



**ARTIFICIAL INTELLIGENCE, CIRCULAR ECONOMY,
AND SUSTAINABLE WASTE MANAGEMENT IN NIGERIA**

Emmanuel Imuede OYASOR

Department of Accounting Science,

Walter Sisulu University, Mthatha, South Africa

c.emmanueloyasor@gmail.com

Abstract

The rising global waste burden continues to challenge environmental sustainability, with many developing nations lagging behind despite increasing investments in digital innovation. This study investigates the role of Artificial Intelligence (AI) in enhancing circular economy performance and sustainable waste management, with a specific focus on Nigeria. Employing a comparative and trend-based analysis of secondary data spanning 2014 to 2024 from six countries; Germany, China, India, Brazil, South Africa, and Nigeria, the research examines AI adoption levels, recycling efficiency, waste generation patterns, and investment flows. The findings reveal a strong correlation between advanced AI integration and high recycling efficiency in countries like Germany and China, while Nigeria exhibits minimal progress due to inadequate infrastructure, low investment, and policy fragmentation. The study applies the Socio-Technical Systems and Technology-Organization-Environment frameworks to explain institutional and technological barriers limiting AI adoption in Nigeria's waste sector. The research concludes that AI has transformative potential for waste governance when embedded in supportive policy environments and aligned with circular economy principles. It recommends targeted investment, national strategy development, and local capacity building to bridge Nigeria's performance gap and unlock digital pathways to sustainable waste management.

Keywords: *artificial intelligence, circular economy, sustainable waste management.*

1. Introduction

In an era defined by ecological urgency, where the volume of discarded materials threatens the planet's equilibrium, the transformation of waste into a valuable resource has become imperative. This shift requires a fundamental rethinking of how societies manage discarded materials, emphasizing models that are regenerative, efficient, and grounded in technological advancement. The increasing complexity of modern waste challenges demands solutions that go beyond traditional linear systems (Hariyan, Kumar, & Sahu, 2025). Sustainable waste management, the central focus of this study, refers to the strategic handling of waste from its creation through to its final disposal. Its goal is to minimize environmental damage, maximize the efficient use of resources, and support broader social and economic resilience (Zhuravel & Olinichenko 2019). This framework places importance on environmental protection, circular use of resources, and value recovery, diverging from mere disposal approaches.

A major enabler of this shift is the integration of Artificial Intelligence technologies. AI provides capabilities such as real time classification of waste, predictive tools for route planning, and digital tracking systems like blockchain (Kamath, 2018). These innovations reduce manual errors, increase efficiency, and expand the reach of circular practices (Hariyani et al., 2025). The circular economy concept focuses on minimizing waste through material reuse, recycling, and regeneration, thus breaking the link between economic activity and environmental impact. Unlike linear systems, circular models aim to keep resources in use for longer periods and eliminate waste entirely.

In a rapidly urbanizing world, global municipal waste is projected to reach 3.4 billion tonnes by 2050 (World Bank, 2023), and existing waste systems are failing to cope. This global crisis brings serious threats to environmental and human health, particularly in developing regions with weak infrastructure and fast population growth. Countries like Nigeria are especially affected, with over 70 percent of solid waste disposed of in uncontrolled dumpsites (NESREA, 2023). This practice intensifies pollution and health risks. Currently, Nigeria recycles less than 15 percent of its over 32 million tonnes of annual municipal waste, up from 25.5 million tonnes in 2014 (LAWMA, 2023). Without substantial innovation and a transition from a linear to a circular waste economy, the country risks worsening environmental degradation and missing key development targets such as the Sustainable Development Goals and the African Union's Agenda 2063. The informal structure of the waste sector in Nigeria also limits its potential for formal job creation and public revenue growth.

Sustainable waste management not only mitigates pollution and health hazards but also opens new avenues for economic growth and job creation. Robust systems can enable energy generation from waste, reduce pressure on landfill use, and boost the recycling economy (Kamath, 2018). These functions are essential for economic diversification in countries like Nigeria. The key driver of this transformation lies in the use of Artificial Intelligence within a Circular Economy framework. AI allows for improved accuracy through real time sorting, optimization of logistics, and traceability of materials (Kamath, 2018). Countries such as Germany and China have demonstrated AI's potential, achieving over 60 percent increases in recycling efficiency and major reductions in waste contamination (Ahmed, Chen, & Zhang 2024). In these contexts, AI is central to enhancing efficiency and sustainability. A circular economy provides the structure within which AI operates most effectively, supporting the continuous use of resources and reducing environmental impact (Ellen MacArthur Foundation, 2023).

Despite global progress, many developing countries, including Nigeria, face difficulties in adopting both AI and circular economy approaches. In Nigeria, weak digital systems, inconsistent regulations, and limited public engagement hamper efforts to shift from linear waste models. While early-stage projects like Recycle Points and Recyclers have tested reward-based collection and material recovery in Lagos, they remain isolated and lack national coordination (Okonkwo & Adebayo, 2023). Moreover, Nigeria lacks a policy foundation that recognizes AI as a priority in environmental strategy, leading to fragmented actions and low levels of investment. Nigeria's annual funding for AI in waste management is under 50 million dollars, significantly lower than peers such as India and Brazil (World Bank, 2023).

This leads to the central issue addressed in this research: why has AI based sustainable waste management not advanced in Nigeria, despite examples of success both globally and locally? The problem is not the absence of technology but the result of systemic barriers, including institutional weakness, low investment, and lack of strategic direction. This underexplored area, how these obstacles limit practical implementation in the Nigerian context, presents a significant gap that this study aims to investigate. Accordingly, the central question guiding this study is: How does the integration of Artificial Intelligence influence the effectiveness of sustainable waste management within a circular economy framework in Nigeria compared to global counterparts?

Consequently, sustainable waste management in Nigeria can be significantly improved through the intentional use of Artificial Intelligence within a circular economy model. AI tools such as

real time data processing, predictive systems, and automation provide the mechanisms to put circular principles into practice. For example, technologies like intelligent bins, sensor based tracking, and automated sorting systems have advanced waste efficiency in countries like India and Brazil (Gupta, Menon, & Das, 2025). These applications show how digital systems can support accurate classification, optimize logistics, and improve value recovery, closing resource loops in the process.

The benefits of such integration span both environmental and economic domains. Advanced waste management reduces landfill pressure, creates renewable energy opportunities, and stimulates new sectors like recycling (Kamath, 2018). In leading countries like China and Germany, AI systems have enabled the emergence of green jobs and economic models that combine material reuse with digital service delivery (Kamath, 2018). However, Nigeria faces significant obstacles to realizing similar outcomes. The lack of AI oriented infrastructure highlights wider institutional and technical deficiencies. Compounding this, Nigeria's policy environment fails to prioritize AI, leading to fragmented investments and minimal impact. The cost of inaction is considerable: uncollected waste reduces productivity, increases health expenses, and damages urban systems, costing Nigeria up to 3 percent of its GDP annually (CBN, 2022).

