

EMERGING TECHNOLOGIES FOR WASTE-TO-WEALTH TRANSFORMATION IN NIGERIA: A SYSTEMATIC REVIEW

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ABSTRACT

Rapid urbanization, industrialization, and population growth have significantly increased solid waste generation in Nigeria, creating major environmental, public health, and socioeconomic challenges. However, emerging technologies provide opportunities to convert waste into valuable resources while promoting sustainable development and circular economy practices. This systematic review was conducted following PRISMA 2020 guidelines, with literature published between 2012 and 2025 retrieved from Scopus, Web of Science, Google Scholar, African Journals Online, and relevant institutional websites. Eligible studies examined emerging technologies for waste management, recycling, resource recovery, the circular economy, and waste-to-energy systems, and 30 of them were synthesized using a narrative thematic approach. The review identified artificial intelligence, machine learning, the Internet of Things, blockchain, digital platforms, biotechnology, and waste-to-energy technologies as key drivers of waste-to-wealth transformation, improving waste segregation, recycling efficiency, resource recovery, operational performance, and environmental sustainability. However, widespread adoption remains constrained by inadequate infrastructure, limited funding, weak policy implementation, insufficient technical expertise, and poor institutional coordination. Overall, emerging technologies have significant potential to transform Nigeria's waste management sector by advancing resource recovery, green entrepreneurship, and the development of a circular economy. Strengthening policies, increasing strategic investments, building technical capacity, and fostering multi-sector collaboration are essential to overcome adoption barriers and achieve scalable, sustainable waste-to-wealth systems in Nigeria.

Keywords: Waste-to-wealth; Emerging technologies; Artificial intelligence; Circular economy; Waste management; Nigeria

INTRODUCTION

The rapid growth of urbanization, industrialization, and population has resulted in unprecedented increases in solid waste generation worldwide, posing significant environmental, public health, and socioeconomic challenges. According to Kaza et al. (2018), global municipal solid waste generation exceeded 2.24 billion tonnes annually and is projected to increase to approximately 3.40 billion tonnes by 2050 if sustainable waste management strategies are not implemented. Similarly, the World Bank (2023) emphasized that poor waste management continues to threaten environmental sustainability, particularly in developing countries where waste collection and disposal systems remain inadequate. In Nigeria, ineffective waste collection, indiscriminate dumping, open burning, and inadequate recycling infrastructure have contributed to environmental pollution, flooding, greenhouse gas emissions, and increased risks to public health (Abila & Kantola, 2013; Federal

Ministry of Environment, 2020).

Traditionally, waste has been regarded as an unwanted by-product to be disposed of. However, the emergence of the circular economy has transformed this perspective by recognizing waste as a valuable resource that can generate environmental, economic, and social benefits. Waste-to-wealth initiatives promote resource recovery through recycling, reuse, composting, waste-to-energy conversion, and material recovery, thereby creating employment opportunities, conserving natural resources, reducing environmental pollution, and supporting sustainable economic growth (Geissdoerfer et al., 2017; Murray et al., 2017). These approaches also contribute directly to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Recent technological innovations have significantly transformed waste management practices worldwide. Emerging technologies such as artificial intelligence (AI), machine learning, the Internet of Things (IoT), blockchain technology, robotics, cloud computing, big data analytics, biotechnology, and advanced waste-to-energy systems and mobile applications have enhanced waste segregation, recycling efficiency, real-time monitoring, predictive analytics, collection route optimization, and resource recovery (Abdallah et al., 2020; Bressanelli et al., 2018; Dawar et al., 2025). Furthermore, IoT-enabled smart waste bins, AI-powered sorting systems, blockchain-based material tracking, and digital platforms have demonstrated considerable potential to improve operational efficiency in sustainable waste management and to promote circular economy practices (Tahiri Alaoui et al., 2025; Zhang et al., 2023; Hassan, 2025).

