REVIEW

Optimization of biogas production using municipal solid waste in sub Saharan Africa: a systematic review

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Abstract

Biogas derived from Municipal Solid Waste presents a viable pathway toward sustainable energy generation and improved waste management in Sub-Saharan Africa. This review synthesizes over 80 studies to evaluate optimization strategies for MSW-based biogas systems across the region. The analysis identifies key technological configurations, fixed-dome, plug-flow, and continuously stirred tank reactors, and their associated optimization techniques, including co-digestion, feedstock pretreatment, and parameter control. Results indicate that co-digestion can increase methane yield by 25–40%, while temperature and hydraulic retention time optimization enhance gas output by up to 30%. However, implementation remains constrained by limited financing, technical capacity, and inconsistent policy support. Comparative insights from Asia and South America reveal that sustained subsidies, training programs, and public–private partnerships significantly enhance adoption and yield outcomes. The review emphasizes the importance of integrating technological optimization with economic feasibility and social acceptance, ensuring scalable and inclusive biogas systems. Unlike previous studies, this review systematically maps optimization pathways specific to the SSA context, linking technology, finance, and governance to guide future sustainable energy transitions.

Keywords Fixed dome digesters, Biogas, Optimization, Sub-Saharan africa, Renewable energy, Anaerobic digestion, Municipal solid waste

1 Introduction

Recently, waste management has become a global concern because of inefficient collection and improper disposal methods [1, 2]. The increase in urbanization and population growth has fueled this problem. According to previous studies, waste generation per person ranges from 0.11 to 4.54 kg, depending on the region [3, 4]. Waste management is a complex and expensive process. It accounts for approximately 19% of the total annual municipal expenses in low-income countries, 11% in middle-income countries, and 4% in high-income countries [5]. This poses a significant challenge for developing and underdeveloped nations, affecting both national and local levels of government. In

many Sub-Saharan (SSA) cities, inadequate infrastructure and weak governance lead to open dumping and burning, contributing to pollution and public health [2, 6]. Nonetheless, efforts are underway to enhance waste management practices in the different cities. For example, the World Bank has supported initiatives like the Nairobi Metropolitan Services Improvement Project in Kenya, which aims to upgrade solid waste management infrastructure and services [2, 7]. Additionally, local governments and non-governmental organizations (NGOs) have implemented community-based waste management programs to promote recycling and composting, reducing the volume of waste sent to landfills. Despite the ongoing intervention from different projects and local recycling initiatives, financial, institutional, and public awareness gaps persist [6, 8, 9].

Biogas provides a promising solution by converting the organic fraction of municipal solid waste (MSW) into renewable energy through anaerobic digestion. Organic waste, a significant component of MSW in the region, can be effectively converted into biogas by anaerobic digestion [10–13]. Various biogas production technologies exist, ranging from simple, low-cost digesters suitable for small-scale applications to more advanced systems suitable for extensive facilities [6, 14]. Small-scale household digesters, such as fixed-dome and floating-drum designs, are popular in rural areas and utilize organic waste from households or agricultural activities to produce biogas for cooking and lighting [14–16]. Larger-scale digesters, such as continuously stirred tank reactors (CSTRs) and plug-flow digesters, are suitable for urban areas and can process higher volumes of organic waste from municipal sources [17–19]. However, the uptake of biogas technologies in SSA is constrained by limited financing, poor waste collection systems, and insufficient technical capacity for design and maintenance [20, 21]. Additionally, insufficient awareness of the benefits of biogas among policymakers and the general population hinders its widespread adoption [12, 17]. Figure 1a and b illustrate small-scale household digesters and large-scale biodigesters, respectively, available in Sub-Saharan Africa.

Biogas production technology is now widely used across Europe, Asia, and America, and with countries such as Germany, Switzerland, Italy, and Brazil leading the way

(a)