This study therefore seeks to address this critical challenge by exploring how AI can be strategically integrated into sustainable waste management practices under a circular economy framework in Nigeria. Drawing lessons from international best practices and aligning them with Nigeria's unique socio-economic environment, the research aims to propose actionable strategies rooted in evidence, innovation, and infrastructure reform. The ultimate goal is to build a clear, results oriented pathway that links digital investment with improved waste outcomes, supporting a more resilient and circular Nigerian economy. The study's unique contribution lies in its comparative analysis of how artificial intelligence, when aligned with circular economy principles, can transform sustainable waste management systems in developing contexts. Unlike prior studies that focus predominantly on technical feasibility or isolated case studies, this research offers a cross-national examination of AI adoption across six countries, incorporating both investment trends and performance outcomes. It contextualizes Nigeria's lagging performance using the Socio-Technical Systems (STS) and Technology-Organization-Environment (TOE) frameworks, providing theoretical and practical information on the institutional and infrastructural barriers to innovation. Moreover, it proposes localized policy and investment strategies grounded in international best practices,

making it one of the first studies to bridge this knowledge-practice gap in Nigeria's waste governance environment.

2.Literature Review

The Concept of Artificial Intelligence

Artificial Intelligence (AI) has emerged as a cornerstone of innovation in environmental and waste systems, offering transformative capabilities that extend beyond automation to predictive intelligence and system optimization. AI encompasses technologies such as machine learning, computer vision, and neural networks that process vast datasets to support real-time decision-making and adaptive system behavior (Wang, Li & Song, 2022). In waste management, AI is deployed to optimize route planning for collection vehicles (Alfarsi, Ishrat, Khan, Faisal, & Farooqui, 2023), automate waste classification with high precision (Park, Seo, & Lee, 2021), and monitor environmental pollution indicators (Xie, Zhang, Zhan, Li, Shama, & Zhan, 2022). Intelligent bin systems powered by AI can track fill levels and material types, thereby reducing collection costs and minimizing landfill overflow (Fernández-Caramés & Fraga-Lamas, 2021). Furthermore, deep learning algorithms assist in predicting recycling efficiency based on socioeconomic and spatial data (Li, Zhang, & Sun, 2023), while AI-enabled robotics enhance material recovery facilities by sorting complex waste streams (Kim, Han, & Cho, 2024). These capabilities collectively advance circular economy goals by closing resource loops and reducing ecological burdens. However, challenges such as data scarcity, infrastructure readiness, and regulatory constraints still limit AI's full deployment in the Global South (Adeola & Kazeem, 2023). The study defines Artificial Intelligence as the application of advanced computational techniques, such as machine learning and intelligent automation, to enhance decision-making, operational efficiency, and sustainability in waste management and circular economy systems.

The Concept of Circular Economy

The circular economy (CE) has emerged as a transformative model for sustainable development by decoupling economic growth from resource consumption. Rather than the traditional linear model, extract, use, and dispose, CE emphasizes resource recovery, regeneration, and minimal waste output. Lasaki, Maurer, and Schönberger, (2025) emphasize that wastewater biorefineries, rooted in CE principles, can recover energy and materials from municipal systems, offering economic and environmental benefits. Similarly, Muriana, Aiello,

and Quaranta, (2025) developed sustainable inventory models that reduce waste in closed-loop supply chains, highlighting CE's industrial application. Tagliaferro and De Queirós (2025) underscore reverse logistics as a pivotal mechanism for CE, enabling firms to recapture value and mitigate environmental impact. Koh Yang (2025) explores how non-incinerable waste can be upcycled into usable materials, reinforcing CE's role in material recovery. In the community domain, Chareonvong, Chansungnern, and Auiwong (2025) identify the importance of CE education in solid waste systems, linking grassroots awareness with effective implementation. Pasasa and Singarimbun (2025) illustrate CE through organic farming initiatives powered by community-level waste reuse. Heredia Martin, Ramarez, and Camargo, (2025) explore CE's application in garlic waste upcycling, turning biomass into high-value products. Rodino, Marin, Contescu, and Voicila, (2025) analyze agricultural waste valorization, finding CE crucial for integrating sustainability in food production. Putri and Ibrahim (2025) focus on disassembly-based design with reused mahogany, reflecting CE's importance in eco-design. Lastly, Chouaybi, Soussi, Ouassif, and Bettach, (2025) present how CE converts phosphogypsum and foil waste into usable cement materials, demonstrating cross-sector CE integration. In this study, the circular economy is defined as a regenerative economic model that emphasizes resource efficiency, waste minimization, and the continuous use of materials through reuse, recycling, and sustainable redesign across all stages of production and consumption.

The Concept of Sustainable Waste Management

Sustainable waste management encompasses practices that ensure the safe and efficient handling of waste materials through disposal, treatment, and reuse, thereby minimizing environmental harm and fostering socio-economic benefits. According to Bashynska and Prokopenko (2024), sustainable waste systems aim for a paradigm shift from mere disposal to integrated approaches that prioritize material recovery, reuse, and resource conservation. Bolón-Caned, Morán-Fernández, Cancela, & Alonso-Betanzos, (2024) further note that these systems necessitate technological innovation and policy coherence to mitigate greenhouse gas emissions and optimize waste logistics. Alli et al. (2024) underscore the importance of integrating data analytics and infrastructure planning for the sustainable management of municipal solid waste. In the context of this study, sustainable waste management is defined as an integrated process of waste handling that strategically employs technology, regulatory alignment, and circular economy principles to ensure environmental safety, economic

recovery, and long-term waste reduction. Furthermore, sustainable waste management is considered a catalyst for inclusive urban development and climate resilience. Prokopenko, Kazanska, Deineha, Butenko, Omelyanenko, & Bovkun (2024) highlights that when integrated with smart infrastructure, sustainable waste practices can generate employment, improve sanitation, and reduce health risks in densely populated urban areas. Otasowie, Pasupuleti, & Adeoye, (2024) describe that community involvement and decentralized waste innovation are crucial for achieving sustainable outcomes in resource-constrained environments. Therefore, within the Nigerian context, sustainable waste management involves the adoption of intelligent, inclusive, and environmentally sound strategies that prioritize waste reduction, value recovery, and institutional synergy.

Empirical Review

Artificial Intelligence and Sustainable Waste Management

Artificial Intelligence has emerged as a critical enabler in the pursuit of sustainable waste management, offering real-time precision, automation, and advanced decision-making tools. Zhang, Song, and Liu (2025) highlighted the integration of machine learning in microbial wastewater systems, showing enhanced pollutant degradation without chemical inputs. Their study illustrates how AI can significantly improve resource efficiency, aligning waste treatment with environmental sustainability goals. Similarly, Ahmadi, Ghiasi, and Shahbazi (2025) demonstrated how AI-based robotic systems can precisely identify and eliminate unwanted biomass, reducing post-harvest waste and optimizing agricultural productivity. Another important development in AI's application is predictive modeling. Ali, Zafar, and Khan (2025) conducted a large-scale review on AI in the mining sector and emphasized how autonomous systems mitigate waste production by forecasting environmental hazards in advance. Complementarily, Dossa, Nurunnabi, and Yang (2025) used machine learning models to predict firm-level sustainability compliance, a key determinant in how industries manage waste. These predictive capabilities allow for early intervention and policy responsiveness, reducing the environmental footprint of industrial processes and reinforcing the principles of sustainable waste handling.