Artificial intelligence has emerged as one of the most promising technologies for modern waste management by improving automated waste classification, recycling processes, forecasting waste generation, and optimizing collection systems (Abdallah et al., 2020; Idrovo-Hurel et al., 2025; Tsai et al., 2020). Likewise, blockchain technology enhances transparency, accountability, and traceability throughout recycling supply chains, thereby strengthening resource recovery and waste valorization (Khumalo & Moyo, 2022; Zhang et al., 2023). The integration of digital technologies with circular economy principles has therefore become a critical strategy for promoting sustainable waste-to-wealth systems (Bressanelli et al., 2018; Geissdoerfer et al., 2017). Nigeria generates millions of tonnes of municipal solid waste annually. However, a substantial proportion remains poorly collected, improperly managed, or disposed of through open dumping and uncontrolled landfilling, among other poor methods (Federal Ministry of Environment, 2020; Lagos State Waste Management Authority, 2021).

Several factors such as inadequate infrastructure, poor policy

implementation, insufficient funding, weak institutional capacity, and limited adoption of emerging technologies continue to constrain effective waste management across the country (Abila & Kantola, 2013; Ibrahim et al., 2022). Nevertheless, significant opportunities exist for transforming waste into valuable products through recycling, waste-to-energy technologies, electronic waste recovery, organic waste valorization, and circular economy initiatives (Nubi et al., 2022; Olujobi et al., 2022). These opportunities enhance job creation, resource recovery, a sustainable environment and economic development.

Recent evidence suggests that digital innovations such as mobile applications, AI, IoT, blockchain, and smart waste collection systems can improve recycling efficiency, increase public participation, enhance waste monitoring, reduce operational costs, and stimulate green entrepreneurship (Lawal et al., 2022; Sharma & Patel, 2021; Tahiri Alaoui et al., 2025). Moreover, policy reforms and strategic investments in emerging technologies are essential to achieving sustainable waste management and accelerating Nigeria's transition towards a circular economy (Onungwe et al., 2023; Abogunrin-Olafisoye et al., 2025).

Although numerous studies have investigated individual technologies such as AI, IoT, blockchain, waste-to-energy systems, and circular economy practices, the available evidence remains fragmented, with limited synthesis specifically examining how these emerging technologies collectively facilitate waste-to-wealth transformation in Nigeria. Consequently, there is a need for a comprehensive synthesis of the existing literature to identify the technologies currently applied, evaluate their effectiveness, examine implementation barriers, and highlight opportunities for future development.

Therefore, this systematic review aims to synthesize existing evidence on the role of emerging technologies in transforming waste-to-wealth initiatives in Nigeria. Specifically, the review examines emerging technologies used in waste management, evaluates their contributions to resource recovery and circular economy development, identifies barriers to technology adoption, and explores opportunities to scale sustainable, technology-driven waste-to-wealth systems.

MATERIALS AND METHODS

Study Design

This study employed a systematic review design to synthesize available evidence on the application of emerging technologies for waste-to-wealth transformation in Nigeria. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure methodological transparency and comprehensive reporting. The review focused on identifying, appraising, and synthesizing published evidence on technological innovations that support sustainable waste management, resource recovery, recycling, circular economy practices, and waste-to-energy initiatives.

Data Sources

A comprehensive literature search was conducted using the electronic databases: Scopus, Web of Science, Google Scholar, and African Journals Online (AJOL). To ensure comprehensive coverage of the available evidence, literature was also searched through the official websites of the World Bank, United Nations Environment Programme (UNEP), Federal Ministry of Environment (Nigeria), National Environmental Standards and Regulations

Enforcement Agency (NESREA), and the Lagos State Waste Management Authority (LAWMA). Reference lists of eligible articles were also manually screened to identify additional relevant studies that were not retrieved during the electronic database search.

Search Strategy and Search Terms

A comprehensive literature search was conducted to identify studies investigating emerging technologies for waste-to-wealth transformation in Nigeria. Searches were performed across the selected electronic databases for articles published between 2012 and 2025. The search strategy was tailored to each database's indexing requirements while maintaining consistency in core search concepts. Boolean operators (AND, OR) and quotation marks for phrase searching were employed to maximize the search's sensitivity and specificity.

The search strategy combined free-text keywords related to waste management, emerging technologies, resource recovery, and circular economy. The following search terms and their combinations were adapted as appropriate for each database.