(b)
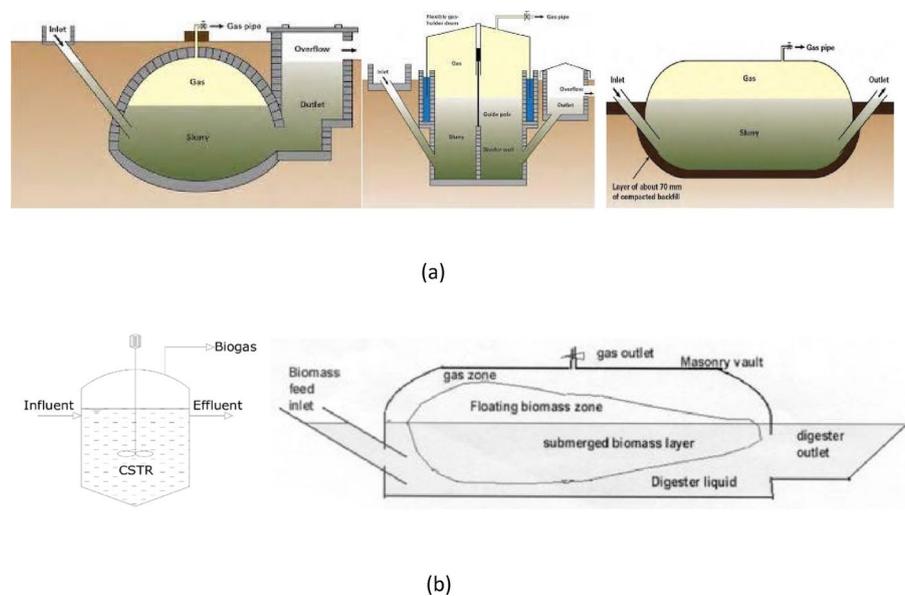
Fig. 1 **a** Small-Scale Biogas Production Technologies, Vögeli et al. [22] . **b** Larger-scale biogas production technologies, Vanhoudt et al. [23]

[24, 25]. The production and utilization of biogas are also expanding in the developing nations such as India, Nepal, Tanzania, Rwanda, Uganda, and South Africa [15, 26, 27]. Despite the potential for biogas to improve energy supply, sanitation, and food security in SSA, the adoption of biogas systems has been slow and inconsistent [11, 28]. Typical feedstocks include livestock manure, human waste, municipal waste, and wastewater [27, 29, 30]. However, many biogas systems have faced challenges in sustaining gas production due to inadequate operating conditions, such as low digester temperatures and poor feed quality [31].

Optimization of MSW-based biogas systems is crucial because yield variability, feedstock inconsistency, and operational inefficiencies remain the primary causes of digesters' underperformance in SSA. Many digesters in SSA operate at sub-optimal temperatures (18–25 °C instead of 30–40 °C) and experience frequent system failures, reducing methane yield by up to 40% [15, 31, 32]. Optimization through feedstock co-digestion, temperatures, and pH regulations, and real-time process control enhances microbial stability, gas retention, and methane concentration. Without these improvements, systems remain inefficient, financially unviable, and prone to failure, undermining the sustainability of waste-to-energy initiatives. Extensive research has examined physical, chemical, and biogas upgrading technologies for enhancing the gas quality [33, 34]. While chemical methods can improve methane concentration, they require high energy inputs and costly chemicals [35]. Biological upgrading and CO_2 conversion within anaerobic digestion systems present a more sustainable, low-energy approach suitable for SSA's resource constraints [36].

To optimize biogas production from MSW, it is essential to carefully evaluate the factors that impact the anaerobic digestion process's effectiveness. Among these factors is the composition of the feedstock, which can vary by location and season, significantly influencing both the quantity and quality of the biogas yield [37–39]. Proper segregation, pretreatment, inoculation, water addition, and mixing ensure optimal microbial activity and methane production [40]. Additionally, Co-digestion of MSW with agricultural residues or animal waste has proven to balance nutrients, improve C/N ratios, and enhance methane yield by 25–30% [41–43]. Despite these opportunities, technical, financial, and infrastructural challenges have slowed adoption in SSA. This review addresses these gaps by evaluating existing technologies, optimization techniques, and implementation barriers. It provides practical insights for policymakers and researchers to scale sustainable waste-to-energy systems in the region. Unlike prior reviews, this study systematically maps optimization pathways specific to the SSA MSW context, integrating technological, economic, and environmental perspectives to inform future waste-to-energy strategies.

2 Methodology

2.1 Literature review

The literature review for this study focused on identifying studies relevant to the optimization of biogas production using MSW in Sub-Saharan Africa. Specific criteria were employed to select literature that aligned with the objectives of this study, including studies that investigated optimization strategies, technological advancements, challenges, and opportunities related to biogas production from MSW in the region. Key selection criteria included the geographical focus on Sub-Saharan Africa, the relevance

to biogas production optimization, and the inclusion of empirical evidence or case studies. A checklist was used to ensure systematic data extraction and assessment for each study. This checklist contained questions designed to evaluate the methodological rigor, relevance, and quality of each selected paper. The questions included in the checklist addressed aspects such as: (a) What are the biogas production technologies? (b) What are the optimization techniques for biogas production? (c) How do feedstock composition and availability variations affect the efficiency of biogas production systems? (d) What challenges are faced in optimizing biogas production in Sub-Saharan Africa?. By using this checklist, the information extracted from each paper was standardized, enabling a consistent and thorough evaluation of the literature.