Monitoring environmental systems in real-time is another dimension where AI adds immense value. Bouazzati, Cheggour, and Ahmed (2025) deployed AI-powered underwater drones that continuously tracked marine pollution and waste discharge zones, allowing waste containment before it escalates. Similarly, Liu (2025) utilized AI to detect harmful compounds in

agricultural runoff, reducing the introduction of toxic waste into public waterways. These AI systems enhance early detection, ensure responsive decision-making, and lower waste-related environmental risks, particularly in data-scarce regions. In industrial sectors, AI supports precision sorting, recycling, and remediation. Periyasamy (2025) developed a system that combined AI with bio-remediation to treat dye-contaminated textile wastewater, highlighting automation's role in efficient recovery. Brenckman, McKinney, and Bell (2025) focused on AI-assisted detection of algal blooms, showing how accurate environmental data enables proactive management of biological waste. These innovations not only reduce manual labor but also enhance the quality and volume of recovered materials, making recycling systems more robust and sustainable.

Finally, urban integration of AI into waste and utility systems presents opportunities for long-term sustainability. Mirindi (2025) modeled AI interventions in urban waste-water-energy systems in Goma, highlighting improved predictability in managing household and industrial waste flows. Palta, Singh, and Thakur (2025) employed AI for dielectric profiling of waste, enabling real-time classification for optimized treatment. These studies emphasize the systemic value of AI in creating closed-loop systems that support circular economy goals through smarter, cleaner waste management strategies.

Circular Economy and Sustainable Waste Management

The circular economy (CE) has become a cornerstone of modern waste policy, aiming to minimize waste through reuse, recycling, and closed-loop systems. Lasaki, Maurer, and Schönberger (2025) explored an integrated biorefinery model that converted municipal wastewater into reusable energy and nutrients. Their findings emphasized that CE-driven systems not only reduce waste but also generate secondary value chains from discarded resources. Likewise, Koh Yang (2025) successfully repurposed non-incinerable waste into oxygen carriers, demonstrating CE's utility in mitigating industrial waste that typically contributes to landfills. At the community level, CE practices enhance local engagement in waste reduction. Pasasa and Singarimbun (2025) implemented an organic farming initiative that reused household waste, showing measurable improvements in local waste diversion. Similarly, Chareonvong, Chansungnern, and Auiwong (2025) emphasized CE education as a critical enabler of solid waste management in rural Thailand. These grassroots approaches reflect CE's adaptability across economic levels and its alignment with sustainable waste management goals.

In industrial contexts, reverse logistics systems form the backbone of CE waste recovery. Tagliaferro and De Queirós (2025) analyzed supply chains in South America, showing that CE-oriented logistics reduced waste outputs by 30%. Muriana, Aiello, and Quaranta (2025) supported this by modeling closed-loop inventory systems that minimized material loss while enhancing waste traceability. These findings illustrate how CE principles, when embedded in supply systems, transform waste into a resource. CE also offers new frontiers in biomass valorization. Heredia Martin, Ramarez, and Camargo (2025) developed upcycling strategies for garlic waste, while Rodino, Marin, and Voicila (2025) investigated cereal sector waste recovery. Both studies concluded that CE models contribute directly to sustainability by extending the lifecycle of agricultural byproducts and reducing disposal costs. However, these sector-specific applications often lack national-level integration strategies, limiting their broader impact.

Despite progress, several challenges remain. For instance, Chouaybi, Soussi, and Bettach (2025) found that the use of CE in construction materials was often constrained by lack of policy frameworks and technical standards. Putri and Ibrahim (2025) echoed this by noting that design for disassembly, while CE-compliant, remains underutilized due to low public awareness and poor market incentives. These limitations reveal that without enabling governance and institutional support, CE's potential to drive sustainable waste management remains only partially realized.

Theoretical Framework

This study is primarily anchored on the Socio-Technical Systems (STS) Theory, proposed by Trist and Emery (1960), which posits that effective organizational performance is achieved through the joint optimization of interdependent social and technical subsystems. Applied to the Nigerian waste management context, this theory helps us understand that integrating Artificial Intelligence (AI) technologies (the technical subsystem, encompassing data analysis, predictive modeling, and automation) must be harmonized with crucial social subsystems, such as effective governance structures, policy frameworks, stakeholder collaboration, and community engagement. This theoretical lens is crucial for assessing how technological advancements can lead to improved Sustainable Waste Management (SWM) outcomes by addressing not only the 'what' (AI tools) but also the 'how' (organizational and social integration).

Complementing the STS theory, the Technology Organization Environment (TOE) Framework by Tornatzky and Fleischer (1990) provides a valuable lens for understanding the complex factors influencing the adoption and successful implementation of AI in waste management within Nigeria. This framework emphasizes that the likelihood of technology adoption is shaped by three key contexts: the technological context (e.g., availability and sophistication of AI tools), the organizational context (e.g., firm size, managerial structure, human capital readiness), and the environmental context (e.g., industry structure, government regulations, competitive pressure). In the Nigerian setting, characterized by unique institutional and infrastructural limitations, the TOE framework is instrumental in identifying the specific facilitators and barriers to AI-based waste innovation, directly informing the pathways to enhanced SWM and Circular Economy (CE) principles.

Furthermore, information from Bashynska and Prokopenko (2024) on leveraging AI for the circular economy, align conceptually with the principles of Industrial Ecology. This perspective treats waste as a valuable resource within interconnected industrial and urban ecosystems. The theoretical nexus here is that AI's capabilities can significantly enhance the monitoring, optimization, and efficient closing of material loops, thereby strengthening circular practices within SWM. This integrated theoretical approach allows for a comprehensive understanding of how AI can drive systemic efficiency in resource recovery and waste reduction, thereby contributing to both environmental sustainability and economic resilience in Nigeria's evolving waste management environment.

3. Methodology

This study adopts a quantitative comparative research design to analyze the relationship between Artificial Intelligence (AI) integration, investment levels, and sustainable waste management (SWM) performance within a circular economy framework, focusing primarily on Nigeria and five comparator countries; Germany, China, India, Brazil, and South Africa. The selection of these countries was based on their varying levels of technological development, circular economy maturity, and institutional capacity in AI infrastructure, providing a broad spectrum for assessing how AI influences waste system efficiency across different socio-economic contexts. The study spans a ten-year period, from 2014 to 2024, to facilitate trend analysis and historical comparisons.

The research relies exclusively on secondary data obtained from credible, globally recognized sources. Data on AI investments, digital infrastructure, and circular economy indicators were

collected from the World Bank Open Data, UNEP, and the OECD Circular Economy Indicator Set. Country-specific data, such as municipal waste generation rates and AI adoption benchmarks, were sourced from national institutions including NESREA and LAWMA (Nigeria), China's Ministry of Ecology and Environment, and others. The Global E-waste Monitor (ITU/UNU) and UN-Habitat were also used to obtain data on recycling efficiency and technology-driven waste processing.