"Waste-to-wealth" AND Nigeria, "Waste management" AND "emerging technologies", "Artificial intelligence" AND "waste management", "Machine learning" AND recycling, "Internet of Things" OR IoT AND "waste management", "Blockchain" AND "waste management", "Circular economy" AND Nigeria, "Waste-to-energy" AND "municipal solid waste", "Smart waste management", "Digital technologies" AND recycling, "Municipal solid waste" AND technology

Inclusion and Exclusion Criteria

Studies were selected based on the following predefined inclusion and exclusion criteria.

Inclusion Criteria: Studies were included if they:

1. were published between 2012 and 2025
2. were published in the English language
3. Investigated emerging technologies for waste management, waste-to-wealth transformation, recycling, resource recovery, circular economy, or waste-to-energy
4. Evaluated technologies such as artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), blockchain, digital platforms, biotechnology, robotics, or other innovative waste management technologies.
5. Focused on Nigeria or provided evidence relevant to Nigeria and other low- and middle-income countries.
6. Were peer-reviewed journal articles, systematic reviews, government reports, or publications from reputable international organizations

Exclusion Criteria: Studies were excluded if they:

1. Were published before 2012 or after 2025.
2. Were conference abstracts, editorials, letters, commentaries, theses, dissertations, or opinion papers.
3. Focused solely on conventional waste disposal methods without addressing emerging technologies or waste-to-wealth approaches.
4. Lacked sufficient methodological details or relevant outcome data.
5. Were duplicate publications.
6. Were published in languages other than English.

Screening and Selection Process

The literature search yielded a total of 100 records across all

electronic databases and institutional repositories. All retrieved records were exported into Mendeley Reference Manager, where duplicate publications were identified and removed. Following duplicate removal, 86 unique records remained for title and abstract screening.

The titles and abstracts were screened against the predefined inclusion and exclusion criteria. During this stage, 24 studies were excluded because they were not directly related to emerging technologies, waste-to-wealth transformation, circular economy, waste management, or the objectives of the review. Consequently, 52 studies were considered eligible for full-text assessment.

Full-text screening further excluded 22 articles due to insufficient methodological information, duplication of published findings, or failure to meet the eligibility criteria. Ultimately, 30 studies satisfied all the inclusion criteria and were included in the final qualitative synthesis.

The complete study selection process is presented using the PRISMA 2020 flow diagram in Figure 1

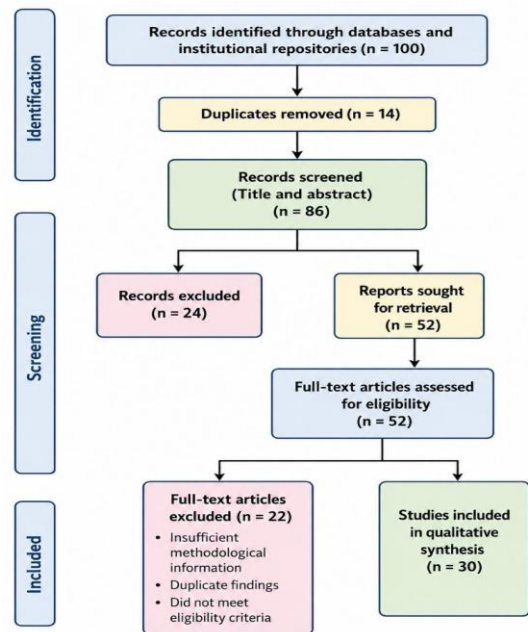


Figure1: Complete Study Selection Process

Data Extraction and Analysis

A standardized data extraction form was developed to ensure consistency across all included studies. Data were extracted independently from each eligible study and verified for accuracy. The extracted information included the first author's name, year of publication, country of study, study design, emerging technology investigated, waste type, study objectives, key findings, and conclusions relevant to waste-to-wealth transformation.

Following data extraction, a narrative synthesis approach was adopted due to the methodological heterogeneity among the included studies, particularly in study designs, evaluated technologies, outcome measures, and geographical settings. A meta-analysis was not performed due to the heterogeneity of the available evidence.

