

Optimizing Waste-to-Energy Technologies in Sub-Saharan Africa: A Systematic Review and Comparative Analysis of Nigeria and Malawi

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Abstract

This review compares Nigeria and Malawi to assess the status of Waste-to-Energy (WtE) technologies and Circular Economy (CE) practices in two contrasting African economies. Using PRISMA 2020 methods, literature reports from 2010–2025 were systematically synthesized from major databases to examine solid waste management (SWM) with respect to CE adoption, WtE applications, and implementation of policies such as the extended producer responsibility (EPR) policy. Across Sub-Saharan Africa, waste is still treated largely as a disposal burden rather than a recoverable resource. Nigeria, a large and complex economy, faces severe logistical challenges in handling massive urban waste volumes. Lagos and Abuja generate 13,000–15,000 t/day and 0.59–0.77 kg/cap/day, respectively. However, there is no substantial record of tapping this potential's energy. Malawi, a smaller, agro-based country, generates lower per-capita waste (0.45–0.6 kg/day), but with extremely high organic content (60–90%), and weak collection systems. The MSW profile of high organic and moisture content, as well as low calorific value in both nations, makes biological WtE pathways such as anaerobic digestion (AD) more suitable than thermochemical options. Generally, the literature shows below-average resource recovery from CE and WtE applications. A vital fraction of the economy (informal recyclers) remains vulnerable to health risks, while weak governance and poor funding undermine system optimization. The existing literature, while valuable, is marked by significant gaps, such as a lack of rigorous comparative and feasibility analyses that connect technical, socio-political, and financial realities. The critical understudy of these key aspects is vital for landfill gas-to-energy (LFGTE), anaerobic digestion (AD), and refuse-derived fuel (RDF) applications in Nigeria, as well as for decentralized AD, controlled landfills, and plastics CE enforcement in Malawi. By doing so, it will provide broader guidance for sustainable SWM in Sub-Saharan African contexts.

Introduction

Waste-to-Energy (WtE) technologies and Circular Economy (CE) principles are particularly significant for a sustainable environment, given that the global waste management challenge is worsening and that we need to manage our resources better in the long run (CPP, 2015; UNEP, 2018). Cities in sub-Saharan Africa are growing swiftly with increasing population, but weak waste management infrastructure makes it hard for them to cope with the resulting increase in waste (Kaza et al., 2018). In many of these cities, 60–80% of their waste ends up in open dumps, with 30–50% collected and properly disposed of by the government (Alao et al., 2024).

The traditional "take-make-dispose" model is a one-way process that involves obtaining raw materials, producing goods, using them, and discarding them without any recovery initiative (Ayad, 2023; John & Mishra, 2023). By assuming that resources are infinitely abundant, this model endangers the environment and public health through uncontrolled waste disposal, thereby incurring substantial management costs (UN-Habitat, 2010; Bongers & Casas, 2022). For instance, as of 2021, less than 20% of plastics were recycled globally (Patel et al., 2022). At the same time, more than half of global CO₂ emissions result from this model (take-make-dispose approach), which also depletes resources more quickly and creates numerous environmental problems (Yang et al., 2022). For this reason, we must adopt circular approaches.

The Paradigm Shift (Circular Economy)

Circular Economy (CE) is an approach to business that seeks to renew and reuse resources rather than waste them. The Ellen MacArthur Foundation (2013) defines the concept through three key principles: reuse, repair, repurpose, or recycle materials to maximize their value. The evolving aim of this model includes redesigning products to prevent waste, thereby transitioning from extractive to restorative practices to restore natural systems. As such, it has expanded over time with the 9R Framework, in which circular approaches are ranked from most to least desired, with waste reduction through efficient use as the most desired (Potting et al., 2017). As such, CE approaches are classified and ranked from high-value activities to lower-value recovery options throughout the material's life cycle. This approach prioritizes actions ranging from making products redundant (abandoning and using an alternative product to prevent waste) to energy recovery via crushing/destruction (when the material is at its lowest value) to waste reduction, emphasizing resource efficiency. Thus, because Waste-to-Energy (WtE) processes involve material destruction even when they recover energy (new value), it is ranked the least (R9: Recovery) among the least popular CE approaches (Potting et al., 2017; Geissdoerfer et al., 2017).

Nevertheless, R9 contributes significantly to long-term system-level circularity by recovering value from residual waste streams that remain beyond the scope of higher-ranked strategies. Over time, as technological capacity improves and regulatory support grows, the relevance of R9 (via WtE processes) is gaining attention, making it an essential component of a comprehensive, future-oriented circular economy framework. Hence, WtE is not only a good idea but also a strategic one in developing nations such as Nigeria and Malawi, which face limited energy resources and abundant unmanaged waste.