2.2 Data acquisition and search

The data acquisition process began by identifying keywords aligned with the research objective, including "Fixed Dome Digesters technology," "optimization," "Municipal Solid Waste," "Anaerobic Digestion," and "Biogas." These keywords were carefully selected to maintain focus on optimizing biogas production through anaerobic digestion. A key limitation was the exclusion of materials not available online. To ensure relevance, we verified that the selected sources had a clear link between biogas optimization and anaerobic digestion, and we assessed their suitability by reviewing titles, abstracts, and conclusions. Familiarizing ourselves with the chosen literature helped reduce bias and enhance understanding. We applied specific inclusion and exclusion criteria, focusing on literature written in English, prioritizing studies from Sub-Saharan Africa while incorporating relevant global insights, and selecting original research and review articles that provided scientific evidence. Letters to the editor were excluded due to their limited scope, and only peer-reviewed publications were considered, with verification based on the editorial board, journal authenticity, and structured content. The search was conducted using reputable scientific databases such as Web of Science, Sage, and Science Direct, resulting in the selection and review of 80 relevant articles, as shown in Fig. 2. Following full-text screening and eligibility assessment, a total of 80 peer-reviewed articles met the inclusion criteria and were included in the qualitative synthesis.

3 Finding and discussion

3.1 Biogas production technologies implemented in Sub-Saharan Africa

Sub-Saharan Africa (SSA) is currently facing significant energy-related challenges, prompting a growing interest in sustainable solutions, particularly biogas technologies [45, 46]. These technologies offer a practical means to meet energy needs while mitigating environmental impacts, especially in the traditional African context. In SSA, biogas production technologies range from simple biodigesters, such as traditional fixed-dome digesters commonly used in rural communities, to more sophisticated anaerobic digestion systems such as floating-drum digesters and continuously stirred tank reactors (CSTRs) [17, 26, 27]. Fixed-dome digesters are favoured because of their simplicity, affordability, and low maintenance costs, with lifespans exceeding 20 years, making them the most popular choice in countries such as Burundi, Ivory Coast, Uganda, and Kenya [47–49]. However, despite their widespread use, these systems often lack efficiency and scalability, with biogas yields ranging from 0.02 to 0.07 m³ per ton of feedstock, and methane content typically between 50 and 70% [50]. Studies, such as those by Mungwe
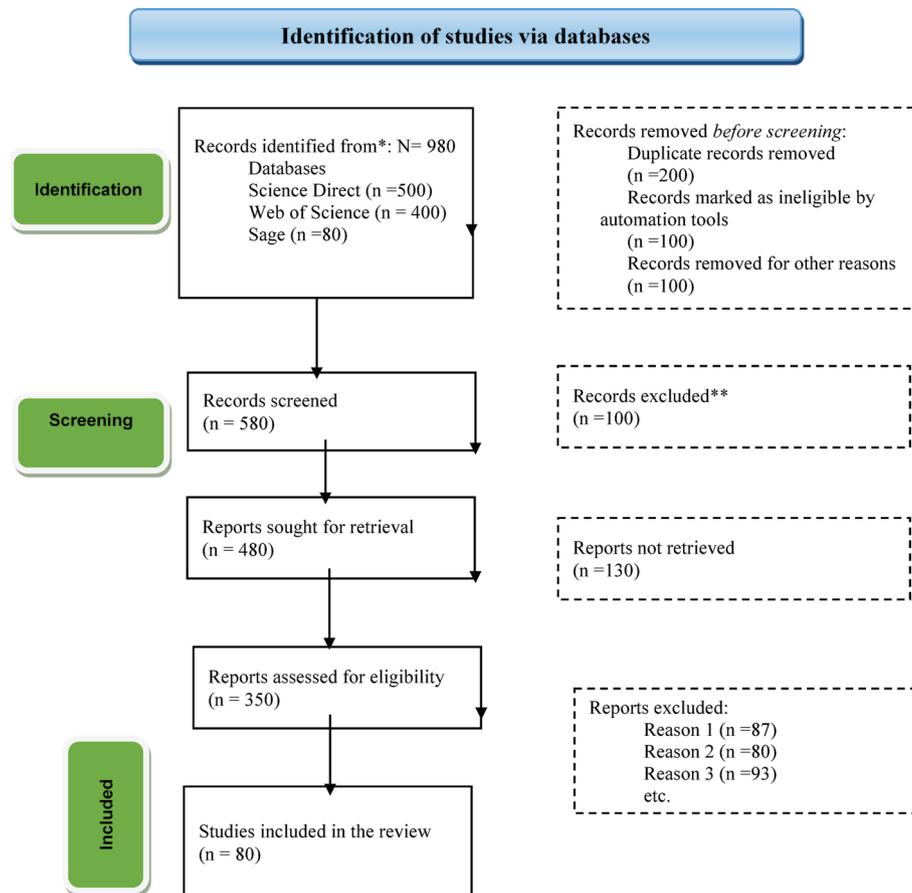
Fig. 2 PRISMA 2020 flow diagram illustrating the identification, screening,eligibility assessment, and inclusion of studies for the systematic review ofMSW-based biogas optimization in Sub-Saharan Africa. Page et al. [44]