The extracted findings were synthesized thematically according to the major emerging technologies identified in the literature,

including artificial intelligence and machine learning, Internet of Things (IoT), blockchain technology, waste-to-energy technologies, digital platforms and mobile applications, electronic waste recycling technologies, circular economy approaches, and policy and institutional frameworks. Similarities, differences, implementation challenges, opportunities, and research gaps across the studies were identified and critically discussed to provide a comprehensive understanding of emerging technologies for waste-to-wealth transformation in Nigeria.

RESULTS

Characteristics of Included Studies

A total of 30 studies published between 2012 and 2025 were included in this systematic review. The studies comprised systematic reviews, literature reviews, case studies, experimental studies, life cycle assessments, government reports, technical reports, and policy documents. The included studies originated from Nigeria and several other countries, including South Africa, India, Rwanda, Taiwan, and multiple global studies, providing broad evidence on the application of emerging technologies in waste management.

The technologies investigated included artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), blockchain technology, waste-to-energy systems, mobile applications, digital platforms, advanced recycling technologies, biotechnology, and circular economy approaches. The waste streams addressed included municipal solid waste, electronic waste (e-waste), recyclable waste, industrial waste, organic waste, and mixed solid waste.

Overall, the studies consistently reported that emerging technologies improve waste collection efficiency, waste segregation, recycling performance, resource recovery, environmental sustainability, operational efficiency, and the implementation of the circular economy. However, several studies have also identified persistent barriers, including inadequate infrastructure, weak policy implementation, limited funding, insufficient digital capacity, poor stakeholder collaboration, and low technological adoption, particularly in developing countries such as Nigeria.

An Overview of the distribution of study designs among the included studies is presented in Figure 2.

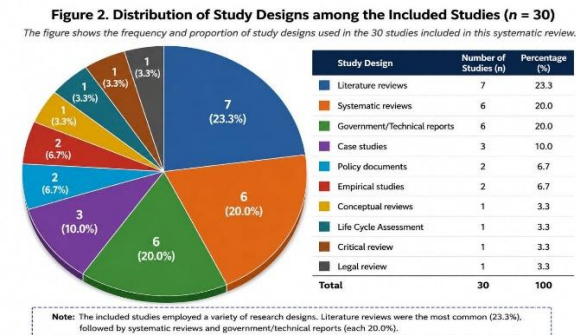


Figure 2: Distribution of Study Designs among the Included Studies (n=30)

Artificial Intelligence and Digital Technologies

The included studies identified several emerging technologies that have been applied to enhance waste management and support

waste-to-wealth initiatives in Nigeria. These technologies varied in their frequency of application and areas of focus. The distribution of the emerging technologies identified across the included studies is presented in Figure 3.

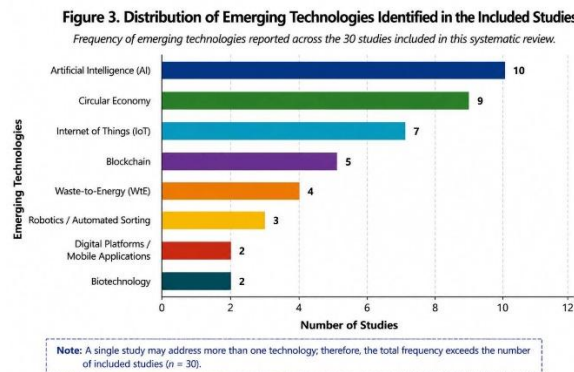


Figure 3: Distribution of Emerging Technologies Identified in the Included Studies

The reviewed studies identified artificial intelligence (AI) and other digital technologies as major drivers of waste-to-wealth transformation by improving the efficiency, accuracy, and sustainability of waste management systems. Across the included studies, AI was applied to waste generation forecasting, automated waste segregation, material classification, route optimization, landfill monitoring, recycling processes, and waste-to-energy systems, demonstrating its broad applicability throughout the waste management value chain (Abdallah et al., 2020; Dawar et al., 2025; Idrovo-Hurel et al., 2025).