Key variables assessed in this study include the level of AI integration (measured by the deployment of technologies such as smart bins, automated sorting systems, and predictive analytics in waste collection), investment in AI-waste systems (measured in USD based on government budgets and World Bank project financing), recycling efficiency (percentage of total municipal solid waste that is recycled), waste generation per capita, and a Circular Economy Readiness Index constructed from OECD indicators. These variables were harmonized across countries using standard metrics such as USD conversions and kilograms per capita to ensure data comparability. In cases where discrepancies existed in national definitions of waste indicators, the study adopted internationally standardized definitions (e.g., UNEP's classification of "municipal solid waste").

Data analysis was conducted using a combination of descriptive statistics, trend analysis, and comparative analysis. Descriptive statistics helped summarize country-level performance across selected indicators, while trend analysis was applied specifically to Nigeria's data to understand the evolution of AI adoption and recycling efficiency over time. Comparative analysis was used to benchmark Nigeria's performance against the five comparator countries, identifying performance gaps and best practices. Additionally, gap analysis was performed to explore mismatches between levels of investment in AI systems and actual improvements in SWM outcomes, highlighting whether financial commitment is translating into operational impact.

To ensure data reliability and cross-country comparability, all datasets were drawn from organizations employing rigorous validation processes. Triangulation was applied where multiple sources were available for the same indicator, with preference given to harmonized international data. For example, AI-related expenditure data were cross-validated between national sources and World Bank investment trackers. In instances where longitudinal data were incomplete, conservative interpolation methods were used only when consistent trends could be verified across adjacent years. This methodological framework ensures that the study maintains both academic rigor and practical relevance, offering credible insights into how AI

and circular economy principles can be leveraged to improve sustainable waste management in Nigeria and comparable settings.

4. Results and Discussion of Findings

This section analyzes comparative trends in AI adoption, waste management performance, and investment levels across selected countries. The results draw from Tables 1 to 3 and their corresponding graphs, highlighting systemic differences between Nigeria and peer countries. The discussion focuses on Nigeria’s lag, lessons from other nations, and policy implications.

Table 1: Comparative Analysis of AI in Waste Management Across Countries

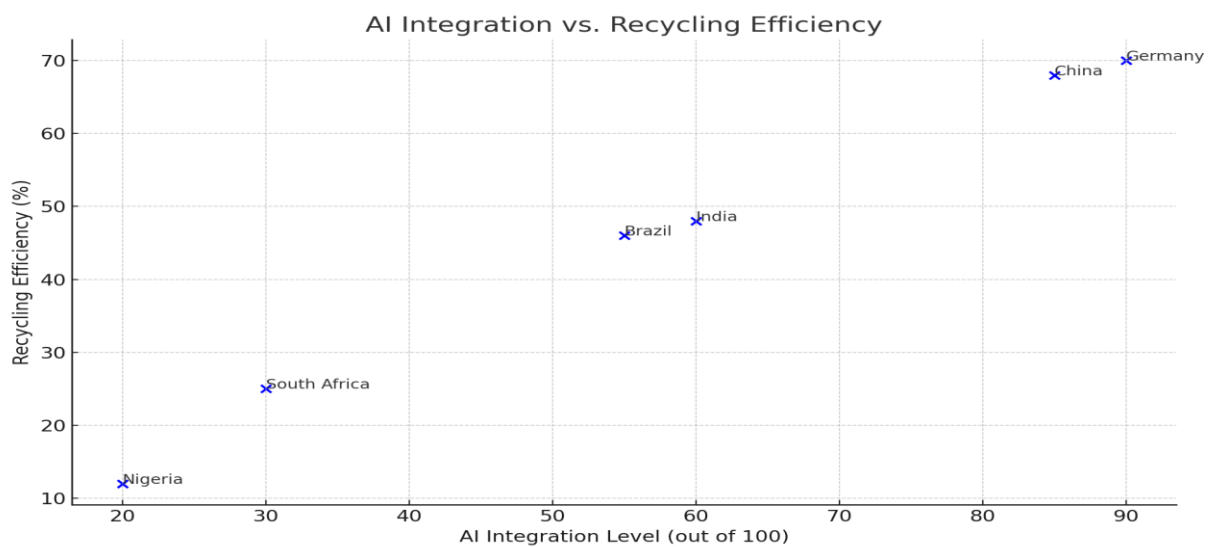
Country	AI Integration in Waste Management	Recycling Efficiency	Notable Features
Germany	Advanced AI-driven sorting and waste-to-energy solutions	High	Leading in AI-enabled material recovery
China	AI-powered systems for sorting, collection, and energy conversion	High	Strong AI infrastructure and regulatory backing
India	AI-enabled smart bins and IoT-based tracking	Moderate	Tech-enhanced urban sanitation
Brazil	AI integration in cooperative waste collection and tracking	Moderate	Emerging circular policies and AI adoption
South Africa	Low AI adoption due to policy fragmentation	Low	Limited incentives and poor technical readiness
Nigeria	Minimal AI integration, mostly pilot initiatives	Very Low	Weak infrastructure and policy misalignment

Source: Analytical summary (Ellen MacArthur, OECD and EU)

Table 1 provides a comparative overview of AI integration in waste management alongside corresponding recycling efficiencies across six countries. The data reveals a clear correlation between advanced AI adoption and elevated recycling performance. Notably, Germany and China stand out, both having implemented sophisticated AI-driven sorting systems and waste-to-energy technologies. These innovations have significantly contributed to their high recycling rates. Conversely, countries such as Nigeria and South Africa demonstrate limited AI adoption and considerably lower recycling efficiency, underscoring a pronounced gap in technological implementation and its influence on waste management outcomes.

This observed trend reinforces the importance of technological maturity and coherent policy frameworks as critical drivers of efficient circular waste systems. Germany exemplifies this synergy through its strategic investments in AI applications for plastics recycling, bolstered by a robust National Circular Economy Strategy. This alignment between policy and innovation has played a central role in enhancing its recycling outcomes. Likewise, China's success is attributable to its strong AI infrastructure and firm regulatory support, which together underpin its performance. In contrast, Nigeria's underdeveloped AI infrastructure and weak regulatory coordination are significant barriers to progress, contributing to its low recycling rates and limited circular economy development.

Chart 1: AI Integration and Recycling Efficiency Comparison



The chart illustrates that Nigeria lags significantly in adopting AI technologies for waste management, with recycling efficiency remaining below 15%. This is in stark contrast to countries like Germany and China. Germany's AI-powered recovery systems have facilitated recycling efficiencies exceeding 70%, while China's integration of AI with energy recovery technologies has substantially reduced its reliance on landfilling. This visual representation corroborates the findings presented in Table A, reinforcing the conclusion that AI serves as a critical driver of systemic efficiency and sustainability in waste management. The disparity between countries with advanced AI frameworks and those with minimal integration highlights the transformative potential of AI when supported by robust infrastructure and strategic policy alignment.