et al. [51] and Erraji et al. [52], highlight the challenges in optimizing biogas production in SSA, pointing to issues such as poor mixing, suboptimal operating temperatures, and the need for further research to maximize the potential of digesters at full capacity [52–54]. Comparatively, regions such as Asia and South America have seen greater success in biogas technology adoption owing to government incentives, advanced technologies, and innovative financing models. For example, in China, extensive subsidies and training programs have resulted in higher adoption rates and methane yields of up to 0.35 m^3 per kg of volatile solids, while in Brazil, large-scale biogas plants benefit from public-private partnerships, generating over 3.5 billion cubic meters of biogas annually [55–57]. However, in SSA, high upfront costs and limited technical expertise remain significant barriers. For instance, the capital cost of a household biogas digester in Nigeria ranges between $700 and $1,200, leading to low adoption rates of approximately 15% [12, 50, 58]. Moreover, the limited adoption of commercial biodigesters across SSA in countries such as Nigeria, Ghana, Uganda, Kenya, and South Africa further underscores the need for supportive policies and financial mechanisms to lower costs and improve technical support [21, 27, 47, 59].

Countries such as Kenya, Tanzania, and Uganda have made notable progress in promoting biogas as a viable renewable energy source, supported by government incentives and grassroots initiatives. Pilot projects and community-based programs in these countries have demonstrated the socioeconomic benefits of biogas technology, particularly

in rural electrification and waste management. However, the lack of published research on biogas technology, especially on biogas upgrading systems and their integration with Artificial Intelligence for monitoring biogas quality and yield, indicates a significant research gap that needs to be addressed. A study conducted by Tshemese et al. [5] in South Africa revealed that combining sugarcane wastewater with municipal solid waste for digestion produced more biogas than using single substrates alone. This finding underscores the potential of this method to help tackle the country's energy issues. However, the research also highlighted a gap in studies on biogas production in South Africa, which has led to unresolved problems with existing biodigesters.

To address these issues, governments in SSA should adopt policies that enable access to cost-effective financing options, such as low-interest loans and subsidies akin to India's National Biogas and Manure Management Programme. Additionally, investing in training initiatives and technical assistance can enhance the long-term viability of biogas systems. By drawing lessons from successful examples in Asia and South America, SSA can create customized policies that promote the integration of biogas technologies with local farming practices and waste management systems, ultimately supporting energy security and environmental sustainability in the region. Conducting relevant research to adapt biogas technology to local conditions could unlock the potential of substantial agricultural residues, animal waste, and municipal and industrial wastewater, thereby providing a renewable energy alternative throughout SSA. As seen in Table 1.

Table 1 Biogas technologies implemented in Sub-Saharan Africa (SSA)