In the global north, WtE has since been operationalised as an effective CE strategy, using large plants to treat unrecyclable or reusable solid waste and recover energy (electricity, gas, and heat), thereby reducing dependence on landfills (Themelis, 2023). However, the direct application of systems from the global north has often failed due to the peculiarities of local waste composition and social, economic, and political circumstances (Alao et al., 2022). Therefore, developing economies must adopt a carefully planned, context-sensitive approach that strengthens upstream circular-economy practices, institutional capacity, and sustainable financing before deploying large-scale WtE technologies. However, the existing literature lacks contextual insights for optimal application of WtE technologies across African countries, focusing on theoretical energy potentials or lab-scale technical performance without integrating the economic, social, and political factors that determine a project's viability. As such, this review aims to systematically analyze the existing literature to identify ways to optimize WtE technology integration into CE principles for effective resource recovery and improved municipal SWM in Sub-Saharan Africa, using Nigeria and Malawi as contrasting yet unique case studies. Nigeria's massive population and economy produce enormous amounts of municipal solid waste (MSW), which is both a significant resource opportunity and a management concern (Abila, 2014; Dickson et al., 2023). Similarly, Malawi, a smaller agro-based economy, struggles with rapidly increasing solid waste generation rates, though on a smaller scale (Wisdom & Sithik, 2024). The review's objectives are to identify the most effective (WtE) technologies for each nation, emphasize the critical role of the informal recycling sector, and, by carefully integrating existing research, propose coherent CE solutions that meet each nation's needs.

Methodology and Data Synthesis

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, a systematic review of the relevant literature was conducted to ensure objective and precise reporting (Page et al., 2021). Three basic research questions: (i) What are the current CE practices being implemented for SWM, and to what extent in Nigeria and Malawi? (ii) What WtE technologies are being used and to what level for resource recovery in Nigeria and Malawi? (iii) What are the major challenges and opportunities for optimizing WtE technologies to enhance resource recovery within a CE framework in Nigeria and Malawi? were used to draw inferences and make informed conclusions.

To do this, this study conducted a comprehensive search across major electronic databases: Web of Science, Scopus, and Google Scholar (for regional indexes and grey literature). This study carefully crafted the search terms using Boolean operators, including combinations of: TITLE-ABS-KEY("waste-to-energy" OR "WtE" OR "anaerobic digestion" OR "landfill gas" OR "Landfill Gas to Energy" OR "biogas" OR "incineration" OR "refuse-derived fuel" OR "RDF" OR "pyrolysis" OR "gasification" OR "Energy Recovery from Waste" OR "Compost" OR "Composting") AND TITLE-ABS-KEY ("circular economy" OR "extended producer responsibility" OR "EPR" OR "solid waste management" OR "Plastics ban" OR "Waste Treatment" OR "Resource Recovery" OR "Material Recovery" OR "Waste Valorization") AND TITLE-ABS-KEY ("Nigeria" OR "Lagos" OR "Abuja" OR "Ogun state" OR "Malawi" OR "Lilongwe" OR "Blantyre" OR "Mzuzu") AND PUBYEAR > 2009 AND PUBYEAR < 2026. Open-web confirmations include World Bank Lagos waste statistics; Lagos Waste Management Authority (LAWMA) releases, Abuja WtE potential; Malawi plastics regulation/enforcement; Malawi market-waste compost and biogas studies. Similar searches were conducted across related databases, using simplified keywords such as "waste management policy Nigeria," "circular economy Malawi," and "waste to energy challenges Lagos".

Inclusion and Exclusion Criteria

This study included reports that met the following criteria: (a) *Focus*: Addressed any aspect of municipal solid waste management, circular economy, or waste-to-energy within the geographical context of Nigeria and/or Malawi. (b) *Study Types*: Original research articles, review articles, government reports, reports from international bodies (e.g., World Bank, UN-Habitat), and doctoral theses and (c) Studies published between January 1, 2010, and August 31, 2025, in the English language. Exclusion criteria include: (i) studies focusing exclusively on hazardous, industrial, or medical waste without relevance to MSW. (ii) Editorials, letters to the editor, and conference abstracts without sufficient data, and (iii) studies not about Nigeria or Malawi. Subsequently, we imported all the records into a reference management system and removed duplicates. Two reviewers independently screened titles and abstracts against inclusion criteria, followed by full-text assessment for eligibility. Where disagreements arose, we resolved them through discussion and consensus. The required data for synthesis was retrieved using a standardized form that captured authors, year, study location, focus (policy, Technology, and informal sector), key findings, reported challenges, and opportunities. The summary of the study selection process is in the PRISMA 2020 flow diagram (Fig. 1).

Results and Discussion

As shown in Fig. 1, the systematic search across Web of Science, Scopus, and Google Scholar initially identified 2,475 records. After removing 125 duplicates, we screened the remaining 2,350 unique records by title and abstract, excluding 2,160 records that did not meet eligibility criteria (e.g., irrelevant to WtE/CE, not focused on Nigeria/Malawi, or outside the publication window). Full texts of 175 articles were assessed, with 125 excluded for insufficient focus on MSWM or lack of scientific/technical detail. Ultimately, we included 51 studies that met all inclusion criteria in the review.