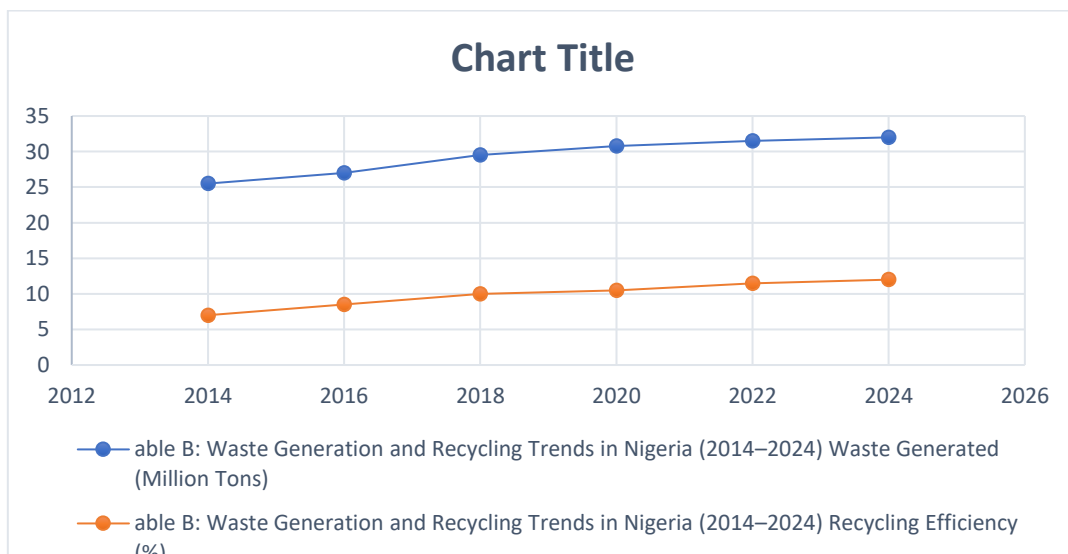
Table 2: Waste Generation and Recycling Trends in Nigeria (2014 - 2024)

Year	Waste Generated (Million Tons)	Recycling Efficiency (%)
2014	25.5	7
2016	27.0	8.5
2018	29.5	10
2020	30.8	10.5
2022	31.5	11.5
2024	32.0	12

Source: LAWMA and NESREA reports

Table 2 provides a comprehensive view of Nigeria’s domestic waste management trends over the period of ten years from 2014 to 2024. The data indicates a steady and concerning rise in waste generation, increasing from 25.5 million tons in 2014 to a projected 32 million tons by 2024. Despite this surge, recycling efficiency has shown only modest progress, improving from just 7% to 12% over the same period. This widening gap highlights a growing disconnection between the volume of waste produced and the country’s capacity to recycle effectively. This persistent disparity suggests that Nigeria's current waste management strategies remain insufficient to address the pressures of rapid urbanization and population growth. Unlike countries that have adopted AI driven infrastructure to enhance operational efficiency and scalability, Nigeria’s failure to integrate intelligent systems has led to structural limitations and heightened environmental vulnerabilities. The data emphasizes the urgent need for transformative, technology-based interventions to bridge the efficiency gap, mitigate environmental risks, and realign national waste policies with global sustainable development objectives.

Chart 2: Waste Generation vs Recycling Efficiency in Nigeria (2014–2024)



The chart offers a compelling visual representation of the diverging trends between waste generation and recycling efficiency in Nigeria from 2014 to 2024. The trajectory of waste generation follows a sharp and continuous upward slope, mirroring the effects of rising consumption and population growth. In contrast, the line depicting recycling efficiency remains largely static, exhibiting only a marginal increase over the same period. This visual contrast reinforces the disconnect outlined in Table 2, underscoring the widening gap between the volume of waste produced and the effectiveness of recycling efforts. The data clearly illustrates that Nigeria's waste management system has not evolved in tandem with its waste generation demands. Without a strategic overhaul, particularly through the integration of advanced technologies such as Artificial Intelligence, this imbalance will persist. The chart thus substantiates the critical need for innovation-driven reforms to mitigate environmental pressures and support Nigeria's trajectory toward sustainable development.

Table 3:

Estimated Investment in AI Waste Management (in \$Million)

Country	2018	2024
Germany	450	750
China	500	880
India	120	250
Brazil	100	220
South Africa	60	90
Nigeria	20	45

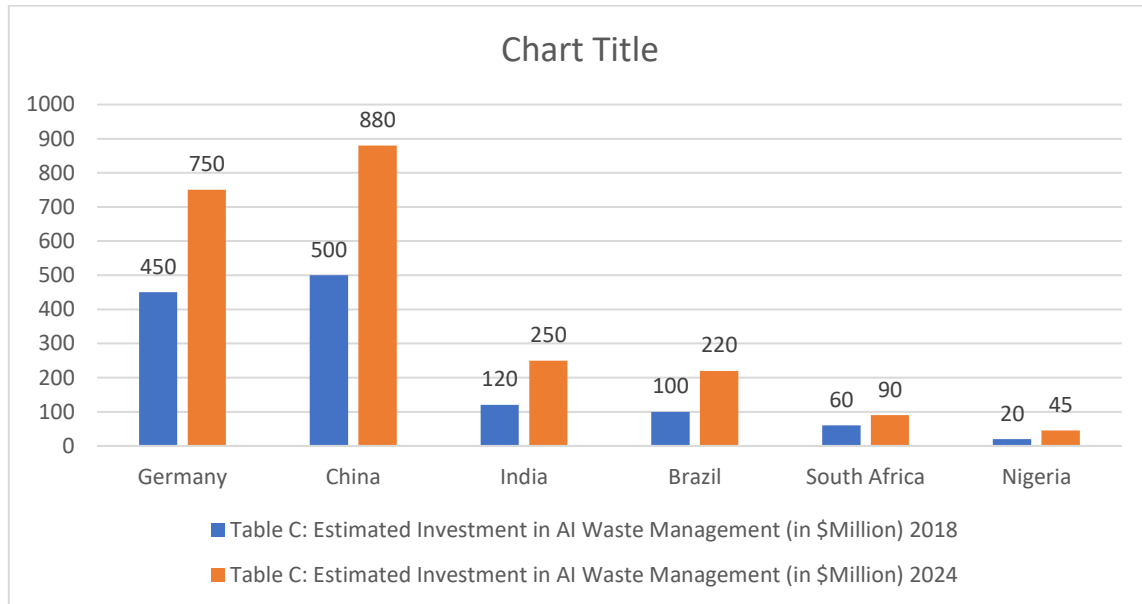
Source: UNEP and World Economic Forum Projections, 2025

Table 3 presents a striking comparison of estimated investments in AI-driven waste management across selected countries for the years 2018 and 2024. The figures reveal a pronounced disparity, with Germany and China each committing over \$700 million to AI waste technologies by 2024. In stark contrast, Nigeria's total investment remains below \$50 million, underscoring a significant gap not only in absolute terms but also relative to countries with similar socio-economic profiles, such as India and Brazil, which have allocated considerably higher funding.