Country	Biogas production technology	Biogas yield (m³ t⁻¹) of Substrate	Biogas quality (% CH₄)	Performance level	Optimization Potential / Limitation	Reference
Kenya, Nigeria, Burundi, Tanzania, Uganda, Burkina Faso, Ivory Coast, and Ethiopia	Fixed dome digesters	0.02–0.03	50–70% CH_4	Moderate to High	Low cost and durable; suitable for small-scale rural use. Limited gas retention and prone to leakage; efficiency depends on temperature control and feedstock consistency.	[6, 15, 16, 50, 60]
Ghana, Burundi, Ivory Coast, Kenya, Ethiopia, and Tanzania	Floating Drum Digesters	0.03–0.05	50–70% CH_4	Moderate	Good for small-to-medium-scale applications; stable gas pressure. High maintenance due to metal corrosion and moving parts.	[8, 61–63]
Tanzania, Ethiopia, Kenya, Rwanda, South Africa, and Uganda	Plug-flow digesters	0.02–0.04	50–70% CH_4	Moderate to High	Efficient for high-solid substrates; maintains microbial stability and gas retention. Requires consistent feeding and careful design to avoid channeling.	[27, 58, 64]
Nigeria, South Africa	Continuous stirred tank reactors (CSTRs)	0.04–0.06	50–70% CH_4	Moderate to High	Provides uniform mixing and high yield; scalable for industrial use. High energy input and skilled operation are required.	[50, 58]
Uganda	Two-stage digestion systems	0.04–0.07	50–70% CH_4	Moderate to High	Allows phase separation for improved hydrolysis and methanogenesis; higher yield and stability. Complex operation and higher capital cost.	[48]

Source: Author's own compilation (2025).

3.2 Design optimization techniques for biogas production in SSA

Optimization of reactor configurations plays a critical role in enhancing microbial performance and biogas yield in Sub-Saharan Africa (SSA). Fixed-dome digesters, though widely adopted due to their simplicity and low cost, often suffer from uneven temperature distribution and the formation of dead zones that limit microbial activity and gas production efficiency [17, 47, 65].

In contrast, plug-flow digesters provide greater microbial stability because the substrate moves progressively through the reactor, minimizing washout and extending microbial retention time [27, 64]. This gradual flow pattern enhances gas retention and stabilizes methane concentration even under variable feeding conditions. Similarly, continuously stirred tank reactors (CSTRs) ensure effective mixing and pH uniformity, improving substrate microbe interaction and resulting in 20–30% higher methane yields compared with conventional systems [50, 58, 66]. Evidence from Kenya and Tanzania confirms that optimized agitation and temperature regulation in CSTRs can raise methane concentration to approximately 70% CH_4, demonstrating the importance of reactor design in performance optimization [64, 66]. Hybrid plug-flow/CSTR systems implemented in Uganda and Ethiopia further highlight the influence of reactor geometry and flow dynamics on microbial balance and energy recovery [47].

Technological improvements in SSA have led to the gradual introduction of advanced digester configurations and process control methods aimed at maximizing gas output. The development of plug-flow and CSTR systems has markedly improved reactor stability and gas production efficiency [62, 67]. Enhanced control of pH and temperature within digesters enables better adaptation to diverse feedstocks and climatic conditions, ensuring optimal microbial activity [68]. Optimization of hydraulic retention time (HRT) and thermal regulation has also proven effective: in Rwanda, extending HRT from 20 to 30 days in fixed-dome digesters increased yield by 25% (from 0.15 to 0.19 m^3 kg^{-1} VS) [51], while in Kenya, maintaining mesophilic conditions at 35 °C improved methane yield by 30% compared to ambient operations [63, 68]. Advances in feedstock flexibility, such as combining agricultural residues, organic waste, and energy crops, have expanded the range of viable substrates, supported by progress in lignocellulosic degradation technologies [68–70].

Comparative evidence from Asia and South America provides valuable insights into the potential trajectory of SSA's biogas sector. In China, integrating microbial consortia and pretreatment methods such as thermal hydrolysis has increased biogas yield by up to 40% [71, 72]. In Brazil, public-private partnerships have enabled large-scale optimization through co-digestion of animal manure with agro-industrial waste, achieving up to 30% higher yields than mono-digestion [73, 74]. Technological advancement in these regions has been further strengthened by intelligent process monitoring systems, including the integration of Internet of Things (IoT) sensors for real-time tracking of temperature, pressure, and gas composition [75, 76]. Automated feedback control using remote sensing has reduced operational downtime and improved methane recovery rates [75–77].

In SSA, the emerging integration of modern digester technologies, diverse feedstocks, and decentralized systems reflects a comprehensive approach toward increasing energy yield and access. These advancements are especially impactful for rural and off-grid areas, where efficient biogas systems improve energy security, support waste management, and reduce greenhouse gas emissions [78]. Decentralized designs and the use

of locally available substrates enhance the economic feasibility of biogas production, encouraging community participation and local entrepreneurship. However, significant challenges remain, including limited technical skills, financing constraints, and inconsistent policy frameworks [79]. Strengthening institutional support for Research and Development (R&D) is essential. Government-led investment in innovation, similar to China's targeted R&D funding that advanced pretreatment and microbial enrichment techniques [16, 23] could accelerate progress. SSA governments can implement policies that allocate research grants to universities and private companies for biogas innovation, particularly for optimizing feedstock utilization and digester design.