Waste-to-Energy Technologies: A Critical Overview

To provide a comparative analysis of WtE implementation in the two countries, it was important to establish the distinctiveness of the technologies in use. The literature generally classifies WtE technologies into thermochemical or biochemical waste conversion processes.

Biochemical Waste Conversion VS. Thermochemical Conversion Pathways

The major waste-to-energy technologies differ significantly in terms of maturity, cost, feedstock compatibility, scalability, complexity, outputs, environmental impact, and public acceptability. The global north nations frequently use incineration, pyrolysis, and gasification processes, which are more sophisticated thermochemical methods applicable for a variety of MSW streams (Brunner & Rechberger, 2015). Whereas, biochemical processes, especially anaerobic digestion (AD), are increasingly being used as they are perfectly suited for the high-organic, high-moisture MSW found in developing regions like Nigeria and Malawi, while the widespread use of landfills is attracting the application of Landfill Gas-to-Energy (LFGTE) technology (Meegoda et al., 2018). Reports further show that incineration is the most expensive Technology to set up because it requires sophisticated pollution control technologies. At the same time, the need for complex reactors and pre-processing systems makes gasification and pyrolysis unusable in these regions (Kaza et al., 2018). Because AD and LFGTE require only reactors, gas wells, and generators, they have the lowest capital costs, depending on project size (Boloy et al., 2021; Erdoğdu, 2025). The same is true for operating costs: pyrolysis, gasification, and incineration all require skilled personnel, extensive maintenance, and occasionally additional fuel. LFGTE requires comparatively little assistance to operate, and AD consumes less energy (Arena, 2012; Chen et al., 2014; Logan & Visvanathan, 2019).

Feedstock compatibility is another evident difference between these WtE processes. Thermochemical systems work best with uniform waste streams, high calorific value, and not overly wet, making them ineffective for the wet, organic-rich MSW typical in Sub-Saharan Africa. At the same time, LFGTE and AD work best with waste that can decompose and contains a lot of moisture (Kaza et al., 2018; Ayodele et al., 2017). Additionally, the scale requirements differ: AD can be used in a variety of systems, from homes to cities, whereas incineration is only economical for systems that process more than 100,000 tons annually (Brunner & Rechberger, 2015; Meegoda et al., 2018). Every process has a unique set of environmental issues. For example, gasification releases wastewater and tar; pyrolysis produces liquid waste; AD releases methane; LFGTE releases fugitive emissions; and incineration releases hazardous ash and toxic gases, among others (Meegoda et al., 2018; Corvellec et al., 2022).

The Sub-Saharan African Context: Defining Realities

A unique set of regional facts greatly influences the practical operation of any CE or WtE paradigm. Sub-Saharan Africa's municipal solid waste differs significantly from that of developed nations. It has a high moisture content (> 50%) and a high organic matter content (57–70%) (Somorin et al., 2017; Kaza et al., 2018; Chikukula et al., 2024). The main source of recycling in most African cities is the informal waste sector. Gathering, sorting, and trading recyclables such as cardboard, metals, and plastics creates jobs for millions of people (Chukwuka, 2025). They prevent 10–20% of garbage from entering landfills, extending the life of dumpsites, conserving resources, and reducing greenhouse gas emissions. This activity provides funds to underprivileged communities (Kaza et al., 2018; Ukala et al., 2020). However, informal waste recyclers are at risk of being forced out by large WtE projects, of injuries and other harms from waste, of being denigrated by society, or of financial exploitation (Velis, 2017; França et al., 2022). Sustainable formal waste management and social justice must integrate informal recyclers through contractual engagement, safety support, cooperatives, or recognition (Ezeudu & Ezeudu, 2019; Chukwuka, 2025). Another existing reality is governance structures, which have a big impact on how well resource recovery initiatives work in Sub-Saharan Africa. The systems are weak due to outdated regulations, ambiguous roles, inadequate institutions, and erratic funding (Armoo et al., 2024; Kaza et al., 2018). Policy makers still rely on a simple "collect-and-dispose" model due to underfunding and sporadic donor assistance, which complicates operational continuity. While there is also a lack of technical know-how and reliable data, political instability and ineffective financial policies can cause public-private partnerships to fail (Olele, 2016; World Bank, 2024).