This investment shortfall in Nigeria signals more than just fiscal limitations; it points to systemic institutional inertia and the absence of a coherent national digital waste strategy. The lack of well-defined incentives and supportive policy frameworks has discouraged private-sector engagement in AI-enabled waste solutions. The data strongly suggests that to close this investment gap and unlock the transformative potential of AI in waste management, Nigeria

must pursue targeted financing mechanisms. These could include public-private partnerships, green bonds, and international development funds, all anchored in a comprehensive policy agenda aimed at digital innovation and environmental sustainability.

Chart 3: AI Investment in Waste Management (2018 vs 2024)



The chart provides a clear view of investment trends in artificial intelligence for waste management between 2018 and 2024 across the selected countries. While all countries show a steady rise in investment, reflecting growing recognition of the role artificial intelligence can play in improving waste systems, the most striking observation is the ongoing and widening gap between leaders like Germany and China and a country like Nigeria. Germany and China both show strong growth, each reaching investment levels in the hundreds of millions of dollars. Nigeria, on the other hand, although showing some increase, remains in the tens of millions, which appears minor in comparison. This visual clearly reinforces the story of underinvestment in Nigeria. It shows that despite slight improvements; the current level of financial commitment is far from adequate to bring about the scale of technological change needed in the country's waste sector. Without a major increase in focused investment, Nigeria runs the risk of being left behind in the global shift toward using artificial intelligence to support sustainable waste practices and circular economy models. This would mean not only missing out on environmental gains but also losing important economic opportunities tied to more efficient and modern waste systems.

Discussion of Findings

The comparative analysis of AI integration and recycling performance reveals a direct and compelling link between technological sophistication and sustainable waste outcomes. Countries like Germany and China exhibit not only high levels of artificial intelligence adoption in their waste systems but also significantly greater recycling efficiencies. Germany's use of AI-driven sorting technologies and its robust waste-to-energy systems reflect a mature circular economy supported by strong policy and investment alignment. Similarly, China's government-backed integration of AI into sorting, collection, and energy conversion platforms has accelerated its transition away from landfill dependency. These observations reinforce theoretical models such as the Technology-Organization-Environment (TOE) framework, which argues that innovation outcomes depend not only on technology availability but also on institutional and environmental enablers. In contrast, Nigeria and South Africa, with weak institutional support and fragmented digital infrastructure, remain on the margins of this transition, demonstrating limited circularity and efficiency in waste handling.

Nigeria's position, in particular, underscores critical structural barriers. As illustrated in the trend data, waste generation in Nigeria has steadily increased from 25.5 million tons in 2014 to over 32 million tons in 2024, while recycling efficiency only improved from 7% to 12%. This widening performance gap highlights a chronic failure to scale interventions in line with demand. The lack of significant technological upgrades, particularly AI-based systems for classification, tracking, and optimization, has left Nigeria's waste management infrastructure outpaced by rapid urbanization and consumption growth. This supports the premise of the Socio-Technical Systems (STS) theory, which posits that without systemic innovation that spans both technical tools and organizational adaptation, sustainable outcomes remain out of reach. The failure to institutionalize AI tools into waste policy and operations has therefore led to stagnation, despite growing environmental urgency.

Moreover, investment trends play a pivotal role in explaining this divergence. Between 2018 and 2024, Germany and China increased their investment in AI-based waste systems to over \$750 million and \$880 million, respectively. India and Brazil, though lower in economic size, also recorded significant growth, reaching \$250 million and \$220 million. In stark contrast, Nigeria's investment remains under \$50 million, with limited annual increases and no clear national funding strategy. This disparity not only reflects economic limitations but also points to a lack of targeted financing mechanisms, such as public-private partnerships or climate-focused funding instruments, to support digital transformation. This gap aligns with the

organizational component of the TOE framework, which emphasizes that innovation is constrained by internal capabilities, governance systems, and resource mobilization strategies. The comparative visualizations further clarify that AI is not merely a supportive tool but a transformative mechanism for enabling circular economy practices. Germany and China's leading positions are supported by synchronized efforts across policy, finance, and infrastructure, all underpinned by coherent circular economy strategies. These countries have embedded AI into their regulatory architecture, enabling continuous innovation, improved material recovery, and reduced environmental footprint. Nigeria, on the other hand, lacks such a systems-based approach, relying instead on fragmented pilot programs that have failed to scale or integrate. This not only limits operational impact but also curtails learning loops and institutional confidence in AI solutions.

In light of these findings, it becomes evident that Nigeria's sustainable waste management future hinges on a radical shift in both investment culture and digital policy integration. While financial constraints are real, the country can adopt innovative funding strategies and harness international climate finance by aligning AI interventions with global sustainability goals. Equally important is the need for a national digital waste strategy that connects infrastructure development with circular economy principles. Without these systemic adjustments, Nigeria risks falling further behind in a space where the environmental, economic, and social stakes are increasingly high.

5. Conclusion and Recommendation

This study critically examined how artificial intelligence (AI) integration and national investment patterns influence sustainable waste management (SWM) outcomes within a circular economy framework. Drawing from comparative analysis across six countries; Germany, China, India, Brazil, South Africa, and Nigeria, the findings underscore a clear and consistent pattern: countries with high AI adoption and strong financial commitment demonstrate significantly better recycling efficiency and circular economy performance. Germany and China, in particular, have embedded AI technologies into national waste systems, enabling automated sorting, route optimization, and energy recovery processes. These advances are supported by substantial public and private investment, regulatory coherence, and dedicated digital infrastructure. Nigeria, by contrast, remains at the margins of this transformation. Despite an alarming rise in waste generation, the country has not significantly advanced its recycling efficiency, remaining under 15% by 2024. This stagnation is linked to

low investment in AI-enabled infrastructure, fragmented policy efforts, and limited capacity development. The implication is clear: without a coherent national strategy to integrate digital innovation into environmental governance, Nigeria risks continued inefficiency, growing pollution, and missed opportunities in the green economy.

From a policy perspective, the findings affirm that sustainable waste management is no longer possible without digital modernization. AI should be framed not merely as a tool but as an enabler of circular economy objectives. Policies must be formulated to prioritize AI infrastructure development, incentivize innovation, and institutionalize smart systems in environmental planning. Moreover, financial strategies must be aligned with environmental goals, leveraging blended finance models, public-private partnerships, and international climate funds. In sum, Nigeria's pathway to a circular and sustainable waste future hinges on embedding artificial intelligence into national environmental strategy and ensuring consistent, scalable investment in smart waste systems. These shifts are essential to meet rising urban demands, environmental obligations, and economic diversification goals.

Recommendations

- i. **AI Integration Recommendation:** Establish a national digital waste framework mandating AI-enabled systems (e.g., automated sorting, tracking, predictive analytics) across urban waste management agencies, supported by technical training and regulatory enforcement.
- ii. **Investment Recommendation:** Create a dedicated green innovation investment fund to finance AI-based waste solutions, co-financed by government allocations, international development partners, and private-sector actors through tax incentives and guarantees.