Abdallah et al. (2020) reported Artificial Neural Networks (ANNs) as the most frequently applied AI technique, with applications ranging from waste generation prediction and automated waste sorting to recycling optimization, landfill management, and waste-to-energy operations. These findings demonstrate the growing global adoption of AI to improve operational efficiency and support data-driven decision-making in waste management.

Similarly, Dawar et al. (2025) reported rapid growth in the application of machine learning and deep learning algorithms for municipal solid waste management. The review identified Artificial Neural Networks (ANNs), Convolutional Neural Networks (CNNs), Support Vector Machines (SVMs), and Random Forest (RF) as the dominant algorithms used for waste prediction, waste classification, image recognition, and collection route optimization. Likewise, Idrovo-Hurel et al. (2025) reported a marked increase in publications on AI applications in urban waste management, indicating growing global interest in artificial technologies for waste forecasting, automated material classification, recycling optimization, and operational planning, among other benefits.

Beyond AI, the reviewed studies highlighted the growing contribution of other digital technologies to sustainable waste management. For instance, Bressanelli et al. (2018) found that Industry 4.0 technologies (the Internet of Things (IoT), cloud computing, and additive manufacturing) facilitate the implementation of the circular economy by improving resource efficiency, enabling real-time monitoring, and supporting intelligent decision-making. Similarly, the Ellen MacArthur Foundation (2019) reported that AI-enabled predictive maintenance, intelligent sorting systems, and resource optimization accelerate the transition

towards a circular economy by improving material recovery and reducing resource losses.

The findings further showed that integrating AI with complementary digital technologies such as IoT, blockchain, robotics, mobile applications, and digital twins enhances waste segregation, real-time monitoring, traceability, recycling efficiency, and operational performance across the waste management system (Hassan, 2025; Tahiri Alaoui et al., 2025; Khumalo & Moyo, 2022; Zhang et al., 2023; Lawal et al., 2022). There is a need to integrate digitalization into waste management by adopting artificial intelligence approaches (Lawal et al., 2022). These integrated technologies support more efficient resource recovery, improve service delivery, and strengthen circular economy practices.

Despite these technological advances, the reviewed studies consistently identified several barriers limiting implementation, particularly in developing countries. Ibrahim et al. (2022) reported that inadequate electricity supply, poor internet connectivity, insufficient digital infrastructure, and limited technical expertise significantly constrain the deployment of AI-enabled waste management systems in Nigeria.

Circular Economy and Resource Recovery

Several studies identified the circular economy as a fundamental framework for promoting sustainable waste-to-wealth transformation through waste reduction, reuse, recycling, remanufacturing, and resource recovery. The findings showed that adopting circular economy principles minimizes waste disposal, conserves natural resources, reduces environmental pollution, and creates economic opportunities by converting waste into valuable products (Geissdoerfer et al., 2017; Murray et al., 2017).

Global evidence highlights the increasing urgency of adopting circular economy strategies. Kaza et al. (2018) reported that the world generates approximately 2.01 billion tonnes of municipal solid waste annually, with projections indicating an increase to 3.40 billion tonnes by 2050, representing a 70% increase if current consumption patterns persist. The report further revealed that 33% of global waste is openly dumped, while high-income countries, representing only 16% of the world's population, generate approximately 34% of global waste. These findings emphasize the need to shift from the traditional linear economy to circular economy models that prioritize waste prevention and resource recovery.

Within the Nigerian context, Onungwe et al. (2023) found that the implementation of circular economy practices remains limited despite increasing awareness of their environmental and economic benefits. It identified inadequate infrastructure, weak policy implementation, limited financial investment, and poor stakeholder participation as major barriers hindering the transition towards a circular economy. The expected benefits of the circular economy may elude Nigeria until lingering problems are addressed.

Nzeadibe and Anyadike (2012) found that informal waste recyclers play a significant role in recovering recyclable materials and reducing waste disposal despite receiving limited institutional recognition and support. Similarly, Bakhiyi et al. (2021) reported that although electronic waste (e-waste) recycling contributes to resource recovery, informal recycling practices expose workers to hazardous heavy metals and toxic chemicals, increasing the risk of respiratory, neurological, and reproductive health disorders. These findings underscore the importance of formalizing recycling systems and strengthening occupational health and safety measures.