Comparative Analysis: System baselines & CE policy environment

Nigeria's Complex Economy vs. Malawi's Agro-Based System

One of Africa's most populous nations, Nigeria, continues to struggle with solid waste management amid rapid urbanization. Its MSW generation is estimated at 32 million tons annually, projected to reach 45 million tons in five years, most of which remains uncollected or untreated and ends up in open dumps (Olusunmade et al., 2019; Oyeboode, 2022; Dennison et al., 2025). Major cities produce high volumes: Lagos generates 12,000–15,000 tons/day with high organic content (50–60%) and with plastics and dry recyclables, while Abuja produces 0.59–0.77 kg/capita/day, totaling 0.7–0.97 million tons/year, indicating substantial energy recovery potential (Ogwueleka, 2013; Somorin et al., 2017; Ondachi et al., 2023; Etim et al., 2024). WtE development in Nigeria is growing as a solution to waste and energy deficits (Oyeboode & Aderomose, 2024). AD is increasingly applied for biogas and fertilizer (digestate) production, while LFGTE is promising with several mega-landfills (Adeleke et al., 2023). Other advanced thermochemical processes like incineration and gasification have remained at pilot-scale level due to limited infrastructure and technical know-how (Etim et al., 2024). Governance largely depends on state-owned organizations, such as the Lagos Waste Management Authority (LAWMA), which employs Private Sector Participation (PSP), extended producer responsibility (EPR), and national frameworks to address solid waste issues (FME, 2022; Anyaogu, 2024). Most past resource recovery projects, such as large-scale composting and other WtE initiatives, have failed due to feedstock mismatches, poor financing, and regulatory constraints (Anestina et al., 2014; Olele, 2016). At the same time, significant studies on the technical and economic potentials have emerged; stakeholders

continue to overlook socio-political and institutional barriers, indicating the need for integrated, empirical socio-technical studies.

Malawi, a smaller, agriculture-dependent economy, generates about 4.8 million tons of waste annually, most of which is uncollected and discarded (Kamanga et al., 2024). Most of the generated MSW is organic, typically between 70–80% as observed in major cities like Lilongwe and Blantyre (CTCN, 2022; Chikukula et al., 2024). Compared to Nigeria, per capita waste generation in the country is lower (0.45–0.6 kg/day), and less than 30% of it is collected (Mpanang'ombe et al., 2018; Kamanga et al., 2024). The literature reports that the two largest cities, Blantyre and Lilongwe, are struggling with inconsistent service. While poorly designed dumpsites show little promise, the WtE development is still in its infancy (Beyene et al., 2018). Only a small number of localized AD systems can handle large amounts of organic waste. Due to their high moisture requirements, limited infrastructure, and low calorific value, thermochemical processes are not particularly beneficial (Mpanang'ombe et al., 2018; Kamanga et al., 2024). Despite limited funding and weak implementation, the 2015 thin-plastics law and the 2019–2029 Waste Management Strategy both incorporate CE principles (Turpie et al., 2019). Composting and biogas are the focus of numerous small-scale initiatives, run primarily by donors or non-governmental organizations. With limited market demand and budgetary inclusion, these initiatives typically fail when the funds run out (Ngwemba, 2024). There is a lot of research on low-tech, organic remedies, but not much on financially feasible, scalable models or Malawi-specific public-private partnership (PPP) strategies.

Prospects and limitations of WtE Technologies Optimization in Malawi and Nigeria

Studies across Nigeria and Malawi highlight diverse WtE and CE potentials. In Lagos, 12,000–15,000 t/day of high-organic, recyclable waste could support RDF-to-cement, AD hubs, and LFGTE at mega-landfills, though source separation and informal sector integration remain limited (Olukanni & Oresanya, 2018; Etim et al., 2024; Amulah et al., 2024). Abuja's MSW (0.59–0.77 kg/cap/day) shows significant WtE potential, but high organic content constrains incineration, and pilot data is limited (Ogwueleka, 2013; Ondachi et al., 2023). In Malawi, > 60–90% organic waste supports AD and composting, but with moderate social acceptance, the installed capacity remains at a pilot level (Chiumia et al., 2025). It is further evident that Nigeria's very large, mixed waste flows are well-suited to co-processing utility-scale LFGTE, AD, and RDF. Malawi's high organic content and lower tonnage suggest decentralized AD/composting, market-level digesters, and sanitary landfilling, with potential for LFG capture.

Implementing WtE and improving its performance in Malawi and Nigeria is fraught with difficulties. WtE utilization offers a rewarding opportunity for Nigeria, given its large population, which generates significant waste while enduring an insufficient energy supply. However, inconsistent collection, a lack of source segregation, a lack of funding, and a lack of technical expertise are the reasons behind the slow progress (Igbinomwanhia et al., 2013; Njewa et al., 2022; Oyebode & Aderomose, 2024; Effiong et al., 2024; Etim et al., 2024). Due to weak national policies, a lack of infrastructure for recycling, low public awareness, financial difficulties, and divided institutional responsibilities, Malawi is working on local, decentralized WtE options, but progress is slow (Kamanga et al., 2024; Chiumia et al., 2025). While both nations are burdened by weak laws and policies, this is further compounded by low compliance with the few that do work (Onungwe et al.,

2023). In addition, despite abundant potential and opportunities, the implementation and optimization of advanced WtE technologies are derailed by limited existing expertise and a lack of public understanding and acceptance of WtE projects due to perceived environmental and health concerns (Beyene et al., 2018).