Moreover, various studies have demonstrated the efficacy of localized biogas systems, especially in rural regions, in fostering energy self-sufficiency and mitigating transmission losses. Small-scale digesters and community-based programs are being developed to solve scalability and flexibility issues in local contexts [17, 78, 80]. For instance, Vivekanandan et al. [81] conducted a study to determine the best conditions for generating biogas from rice straw through anaerobic digestion in a 1.00 m³ floating drum anaerobic digester, utilizing Response Surface Methodology (RSM). They focused on variables such as temperature, pH, substrate concentration, and agitation time. The maximum biogas yield, reaching 0.72 m³, was achieved at an optimal temperature of 50 °C, pH of 7.5, substrate concentration of 110.70 kg, and agitation time of 5 s. Despite significant progress, future research should aim to refine digester design, evaluate life cycle performance, and develop innovative financing mechanisms to scale up adoption. Table 2 summarizes key optimization strategies and their impact on biogas yield.

3.3 Variations in feedstock composition and availability impact the efficiency of biogas production systems in Sub-Saharan Africa

Optimization outcomes in biogas production are highly influenced by the interaction between feedstock composition and reactor configuration. In Sub-Saharan Africa (SSA), plug-flow digesters have proven particularly effective for treating fibrous and high-solid

Table 2 Optimization techniques for biogas production in SSA

Optimization techniques	Description	Impact on Biogas Yield and Quality
Feedstock Selection and Mixing	Balancing carbon-to-nitrogen (C/N) ratio; using diverse feedstock sources.	-Enhances yield and nutrient balance; improves CH_4 concentration
Process Parameter Optimization	Adjusting temperature, pH, and hydraulic retention time (HRT).	-Improves microbial activity; stable and higher yields.
Bioreactor Design and Configuration	Optimized geometry, mixing, and gas retention	-Promotes efficient digestion and uniform substrate breakdown
Heat Integration and Energy Recovery	Use of heat exchangers, cogeneration, Combined Heat and Power (CHP) systems.	-Reduces operational costs (OPEX); indirectly supports higher efficiency.
Digestate Management and Recycling	Nutrient recovery; digestate reuse as bio-fertilizer.	-Supports circular economy; enhances microbial performance.
Biogas Upgrading and Purification	PSA, water scrubbing, biological upgrading.	-Produces biomethane ($\geq 95\%$ CH_4) for higher-value uses.
Monitoring, Control, and Automation	IoT sensors, AI-based control, remote monitoring.	-Ensures process stability; minimizes human error.
Integration with Other Systems	Linking with solar, wind, or waste management chains.	- Enhances resource utilization; broadens sustainability impact.

Source: Author's own compilation (2025)

substrates commonly derived from agricultural residues such as cassava peels, maize stalks, and sisal fiber [13, 18, 69]. Their gradual substrate movement and limited agitation preserve microbial consortia capable of degrading lignocellulosic materials, resulting in higher methane conversion efficiency [82, 83]. In Tanzania and Ghana, co-digestion of municipal solid waste (MSW) with agricultural residues in plug-flow reactors has enhanced biogas yield by up to 30% [30, 62]. Conversely, CSTR are more suitable for slurry-type substrates such as animal manure and wastewater, where constant mixing prevents stratification and promotes balanced microbial activity [27, 50]. Fixed-dome digesters, while appropriate for decentralized rural use, often require retrofitting, such as insulation or temperature regulation, to maintain mesophilic conditions and achieve stable yields [47, 84]. Collectively, these findings demonstrate that matching reactor configuration to feedstock characteristics is fundamental to improving methane output and process efficiency in SSA.

Feedstock quality and availability also play a decisive role in determining biogas potential. Studies by Kabeyi and Olanrewaju [78] and Sawyerr et al. [85] highlight that substrates rich in carbohydrates, proteins, lipids, cellulose, and hemicellulose have a significant potential for biogas production. However, variability in feedstock composition and availability in Sub-Saharan Africa (SSA), particularly in urban settings, poses challenges for optimal biogas production. Key parameters such as volatile solids (VS), moisture content, and total solids (TS) influence the digestion rate and methane quality, with higher VS/TS ratios linked to improved biogas yields. Co-digestion strategies that balance nutrient composition and microbial activity have proven particularly effective in addressing nutrient imbalances common in mono-digestion. In rural areas, animal dung remains the dominant substrate, while crop residues and organic waste are increasingly being explored to expand feedstock diversity and ensure year-round operation. Notably, South Africa has documented successful use of technologies such as lagoons, plug-flow, and up-flow anaerobic sludge blanket (UASB) reactors, showing potential for scaling up commercial biogas systems.