Emerging technologies were also found to support the

implementation of the circular economy. Digital technologies such as artificial intelligence, the Internet of Things, and cloud computing improve resource efficiency and facilitate circular production systems. (Bressanelli et al., 2018) Likewise, Abogunrin-Olafisoye et al. (2025) emphasized that integrating AI, IoT, robotics, and automated sorting technologies can significantly improve electronic waste recycling in Nigeria, while the United Nations Environment Programme (2020) highlighted Rwanda's establishment of one national e-waste recycling facility as an example of successful policy-driven circular economy implementation.

Overall, the reviewed evidence demonstrates that circular economy approaches, supported by technological innovation, effective recycling systems, and strong institutional frameworks, have considerable potential to enhance resource recovery, reduce environmental degradation, and promote sustainable waste-to-wealth transformation. However, achieving these benefits requires stronger policy implementation, increased investment, improved infrastructure, and greater stakeholder collaboration, particularly in developing countries such as Nigeria.

Mobile Applications and Waste Management

Digitalisation of waste management has enabled transformation from conventional collection systems towards technology-enabled approaches. This has helped to improve communication, monitoring, routing, recycling and citizen participation in waste management. Mobile applications have become an important component of smart waste management because they connect various actors in the system. A systematic review by Wirani et al. (2024) reported that mobile applications are used to monitor collection locations, locate disposal points, and communicate with waste services. Similarly, Onur et al. (2024), in their study on digital applications for waste recycling, reported a rapid expansion of web- and mobile-based applications.

In developed countries (USA, UK, Japan and Sweden), mobile applications are generally embedded within broader smart-city infrastructures involving geographic information systems (GIS) and the Internet of Things (IoT). For example, the European *Waste App* project incorporated geolocation and gamification. This helped to identify nearby recycling points and encourage household waste separation through rewards (Gabrielli et al., 2018). As a result, various job opportunities are created, and large quantities of electricity and energy are generated to support economic development.

Evidence from developing countries shows a similar technological transition. Many African countries have integrated mobile apps into their waste management systems. In Uganda, the *Yo-Waste* digital platform has been identified as an example of a mobile-enabled service. This connects households and businesses with waste collectors, enables collection requests and supports the generation of operational data to improve waste management.

In Nigeria, there is evidence of growing interest in mobile-enabled waste management. Ekwuaju and Okeke (2022), in their study on residents of Onitsha, found substantial exposure to mobile technologies. Mobile applications helped to connect residents with waste pickers and facilitate waste collection. In Enugu State, Ekwuaju and Okeke (2022) reported integrating mobile apps into waste management to improve waste collection and citizen participation. Hamzat et al. (2025) developed an IoT-enabled waste-management system incorporating an Android application. This is capable of monitoring bin levels and locations in near real time, with potential applications for municipal monitoring and

collection-route optimisation. Recent reviews similarly stress that smart waste management should not be understood merely as technological deployment. Successful systems require integration of technology with institutional arrangements, stakeholder participation, reliable data and appropriate policy frameworks (Alavi et al., 2024; Zoumpoulis et al., 2024).

Waste-to-Energy Technologies

The reviewed papers showed that waste-to-energy (WtE) technologies effectively convert municipal and organic waste into renewable energy while reducing environmental pollution and reliance on landfills. The evidence showed that integrating energy recovery with conventional waste management practices improves resource utilization and supports sustainable waste-to-wealth initiatives (Nubi et al., 2022; Olujobi et al., 2022). Improvements in resource recovery and the achievement of sustainable waste-to-wealth will surely enhance job creation, resource recovery and economic development.

The studies also reported that linking recycling to waste-to-energy technologies yields superior environmental performance compared with conventional waste disposal methods. In particular, life cycle assessment findings indicated that integrated recycling and waste-to-energy systems generated the lowest environmental burden among the four waste management scenarios evaluated, highlighting the environmental benefits of recovering energy from municipal solid waste (Nubi et al., 2022).