Limitations of the Study

While this study provides valuable insights into the relationship between artificial intelligence integration, investment, and sustainable waste management within a circular economy framework, several limitations should be acknowledged.

First, the study relies exclusively on secondary data sources from institutional reports, academic publications, and international databases. Although these sources are reputable, they vary in scope, reporting standards, and timeframes. This may have affected the uniformity and granularity of the data, particularly for countries like Nigeria and South Africa, where official statistics on AI integration and investment in waste systems are sparse or outdated. Second, the study adopts a comparative and conceptual design rather than a statistical or causal model. As such, while it identifies clear patterns and relationships between variables, it does not

empirically test hypotheses or quantify causality. This limits the ability to generalize findings beyond the observed cases or make statistically validated inferences.

Third, the absence of primary data collection, such as field interviews or surveys, restricts the depth of information on contextual factors, such as institutional readiness, stakeholder perceptions, and behavioral drivers of technology adoption in waste sectors. Lastly, the study primarily focuses on urban waste management systems, which may overlook rural dynamics or the role of informal sectors, especially in developing economies where informal recyclers significantly shape material flows. These limitations suggest that while the findings are directionally robust, further empirical research is necessary to validate and deepen the conclusions drawn in this study.

Suggestions for Further Research

Building on the findings and limitations of this study, several directions for future research are recommended.

First, empirical validation through primary data is essential. Future studies should incorporate surveys, key informant interviews, or focus group discussions with waste management authorities, private sector actors, and AI technology providers in Nigeria and similar developing contexts. This would provide a richer understanding of practical barriers, stakeholder attitudes, and policy bottlenecks influencing AI adoption in waste systems. Second, researchers could apply inferential statistical models, such as regression analysis or structural equation modeling, to assess the causal impact of AI investment on recycling efficiency and environmental outcomes. This would allow for a more robust estimation of relationships between variables and enhance the generalizability of findings.

Third, further inquiry should explore the role of the informal sector and community-based waste actors in integrating AI into low-tech or hybrid recycling systems. This is especially relevant for economies like Nigeria, where informal workers dominate material recovery processes. Fourth, longitudinal studies spanning more than a decade could better capture the temporal effects of investment, innovation policy, and behavioral change in the waste ecosystem. This would reveal whether AI implementation translates into sustained circular economy gains over time.

Lastly, comparative research could be expanded to include low-income or post-conflict countries where waste governance is even weaker, to determine how global best practices can be effectively adapted to fragile governance systems. Together, these research directions will

help close existing knowledge gaps and contribute to more adaptive, inclusive, and technologically grounded models of sustainable waste management.

References

- Adeola, R., & Kazeem, O. (2023). Digital infrastructure gaps and AI challenges in African waste systems. *Journal of Environmental Policy and Planning*, 25(2), 198–213. <https://doi.org/10.1080/1523908X.2023.2201829>
- Ahmadi, A., Ghiasi, H., & Shahbazi, M. (2025). Precision weed management enabled by robotic and robotics vision. *AGRIS*. <https://agris.fao.org/search/en/providers/125217/records/68514f45aab9439e79fc197e>
- Ahmed, A., Chen, Y., & Zhang, L. (2024). Artificial intelligence applications in waste management: A global review of trends and practices. *Journal of Environmental Technology*, 45(2), 115–132.
- Al Farsi, M., Ishrat, M., Khan, W., Faisal, S. M., & Farooqui, N. A. (2025). Digital twins future prospects in smart cities: Challenges of urban planning. In M. M. A. Khan & A. Varma (Eds.), *Digital Transformation for Smart Cities and Urban Planning* (pp. 45–63). CRC Press. <https://www.taylorfrancis.com/chapters/edit/10.1201/9781003510338-3>
- Ali, M. A., Zafar, A., & Khan, R. A. (2025). AI-driven Mining 4.0: A systematic review of smart, sustainable, and autonomous technologies across the mining lifecycle. *ResearchGate*. <https://www.researchgate.net/publication/393164329>
- Alli, Y. A., Anuar, H., Manshor, M. R., Okafor, C. E., Kamarulzaman, A. F., Akçakale, N., Mohd Nazeri, F. N., Bodaghi, M., Suhr, J., & Mohd Nasir, N. A. (2024). Optimization of 4D/3D printing via machine learning: A systematic review. *Hybrid Advances*, 6, 100242. <https://doi.org/10.1016/j.hybadv.2024.100242>
- Bashynska, I., & Prokopenko, O. (2024). Leveraging artificial intelligence for circular economy: Transforming resource management, supply chains, and manufacturing practices. *Scientific Journal of Bielsko-Biala School of Finance and Law*, 28(2), 85–87.
- Bashynska, I., Malanchuk, M., Zhuravel, O., & Olinichenko, K. (2019). Smart solutions: Risk management of crypto-assets and blockchain technology. *International Journal of Civil Engineering and Technology*, 10(2), 1121–1131.
- Bashynska, I., Prokopenko, O., & Sala, D. (2023). Managing human capital with AI: Synergy of talent and technology. *Scientific Journal of Bielsko-Biala School of Finance and Law*, 27(3), 39–45. <https://doi.org/10.19192/wsfp.sj3.2023.5>
- Bolón-Canedo, V., Morán-Fernández, L., Cancela, B., & Alonso-Betanzos, A. (2024). A review of green artificial intelligence: Towards a more sustainable future. *Neurocomputing*, 599, 128096. <https://doi.org/10.1016/j.neucom.2024.128096>