Circular Economy Integration and WtE Optimization Strategies

The concept of CE is gaining recognition among the wider public as a fundamental principle for sustainability in Nigeria, although it is still in its early stages of implementation (Onungwe et al., 2023). The literature shows that the often overlooked informal sector is the major driver of recovery of plastics, metals, and electronic waste, as well as other resources from waste. New private businesses and international partnerships are the main forces behind CE projects (Ezeudu & Ezeudu, 2019; Chukwuka, 2025). EPR programs and other policies that support CE practices are still in their early stages and often focus more on resolving problems at the end of the process than on implementing significant reforms (OECD, 2016; Ezeudu & Ezeudu, 2019; Onungwe et al., 2023). WtE technologies, when properly designed, can serve as a key enabler of the CE by diverting waste from landfills, recovering energy, and, in the case of AD and pyrolysis, producing valuable by-products (e.g., digestate, biochar) that can re-enter the economy (Ighalo & Adeniyi, 2020; Aigbavboa, 2020). By converting organic waste into energy and soil nutrients, WtE applications such as composting and AD systems help create localized CE loops in regions (Mpanang'ombe et al., 2018; Kaza et al., 2018). One of the major strategies to maximize resource recovery and optimize WtE technology applications in Nigeria and Malawi is the formal engagement of informal waste workers through cooperatives, the implementation of safety precautions at material recovery facilities (MRFs), and social protection supported by EPR policies (Kasinja & Tilley, 2018). Using the framework in Fig. 2 and implementation of the strategies outlined in Table 1 will enable the countries to transform their challenge into opportunities for energy security and a long-term circular economy implementation (Mpanang'ombe et al., 2018; Turpie et al., 2019; Okeniyi et al., 2020; Chitempa et al., 2020; Kumwenda et al., 2021; Yesaya, 2021; OECD, 2024; World Bank, 2024; Chiumia, 2025; Chamdimba, 2025; RPRA, 2025)

Table 1
Strategies for Optimizing WtE and CE in Nigeria and Malawi

Strategy Area	Actions Points for Nigeria	Actions Points for Malawi
WtE Technology Implementation	- <i>LFGTE at Priority Landfills</i>: Phased capping, vertical wells, flares to gensets; leverage carbon finance/methane abatement at Olusosun & other Lagos sites. - <i>AD Hubs for Segregated Organics</i>: Co-located with produce markets/transfer stations; digestate sold as biofertilizer; enforce contamination thresholds via contracts. - <i>RDF for Cement Kilns</i>: Scale MRFs to extract recyclables, then densify high-calorific value fractions; align with Lafarge/Dangote co-processing protocols and emissions compliance - <i>Invest in Diversified WtE Technologies</i>: Explore and scale up advanced thermochemical technologies (pyrolysis, gasification) that offer higher resource recovery potential, alongside well-managed AD systems.	- <i>Decentralized AD at Markets & Institutions</i>: Replicate Lizulu-scale pilots; standardize 40–500 m³ digesters; bundle carbon + cooking fuel substitution in Lilongwe, Blantyre, Mzuzu. - <i>Upgrade Dumpsites → Controlled Landfills</i>: Phased cells, leachate control, cover material management for future LFG capture readiness (City assessments). - <i>Organics Management</i>: Pair AD with composting for overflow seasons; establish quality standards for compost/digestate to stimulate agricultural uptake. - <i>Prioritize Decentralized, Appropriate WtE</i>: Focus on scaling up biogas, composting, and potentially small-scale pyrolysis or gasification for organic waste, aligning with local needs and capacities.
Policy & Regulatory Frameworks	1 <i>Strengthen Policy and Regulatory Frameworks</i>: Enact and enforce policies supporting CE principles, including EPR schemes, WtE tariffs, and incentives for private investment. 1 <i>Operationalize plastics EPR</i> through Producer Responsibility Organisations (PROs): execute 2024–2025 plastics restrictions; publish gate-fees + quality specs for organics/RDF; embed CE key performance indexes (KPIs) in state concessions. 1 <i>Issue organics & RDF quality specs + gate fees</i>; close procurement on LFGTE; sign RDF supply MoUs with cement; enforce plastics EPR/ban phases; integrate informal sector into MRFs.	1 <i>CE Policy Execution</i>: Sustain thin-plastics enforcement; pilot plastics EPR in packaging; integrate informal sector in collection/sorting co-ops (Blantyre feasibility). Create a comprehensive policy that guides waste management from source to final disposition, with clear targets for resource recovery and CE integration.