Nigeria possesses great potential for electricity generation from organic waste. For instance, Nigeria generated over 35,000 tonnes of municipal waste per day in 2024 (Alamu, 2025). This is enough to generate several kilowatts of electricity for distribution to the national grid. However, inadequate legal frameworks, weak institutional support, limited investment, and insufficient technological infrastructure continue to restrict the large-scale deployment of waste-to-energy technologies (Olujobi et al., 2022). Global evidence further reported the importance of adopting waste-to-energy solutions in response to increasing waste generation. Data from 217 countries and economies showed that approximately 2.01 billion tonnes of municipal solid waste are generated annually and are projected to increase to 3.40 billion tonnes by 2050, representing a 70% rise if current trends continue (Kaza et al., 2018). Similarly, the World Bank (2023) reported that global waste generation has already exceeded 2 billion tonnes per year, emphasizing the need for greater investment in sustainable waste management and energy recovery technologies. By doing so, the large quantity of waste will cease to be an environmental problem, while the energy generated will boost industrial and domestic activities.

Policy, Governance, and Implementation Challenges

Policy and institutional frameworks have consistently been identified as critical determinants of the successful adoption of emerging technologies for waste-to-wealth transformation. Although several national and state-level policies promote integrated waste management, recycling, and circular economy practices, implementation remains constrained by inadequate infrastructure, weak regulatory enforcement, limited financial investment, and insufficient institutional coordination (Federal Ministry of Environment, 2020; NESREA, 2021; Onungwe et al., 2023).

Evidence from the reviewed literature showed that Nigeria has established policy instruments to support sustainable waste

management. This includes the National Policy on Solid Waste Management and environmental regulations that encourage waste segregation, recycling, extended producer responsibility, and public-private partnerships (Federal Ministry of Environment, 2020; NESREA, 2021). At the sub-national level, the Lagos State Waste Management Authority reported that Lagos alone generates approximately 13,000–14,000 tonnes of municipal solid waste daily, highlighting the urgent need for improved waste collection, segregation, recycling, and resource recovery systems (LAWMA, 2021).

Despite these policy initiatives, the studies consistently reported significant implementation challenges. Poor waste governance, inadequate funding, limited technical capacity, weak enforcement of environmental regulations, and insufficient digital infrastructure continue to hinder the effective deployment of emerging technologies for waste management (Abila & Kantola, 2013; Adeyemi et al., 2016; Ibrahim et al., 2022). In addition, limited stakeholder collaboration and low investment in digital innovation were identified as major barriers to scaling waste-to-wealth initiatives across the country (Onungwe et al., 2023).

DISCUSSION

Emerging Technologies as Drivers of Waste-to-Wealth Transformation

The evidence from the reviewed studies indicates that emerging technologies are central to transforming waste management systems from linear disposal models to value-generating circular systems. Across contexts, artificial intelligence (AI), machine learning, Internet of Things (IoT), blockchain, robotics, and digital platforms were consistently identified as enabling technologies that enhance efficiency, transparency, and resource recovery in waste systems.

AI and machine learning applications are particularly influential in enabling predictive and automated systems for waste generation forecasting, route optimisation, and material classification. These capabilities reduce operational inefficiencies and improve decision-making across the waste value chain. Similarly, IoT-enabled sensors and smart devices facilitate real-time monitoring of waste levels, collection systems, and landfill operations, enabling more responsive, data-driven waste management strategies.

Blockchain technology contributes to waste-to-wealth systems by improving traceability and accountability in recycling supply chains, particularly by tracking recyclable materials and verifying waste transactions. Robotics and automated sorting systems further enhance the efficiency of material recovery facilities by improving the speed and accuracy of waste segregation.

Collectively, these technologies shift waste management from reactive systems to intelligent, data-driven infrastructures that prioritise resource recovery over disposal. This transition is fundamental to the waste-to-wealth paradigm, where waste is increasingly viewed as a secondary resource rather than a liability.