Several SSA-based studies have validated the benefits of co-digestion and temperature optimization in improving yield and process stability. Dahunsi [86] conducted research that underscored the significant potential of co-digesting food waste and human excreta for biogas production in developing nations like Nigeria. Similarly, Rupf et al. [15] observed biogas generation rates between 0.06 and 0.21 m³/kg of dry mass/day from faecal sludge under mesophilic (25–45 °C) and thermophilic (50–60 °C) conditions, highlighting temperature control as a critical optimization parameter. Other studies across SSA have confirmed the potential of mixed substrates such as fruit waste, poultry litter, and cassava peels inoculated with cow dung, yielding higher methane concentrations than single-feed systems [18, 82]. Despite these promising results, certain underutilized residues such as rice husks and sawdust remain largely unexplored, representing potential future resources for co-digestion systems. Comparative evidence from other regions offers lessons for SSA. In Asia, particularly China, consistent availability of easily digestible organic matter, mainly food waste, supports high biogas yields [70]. In South America, homogeneous agricultural residues such as sugarcane bagasse in Brazil and Argentina have achieved methane yields of approximately 0.35 m³/kg VS [55, 78]. These successes underline the value of consistent feedstock supply and preprocessing. For SSA, the seasonal nature of agricultural residues requires adaptive strategies such as ensiling

to preserve feedstocks during peak production periods, ensuring a steady substrate supply year-round. Low-cost pretreatment approaches, including composting, mechanical shredding, or alkali soaking, can further enhance the digestibility of lignocellulosic materials, improving gas yields without substantial financial burden.

Empirical studies provide compelling support for the effectiveness of current optimization strategies in enhancing biogas production. For example, co-digestion of food waste and livestock manure in Uganda produced a 40% higher methane yield 0.3 m³/kg VS compared to mono-digestion of manure [87]. In South Africa, methane yields of 0.2 m³/kg VS were achieved from fruit and vegetable waste, reinforcing the effectiveness of combining multiple organic substrates [58, 88]. To accelerate such progress, SSA governments should promote policies that encourage co-digestion and feedstock diversification, mirroring Brazil's incentive schemes for agro-industrial residues, which raised methane yields by up to 30% [78]. Policy instruments such as targeted subsidies, tax incentives, and feed-in tariffs could stimulate investment in integrated biogas systems capable of utilizing diverse organic wastes efficiently. As summarized in Table 3, the feedstock types for biogas production in selected SSA Countries.

3.4 Challenges and perspectives in optimizing biogas production in Sub-Saharan Africa

Although significant progress has been made in optimizing biogas technologies, several design and performance constraints continue to hinder their large-scale implementation across SSA. Fixed-dome digesters, while widely deployed due to their affordability and simplicity, frequently exhibit issues such as gas leakage and suboptimal pressure retention, which adversely affect conversion efficiency. By contrast, more advanced configurations such as plug-flow and CSTR have demonstrated enhanced gas quality and process stability; however, their operation often requires advanced technical expertise and maintenance capacity. Fixed-dome digesters, while widely deployed due to their

Table 3 Feedstock types for biogas production in selected SSA countries:

Country	Feedstock type	Authors
Tanzania	Sisal fibre waste	Mshandete, [13]
	Fresh cow dung	Mkhize et al. [53]
	Faecal Sludge (FS) and food waste (FW)	Kilucha et al. [30]
Uganda	Organic Solid waste and livestock manure	Mohamed et al. [82]
South Africa	Fruit and Vegetable waste	Masebinu et al. [18]
	Organic Fraction of Municipal Solid Waste (OFMSW)	Nkosi et al. [58]
	Water Hyacinth	Ilo et al. [84]
	Cassava Peels	Okudoh et al., [38]
Kenya	Animal manure and Crop residues	Wamuyu, [66]
Zambia	Livestock manure	Shane et al. [62]
	Agricultural residues	
Zimbabwe	Municipal biodegradable waste	Masebinu et al. [18];
	Chicken Manure	Njuguna Matheri et al. [89]
Malawi	Animal Manure	Shane et al. [62]
Ghana	Crop Residues	Erraji et al. [52]
	Miscanthus Fuscus and Cow Dung	Tetteh et al. [54]
	Faecal Sludge with Paper or Fruit Waste	Adjama et al. [90]
	Human Feces with Rice Straw	
Nigeria	Organic Fraction of Municipal Solid Waste (OFMSW)	Ajaero et al. [24]
	Cassava peels and Faecal Sludge	Fagbenle & Olukanni, [91]
	Food waste and Human excreta	Dahrusi et al. [86]