Strategy Area	Actions Points for Nigeria	Actions Points for Malawi
Integrated SWM & Infrastructure Development	– <i>Develop Integrated SWM Systems</i>: Prioritize source segregation, comprehensive waste characterization, and establishment of material recovery facilities alongside WtE plants.	– <i>Malawi (Lilongwe/Blantyre Specifics)</i>: Replicate 40–500 m³ market digesters; publish digestate standards; ring-fence user tariffs/landfill tipping fees; sustain thin-plastics enforcement; pilot packaging EPR; phase sanitary landfill cells with design provision for future Landfill gas (LFG).
Capacity Building & Stakeholder Engagement	• <i>Capacity Building and Technology Transfer</i>: Invest in training for WtE plant operation and maintenance, and foster international collaborations for technology transfer. • <i>Formalize and Integrate the Informal Sector</i>: Develop policies to recognize, support, and integrate informal waste pickers into formal recycling and resource recovery value chains.	• <i>Community Engagement and Awareness</i>: Implement robust public awareness campaigns to promote waste reduction, segregation, and the benefits of WtE and CE • <i>Strengthen Local Government Capacity</i>: Provide technical and financial support to local authorities for effective SWM planning and implementation. • <i>Seek International Partnerships and Funding</i>: Leverage global climate finance and technical assistance to invest in sustainable SWM and WtE infrastructure.

Summary and Gaps for Future Studies

This review highlights the intricate, situation-specific characteristics of resource recovery in Sub-Saharan Africa. However, the CE paradigm and WtE technologies offer a variety of opportunities. Successful application depends on navigating socio-political and financial constraints, understanding technology peculiarities, acknowledging the critical role of informal recyclers, and adapting to local waste characteristics.

Comparing Nigeria and Malawi reveals both common issues and variations in the implementation of CE and WtE initiatives. While Nigeria, with its economic capacity and high waste generation, shows greater readiness for larger-scale, more advanced WtE technologies, Malawi's strength lies in its potential for decentralized, community-based composting and AD operations that align with its agrarian economy and local energy needs. To optimize WtE for resource recovery within a CE framework in Nigeria, it is necessary to shift towards integrated SWM, emphasizing waste segregation and upstream reduction. The nation should prioritize investment in thermochemical processes such as pyrolysis and gasification to handle mixed waste and produce valuable resources, including syngas, biochar, bio-oil, and energy. Furthermore, concerned stakeholders need to strengthen frameworks that encourage private-sector participation, EPR schemes, and the formalization of the informal sector. For Malawi, scaling up existing successful biogas and composting initiatives, especially in rural and peri-urban areas, is essential. The development of a national SWM policy that explicitly integrates CE principles and supports decentralized WtE solutions is crucial. Capacity-building initiatives at local and regional levels, along with public awareness campaigns, will be vital for successful implementation. Generally, for both nations, the 'waste hierarchy' principle of CE must be upheld, prioritizing waste reduction, reuse, and recycling before WtE. Before adopting any WtE technology, a detailed understanding of the existing realities is fundamental. Nevertheless, WtE should be viewed as a Key option for managing residual waste while ensuring that valuable materials are not unnecessarily incinerated or

anaerobically digested. In addition, regulators should thoroughly evaluate the environmental and social impacts of WtE technologies to avoid detrimental and unsustainable practices.

The results of this review show that three critical literature gaps become apparent: (i) *Comparative Gap*: There is limited rigorous comparative research that juxtaposes the realities of different African economies. This comparison is essential for understanding how varying political, economic, and social contexts shape resource recovery pathways. (ii) *Integration Gap*: Existing research often remains siloed, focusing on either technical feasibility, policy analysis, or social aspects. A holistic approach that *integrates* these dimensions, linking waste composition to technology choice, financial models to policy frameworks, and formal projects to the informal sector, is critically needed (iii). *Practicality Gap*: More research on the life-cycle assessment (LCA) of various WtE technologies in the specific contexts of Nigeria and Malawi is needed to understand their environmental footprints fully. Economic feasibility studies that consider local market conditions and policy incentives are also crucial. Additionally, research into social acceptance and the role of indigenous knowledge in sustainable SWM and resource recovery could provide valuable insights.