Opportunities and Challenges in the Adoption of Emerging Technologies

The findings demonstrate significant opportunities associated with adopting emerging technologies in waste management. Key benefits include improved operational efficiency, higher recycling rates, reduced environmental pollution, and new economic opportunities through resource recovery and secondary material markets. In addition, the integration of digital technologies supports job creation in green economy sectors such as digital waste

monitoring, recycling technologies, and waste logistics optimisation.

Despite these benefits, substantial barriers continue to limit widespread adoption, particularly in developing countries. A recurring challenge across the reviewed studies is inadequate infrastructure, unreliable electricity supply and weak digital connectivity. These constraints significantly limit the deployment of AI, IoT, and other digital systems that rely on stable energy and internet access.

Financial constraints also remain a major barrier, as many waste management authorities and municipalities lack the capital investment required to implement advanced technologies at scale. In addition, limited technical expertise and low digital literacy among waste sector stakeholders reduce the effectiveness of technology deployment.

Institutional and policy-related challenges further exacerbate these constraints. Weak regulatory enforcement, fragmented institutional responsibilities, and insufficient policy support for innovation create an enabling environment that is not yet conducive to large-scale technological adoption. Furthermore, low levels of stakeholder collaboration among government, private-sector actors, and informal waste collectors limit system integration.

Waste-to-Wealth Transformation in the Context of Sustainable Development

The findings of this review have important implications for sustainable development, particularly within the framework of the circular economy and the Sustainable Development Goals (SDGs). The transition from waste disposal to waste valorisation supports SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) by reducing environmental pollution, improving resource efficiency, and lowering greenhouse gas emissions.

From an environmental perspective, integrating emerging technologies into waste management systems enhances recycling efficiency and reduces reliance on landfills, thereby mitigating land degradation and environmental contamination. Economically, waste-to-wealth systems create green jobs through recycling industries, digital waste platforms, and waste-to-energy facilities. This is particularly relevant in developing countries such as Nigeria, where unemployment rates remain high and informal waste sectors already play a significant economic role.

Socially, improved waste management systems contribute to better public health outcomes by reducing exposure to hazardous waste and environmental pollutants. However, the persistence of informal recycling systems also highlights inequalities in occupational safety, as many workers operate without adequate protection or institutional support.

Future Outlook for Technology-Driven Waste Management in Nigeria

The future of waste management in Nigeria will depend on the extent to which emerging technologies are effectively integrated into existing institutional and infrastructural systems. The evidence suggests that while technological solutions are available, their impact remains limited by systemic governance and infrastructural constraints. Efforts must be made to address these challenges to reap the benefits of applying technology to waste management.

A key priority is developing supportive policy frameworks that explicitly integrate digital technologies into national waste management strategies. This includes strengthening enforcement

mechanisms, improving regulatory coherence, and creating incentives for private-sector investment in waste-management innovation.

Investment in infrastructure is equally critical, particularly for expanding reliable electricity supply, digital connectivity, and modern waste-processing facilities. Without these foundational systems, the scalability of AI, IoT, and other advanced technologies will remain a mirage.

Capacity building is another essential requirement. Training programs for waste management professionals, municipal workers, and informal sector actors are needed to improve digital literacy and technical competence. In addition, stronger collaboration among government agencies, private companies, research institutions, and informal waste collectors is essential to ensure inclusive and effective system transformation.

Future research should also focus on context-specific technological adaptation, particularly solutions designed for low-resource environments such as Nigeria. Hybrid systems that integrate informal recycling networks with formal digital waste management platforms may offer a more realistic pathway for scalable transformation.

Conclusion

In conclusion, the transition toward technology-driven waste management is a critical pathway for improving environmental sustainability and promoting resource efficiency in modern waste systems. The integration of emerging technologies and circular economy principles offers a structured approach for addressing long-standing inefficiencies in waste management and supporting broader sustainable development goals.

However, the successful realization of waste-to-wealth systems depends largely on the strength of institutional arrangements, availability of enabling infrastructure, adequate financing, technical capacity, and effective policy implementation. Strengthening these foundational elements is essential to ensure that technological innovations translate into practical, scalable, and sustainable outcomes, particularly in developing countries like Nigeria.

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