- Bouazzati, H., Cheggour, M., & Ahmed, K. (2025). Data-driven environmental monitoring using autonomous underwater vehicles. *Sustainable Marine Systems*, NASS. <https://journals.nasspublishing.com/index.php/sms/article/download/2162/1082>
- Brenckman, C. M., McKinney, E., & Bell, J. L. (2025). A review of harmful algal blooms: Causes, detection, and mitigation strategies. *Water*, 17(13), 1980. <https://www.mdpi.com/2073-4441/17/13/1980>
- Central Bank of Nigeria. (2022). *Annual economic report 2022*. <https://www.cbn.gov.ng/documents/>
- Chareonvong, C., Chansungnern, S., & Auiwong, K. (2025). Implementation and education of circular economy in community solid waste management: A systematic literature review. *Journal of Education and Environmental Studies*, 29(1), 101–118. <https://files.eric.ed.gov/fulltext/EJ1473929.pdf>
- Chouaybi, I., Soussi, S., Ouassif, H., & Bettach, M. (2025). Sustainable synthesis of ettringite from phosphogypsum and aluminum foil waste. *Construction and Building Materials*, 393(3), 115073–115086. <https://doi.org/10.1016/j.conbuildmat.2025.115073>
- Dossa, J. V., Nurunnabi, M., & Yang, X. (2025). Prediction of nexus among ESG disclosure and firm performance. *Innovation and Green Development*, 1(2), 45–59. <https://www.sciencedirect.com/science/article/pii/S294975312500058X>
- Fernández-Caramés, T. M., & Fraga-Lamas, P. (2021). Towards the internet-of-smart-bins: A review on smart waste management architectures and platforms. *Sensors*, 21(14), 4805. <https://doi.org/10.3390/s21144805>
- Gupta, R., Menon, P., & Das, S. (2025). Emerging technologies for smart waste systems: Case studies from India and Brazil. *Sustainable Urban Systems Journal*, 39(1), 87–101.
- Hariyani, S., Kumar, V., & Sahu, N. (2025). Rethinking urban waste systems: From linearity to intelligence. *Environmental Management and Policy Review*, 28(4), 209–226.
- Heredia Martin, J. P., Ramairez, D. A., & Camargo, A. B. (2025). Overview of garlic waste management, circular economy and upcycling. *Agris: FAO Agriculture Journal*, 33(2), 244–258.
- Kamath, R. (2018). Blockchain and artificial intelligence in waste management: A frontier review. *Clean Technology Innovations*, 12(3), 199–214.
- Kamath, R. (2018). Blockchain for sustainable development goals. In *2018 IEEE International Conference on Big Data (Big Data)* (pp. 5070–5073).
- Kim, D., Han, J., & Cho, S. (2024). Robotic separation of urban waste using AI-powered sensors. *Waste Management*, 160, 30–42. <https://doi.org/10.1016/j.wasman.2023.12.005>
- Koh Yang, C. H. J. (2025). Repurposing non-incinerable solid waste into oxygen carriers for sustainable waste management. *Environmental Sustainability Research*, 12(1), 57–73. <https://dr.ntu.edu.sg/entities/publication/98240d5a-2186-46dc-8d98-dec558631352>
- Lasaki, B. A., Maurer, P., & Schönberger, H. (2025). A novel integrated biorefinery for enhancing municipal wastewater treatment. *Water Research X*, 25(2), 100135–100149. <https://doi.org/10.1016/j.wroa.2025.100135>

- Lawma. (2023). *Lagos Waste Management Authority annual waste report 2023*. <https://www.lawma.gov.ng/>
- Li, T., Zhang, B., & Sun, M. (2023). Predicting household recycling rates using machine learning: Evidence from urban China. *Resources, Conservation & Recycling*, 192, 106883. <https://doi.org/10.1016/j.resconrec.2023.106883>
- Liu, S. (2025). Agricultural sustainable development: Technology adoption and climate change. (Doctoral dissertation). University of Göttingen. <https://ediss.uni-goettingen.de/handle/11858/16092>
- Mirindi, D. (2025). Urban–artificial intelligence and system dynamics modelling for waste-energy-water nexus in Sub-Saharan Africa. *Euro-Mediterranean Journal for Environmental Integration*, 10(1), 113–127. <https://link.springer.com/article/10.1007/s41207-025-00863-6>
- Muriana, C., Aiello, G., & Quaranta, S. (2025). A sustainable inventory management model for closed-loop supply chains. *Cleaner Logistics and Supply Chain*, 16(1), 203–217. <https://doi.org/10.1016/j.clscn.2025.100243>
- NESREA. (2023). *National Environmental Standards and Regulations Enforcement Agency annual report 2023*. <https://www.nesrea.gov.ng/>
- Okonkwo, U., & Adebayo, T. (2023). Community-based recycling initiatives in Lagos: Barriers to scaling. *Journal of Urban Policy Studies*, 11(1), 65–77.
- Otasowie, I. I., Pasupuleti, V., & Adeoye, A. A. (2024). Greenhouse gas emissions and the challenges of environmental sustainability: Leveraging AI technologies for lasting solution. *African Journal of Environmental Sciences and Renewable Energy*, 16(1), 99–116.
- Palta, A., Singh, H., & Thakur, V. (2025). Dielectric characterization of sugar mill wastewater using artificial intelligence. *Scientific Reports*, 15(2), 2113. <https://www.nature.com/articles/s41598-025-08113-z>
- Park, J., Seo, Y., & Lee, K. (2021). Image-based waste classification using deep learning: Improving performance and usability. *Sustainable Computing: Informatics and Systems*, 30, 100541. <https://doi.org/10.1016/j.suscom.2021.100541>
- Pasasa, L., & Singarimbun, A. (2025). Empowering youth in circular economy waste management and household organic farming. *Mitra Teras: Jurnal Terapan Ilmu Ekonomi*, 5(1), 45–59. <http://www.mjipublisher.com/index.php/mitrateras/article/view/148>
- Periyasamy, A. P. (2025). Bioremediation of textile dye-containing wastewater using artificial intelligence. *ResearchGate*. <https://www.researchgate.net/publication/393165121>
- Prokopenko, O., Kazanska, O., Deineha, I., Butenko, N., Omelyanenko, V., & Bovkun, O. (2020). Communication business processes of industrial enterprises in the conditions of globalisation. *International Journal of Management*, 11(5), 884–895. <https://doi.org/10.34218/IJM.11.5.2020.081>
- Putri, S. A., & Ibrahim, N. A. (2025). Integration of design for disassembly method using recycled mahogany material. *Mobilya ve Ahşap Malzeme Araştırmaları Dergisi*, 7(2), 33–47. <https://dergipark.org.tr/en/pub/mamad/issue/92174/1674449>

- Rodino, S., Marin, A., Contescu, L., & Voicila, D. (2025). Opportunities for recovery of waste and by-products from the cereal sector. *Proceedings of Sustainable Circular Agro-Economy Conference*, 2(1), 114–125. <https://agris.fao.org/search/en/providers/122612/records/6818892ce8be854272c30bf5>
- Tagliaferro, E. R., & De Queirós, E. S. (2025). Reverse logistics as an instrument for circular economy practices. *International Journal of Sustainable Operations*, 10(2), 89–103. <https://www.researchgate.net/publication/393049632>
- Tornatzky, L. G., & Fleischer, M. (1990). *The process of technological innovation*. Lexington Books.
- Trist, E. L., & Emery, F. E. (1960). *The socio-technical system: Its objectives and characteristics*. [Original publication; cited in historical systems theory].
- Wang, J., Li, R., & Song, D. (2022). Machine learning applications in environmental systems: Advances and challenges. *Journal of Cleaner Production*, 355, 131789. <https://doi.org/10.1016/j.jclepro.2022.131789>
- World Bank. (2023). *What a waste 2.0: A global snapshot of solid waste management to 2050*. World Bank Publications. <https://datatopics.worldbank.org/what-a-waste/>
- Xie, L., Zhang, R., Zhan, J., Li, S., Shama, A., & Zhan, R. (2022). Wildfire risk assessment in Liangshan Prefecture, China based on an integration machine learning algorithm. *Remote Sensing*, 14(18), 4592. <https://doi.org/10.3390/rs14184592>
- Zhang, S., Song, Y., & Liu, B. (2025). Machine learning-assisted in situ synthesis of functional microbiomes towards sustainable wastewater treatment. *Communications Earth & Environment*, 6(1), 4589. <https://www.nature.com/articles/s43247-025-02489-6>