Conclusion and Recommendations

In conclusion, it is safe to say the dual crises of waste management and energy deficiency in Sub-Saharan Africa demand urgent and innovative solutions. While existing research has established the theoretical potential for WtE, it has largely failed to address the integrated, social-to-technical question of how this potential can be sustainably and rightly realized within the unique economic realities of the regions. This review highlights the importance and available opportunities of optimizing WtE technologies for resource recovery and CE advancement in Nigeria and Malawi. While both countries face distinct challenges, strategic interventions can unlock substantial environmental, economic, and social benefits. Nigeria's large economy enables widespread LFGTE and RDF use in cement production, provided EPR policies are effective and material recovery facilities ensure consistent feedstock quality through improved waste sorting. Malawi's advantage is the *quality* of organic feedstock available in markets, schools, and commercial hubs, making decentralized AD the fastest, lowest-risk WtE entry. At the same time, CE enforcement for plastics and gradual landfill engineering lay the foundations for medium-term LFGTE. Hence, Nigeria can prioritize LFGTE at mega-landfills, scale AD hubs for organics, and lock in RDF offtake for cement manufacturing, under a tightened EPR/plastics regime. While Malawi can replicate market- and institution-based AD, enforce thin-plastics rules, and pilot EPR, engineer-controlled landfills to enable future FRDFLFG capture. The way forward requires moving beyond diagnosis to prescription. Future research must address the identified gaps by conducting in-depth, mixed-methods comparative analysis of different national contexts. By systematically evaluating WtE technologies and CE practices against the unique technical, economic, policy, and social realities of each country, it is possible to develop the integrated, context-sensitive frameworks that are currently lacking. The ultimate aim is not to analyze the problems, but to synthesize the findings into a practical tool to guide policy and investment toward optimized, sustainable resource recovery. Such a framework must answer critical, practical questions, such as how to structure a public-private partnership to mitigate risks in the Nigerian political context, or what specific policy levers can create a viable market for compost in an agro-based economy like Malawi's. By filling this void, research can make a significant contribution to advancing a truly sustainable and equitable circular economy in diverse African settings.

Limitations of the Study

Open-access journals and official sources were the main sources of the synthesized reports and comparative analysis. Due to their inability to access subscription-based publications, the user could not access all WoS/Scopus products. The study cited reputable sources to support the primary data, including Lagos tonnage, Abuja per capita ranges, Malawi organics supremacy, and plastics policy regimes.

Abbreviations

- i. SWM = Solid waste management
- ii. CE = Circular economy
- iii. WtE = Waste to Energy Technology
- iv. MSW = Municipal Solid Waste
- v. LAWMA = Lagos Waste Management Authority
- vi. EPR = Extended producer responsibility
- vii. RDF = refuse-derived fuels
- viii. AD = Anaerobic digestion
- ix. LFGTE = Landfill gas to energy

