight the growing potential of technological innovations in improving waste management systems in Nigerian urban centers. Emerging technologies such as IoT-enabled smart bins, AI-based sorting systems, and blockchain traceability have shown promise in enhancing various aspects of waste management, from efficiency in collection to improved material recovery and transparency. Olawade et al. (2024) emphasize that IoT-enabled smart bins, which monitor waste levels in real time, can optimize waste collection

schedules and reduce unnecessary collection trips. This reduces operational costs and prevents overflow, thereby improving urban cleanliness. Furthermore, AI sorting systems, particularly those using computer vision and machine learning algorithms, significantly enhance the efficiency of material recovery by accurately identifying and segregating recyclable materials. Gulyamov (2024) further supports this by highlighting how AI technology can reduce contamination in recycling processes, which is crucial for increasing recycling rates. Additionally, blockchain technology has been found to enhance the traceability of waste, ensuring transparent, secure tracking of waste from collection to disposal or recycling. This fosters accountability among stakeholders and discourages illegal dumping, which is a persistent challenge in many Nigerian cities. Overall, these technologies contribute to creating a more sustainable and efficient waste management system, though their full potential can only be realized with appropriate infrastructure and policy support. This has been illustrated on Figure 1 and Figure 2 to illustrate the application of AI so far in smart waste management initiatives.



**Figure 1: Artificial Intelligence and Application in Waste Management**

*Source: (Olawale et al, 2024)*



**Figure 2: AI and Use In Waste Recycling**

*Source: Olawale et al, (2024)*

- ii. **Circular Economy Implementation:** Nigeria’s policy frameworks, such as the National Policy on Waste Management and the Nigerian Circular Economy Roadmap (NCERM), reflect a growing commitment to integrating circular economy principles, focusing on sustainability, resource recovery, and waste reduction (Olagunju, 2024). However, the operationalization of these policies remains hindered by several systemic challenges. While there is an increasing recognition of the importance of digital transformation and the adoption of local technological innovations, the absence of clear accountability mechanisms impedes the full realization of circular economy objectives. As Bello et al. (2023) point out, weak regulatory enforcement and fragmented efforts between governmental bodies and private sector stakeholders contribute to the slow pace of implementation. This issue is further exacerbated by insufficient infrastructure, which limits the capacity to support circular economy practices, especially in waste recovery and recycling processes. The lack of a cohesive strategy for stakeholder collaboration particularly between public and private sectors also undermines the effectiveness of these policies. Strengthening governance structures is crucial to creating a framework for accountability and oversight, ensuring that all actors in the waste management sector are aligned with circular economy goals. Moreover, fostering stronger public-private sector partnerships would facilitate the necessary investment in infrastructure and technology, helping Nigeria unlock the full potential of the circular economy.
- iii. **Barriers:** The implementation of circular economy innovations in Nigeria faces several key barriers that hinder their effective scaling. One of the primary challenges is limited infrastructure, particularly in waste management systems, which is crucial for supporting technological solutions like recycling facilities or smart waste bins (Unegbu et al., 2025). The lack of technical expertise also significantly limits the ability to adopt and maintain advanced waste management technologies, with skilled

professionals in AI, IoT, and blockchain in short supply (Adesua-Lincoln, 2025). This knowledge gap prevents the proper integration of these technologies into existing waste systems. Furthermore, inadequate financing remains a persistent issue, with both government and private sectors struggling to secure the necessary funds to invest in infrastructure upgrades and innovation (Unegbu et al., 2025). Lastly, low awareness among stakeholders, including government bodies, businesses, and the general public, further impedes the adoption of circular economy principles. This lack of understanding reduces support for policy initiatives and public participation in waste management efforts, limiting the overall impact of technological advancements.

**iv. Policy and Institutional Gaps:** The adoption of a circular economy in Nigeria is significantly hindered by policy and institutional gaps, particularly in the coordination between municipal authorities, the private sector, and local communities. As Zuofa et al. (2022) posit, the lack of effective coordination among these stakeholders impedes the implementation of circular economy strategies. This disjointed approach is particularly evident in the relationship between federal and subnational governments, where the National Development Plan (NDP) 2021-2025 identifies a lack of synergy that weakens policy execution and limits the impact of national waste management and sustainability initiatives.

Furthermore, the involvement of the private sector in driving circular economy initiatives remains minimal. This is primarily due to insufficient incentives and the absence of clear frameworks for collaboration with both government and local communities. While Nigeria's environmental regulations outline waste management and sustainability goals, their implementation is hampered by weak enforcement mechanisms. This failure to ensure compliance reduces the effectiveness of policies designed to promote waste reduction, recycling, and resource recovery.

The ambiguity in the distribution of responsibilities between local and national entities also contributes to the inefficiencies in policy execution. Local governments, which are often closest to waste management challenges, lack the authority, resources, and support to implement circular economy practices effectively. Meanwhile, national entities tend to impose broad frameworks without providing sufficient practical guidance or funding for local governments to meet these mandates. As the Federal Republic of Nigeria (2021) points out, without clarity and proper coordination, the adoption of circular economy principles remains fragmented and underdeveloped, preventing meaningful progress in urban waste management and sustainability.

## **6.0 RECOMMENDATIONS**

To address the challenges in waste management and the adoption of circular economy principles in Nigeria, integrated policy measures are essential. These policies should first focus on incentivizing the adoption of advanced technologies, such as AI-based sorting systems, IoT-enabled smart waste bins, and waste-to-energy technologies. Offering subsidies, or grants to private companies and local governments could lower the financial barrier to adopting these innovations (Okafor et al., 2025). Furthermore, fostering capacity building is critical, as it would empower local government officials, waste management personnel, and private sector workers with the skills needed to effectively implement and maintain new technologies.

Stakeholder engagement is another crucial element. Policies must facilitate collaboration between municipal authorities, private sector entities, and local communities to ensure that all relevant stakeholders are actively involved in the planning and execution of waste management strategies. Public-private partnerships could be incentivized to create sustainable models for waste management (Rena et al., 2022). Public awareness campaigns are equally important, educating citizens about the benefits of

waste segregation, recycling, and circular economy principles. These campaigns should target urban populations, fostering a culture of sustainability and encouraging participation in waste reduction initiatives. Together, these measures can address Nigeria's waste management challenges and promote a more sustainable and circular economy.

## 7.0 CONCLUSION

This study highlights the transformative potential of emerging technologies such as IoT, AI, and blockchain in enhancing waste management systems and fostering the adoption of circular economy principles in Nigerian urban centers. The study offers a comprehensive analysis of both the opportunities and challenges surrounding these technologies, focusing on their integration into existing waste management frameworks. In examining pilot projects and existing technologies elsewhere, policy frameworks, and stakeholder engagement efforts, this work identifies key barriers including infrastructural deficits, weak regulatory enforcement, and socio-cultural resistance, all of which impede the full realization of a sustainable circular economy.

Furthermore, this research contributes to the broader sustainability literature by providing an in-depth analysis of the nexus between technology, policy, and circularity in a developing country context. It fills an important gap by highlighting the need for coordinated efforts across various sectors public, private, and local communities to facilitate the adoption of circular economy practices. The recommendations provided offer practical insights for policy makers, urban planners, and technology developers, making this study a valuable resource for researchers and practitioners seeking to address the pressing waste management challenges in Nigeria and similar urban settings globally.

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