Declarations

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Figures

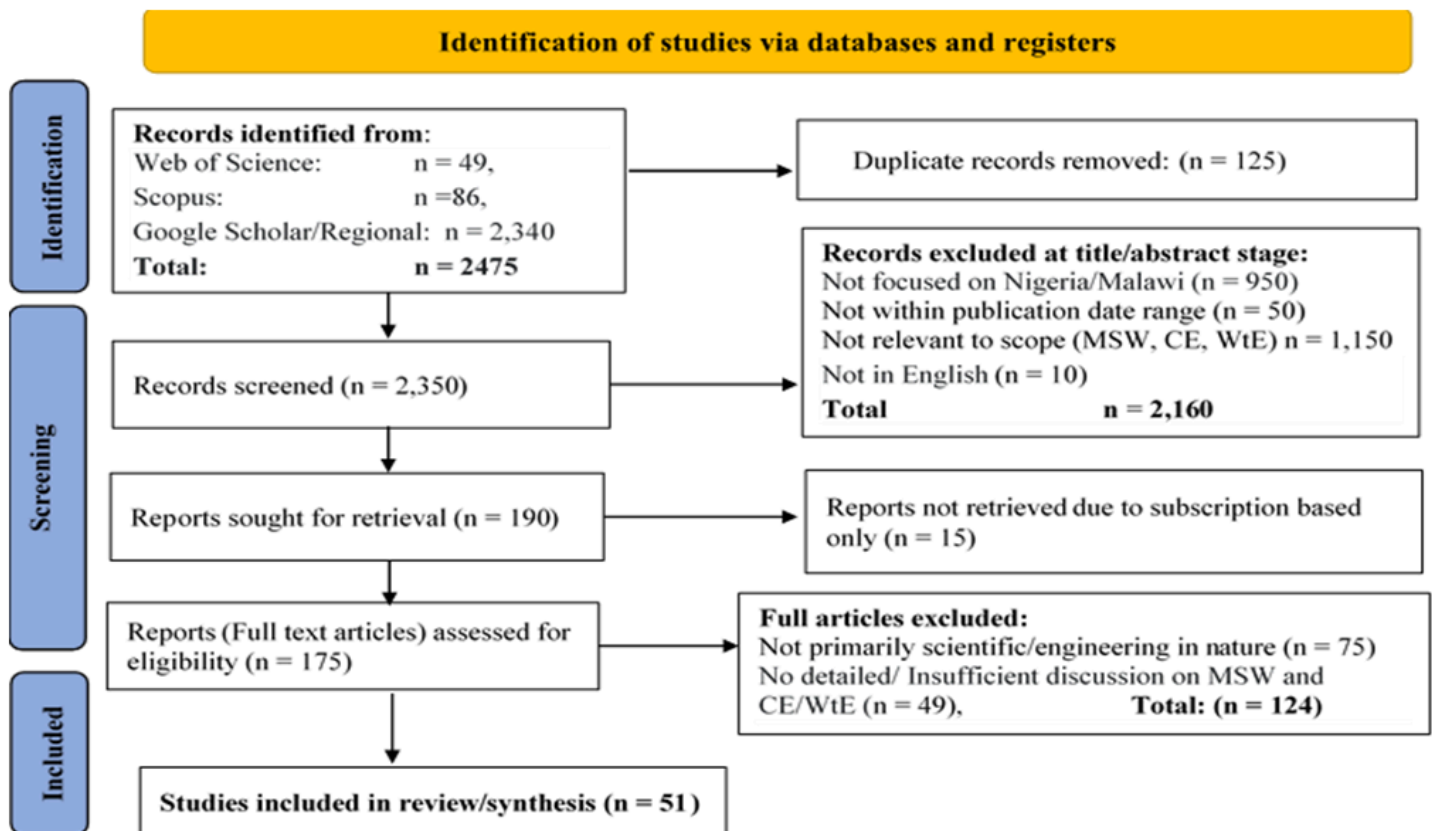


Figure 1

PRISMA 2020 Flow Diagram for Study Selection (Page et al., 2021)

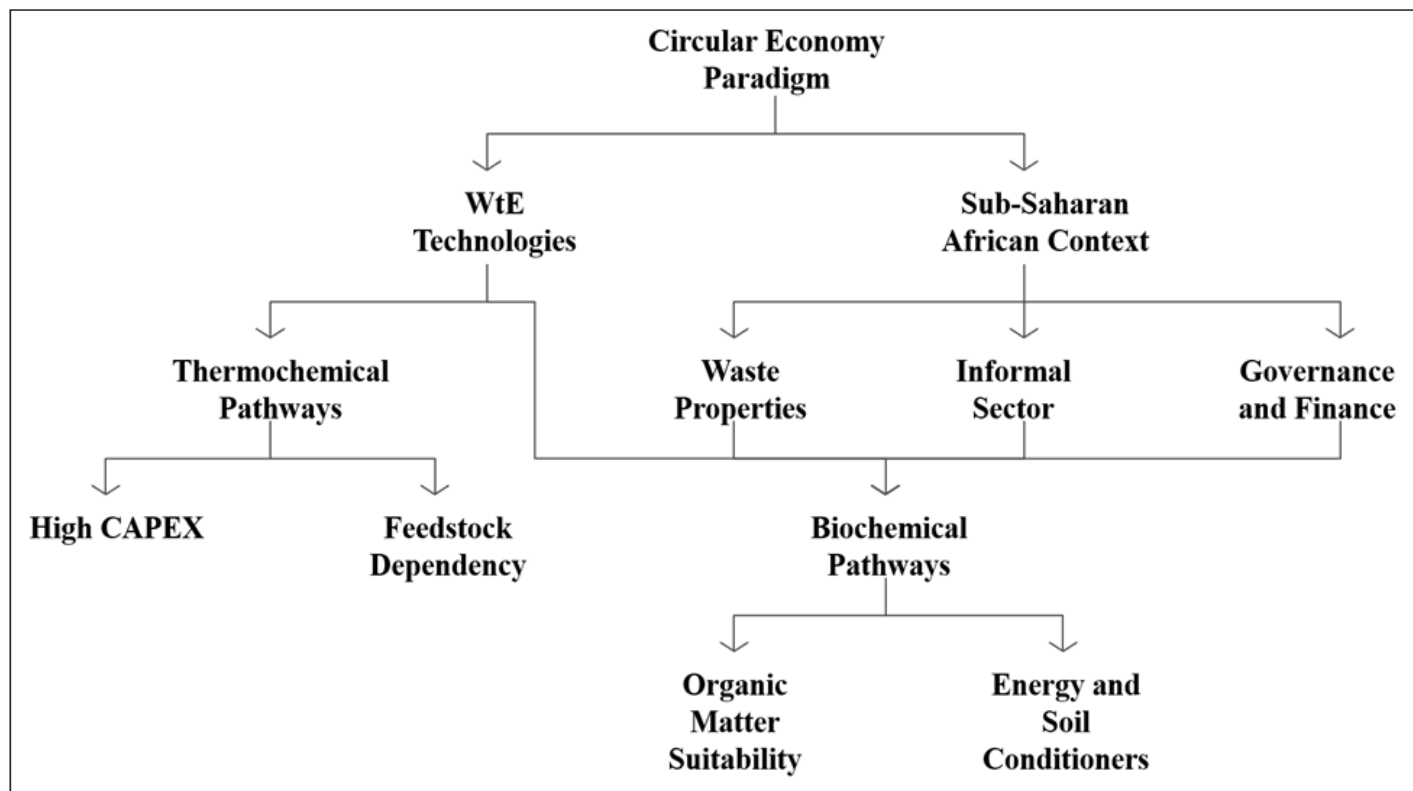


Figure 2

Framework for choosing appropriate WtE technology for CE implementation