Source: Author's own compilation (2025).

affordability and simplicity, frequently exhibit issues such as gas leakage and suboptimal pressure retention, which adversely affect conversion efficiency. By contrast, more advanced configurations such as plug-flow and CSTR have demonstrated enhanced gas quality and process stability; however, their operation often requires advanced technical expertise and maintenance capacity [50, 65]. To address these limitations, strengthening local manufacturing capability and standardizing digester designs for tropical climatic conditions are essential measures that could improve reliability and cost-effectiveness while reducing reliance on imported components [27, 92]. Furthermore, the integration of smart monitoring technologies such as Internet of Things (IoT)-based sensors has the potential to facilitate predictive maintenance, optimize process parameters, and minimize downtime [76, 77]. Nevertheless, such innovations will remain underutilized unless supported by adequate institutional, financial, and technical frameworks that ensure equitable accessibility and long-term functionality. At the institutional level, persistent governance and capacity-related barriers continue to constrain the scalability of optimized biogas systems in the region. Evidence from countries such as Tanzania, Kenya, Nigeria, Zambia, Malawi, and Ethiopia indicates that technological progress has been uneven, with many initiatives remaining at pilot or demonstration stages [12, 62, 63]. The lack of coherent policy frameworks, weak coordination among implementing agencies, and insufficient quality control mechanisms have further limited the diffusion of these technologies. For instance, inadequate training and after-sales support have led to premature digester failure and reduced operational lifespans in several national programs [93, 94].

Lessons from other developing regions provide valuable insights into pathways for overcoming these challenges. In Asia, for example, well-structured policy instruments, combined with government-backed training programs and financial incentives, have led to remarkable progress in biogas dissemination [33, 95]. Similarly, in South America, countries such as Brazil have benefited from public–private partnerships that foster large-scale infrastructure development and stable energy generation from biogas [55, 74]. Collectively, these cases suggest that policy coherence, sustained investment, and multistakeholder collaboration are key enabling conditions for transforming biogas initiatives into viable, long-term energy solutions.

Looking ahead, the optimization of biogas production in SSA requires an integrated and multi-dimensional approach that bridges technology, policy, finance, and social inclusion. National strategies should focus on developing context-specific financial instruments, such as blended public–private investments, performance-based incentives, and targeted microcredit facilities, modeled on successful international experiences like India's National Biogas and Manure Management Program (NBMMP) [96]. Technologically, the deployment of locally adapted digester designs that can withstand feedstock variability and climatic fluctuations remains a critical priority. Incorporating artificial intelligence (AI) and IoT-driven process monitoring could further enhance system efficiency and operational resilience [77].

In parallel, efforts to build regional innovation capacity and strengthen human capital are indispensable. Establishing biogas innovation hubs and research consortia would promote technology transfer, local fabrication, and applied research on optimization under African conditions. Capacity development initiatives, particularly those targeting smallholder farmers, cooperatives, and women-led enterprises, can enhance awareness,

Table 4 Summary of optimization strategies, parameters, and performance outcomes for biogas systems in SSA

Optimization Strategy	Reactor/process applied	Parameter Optimized	Observed improvement	Reported Yield/Quality	Source
Reactor design modification	CSTR vs. fixed dome	Mixing regime, temperature control	+20–30% methane yield	70% CH_4 achieved	[6, 16, 50, 60, 97]
Reactor configuration adjustment	Plug-flow and hybrid plug-flow/CSTR	Hydraulic flow, retention time	Improved microbial stability, +25% increase in yield	0.04–0.06 $m^3 kg^{-1} VS$	[8, 61, 62, 63]
Hydraulic Retention Time (HRT) optimization	Fixed-dome digesters (Rwanda)	HRT 20–30 days	+25% increase in yield	0.15–0.19 $m^3 kg^{-1} VS$	[27, 58, 64]
Temperature control	CSTR system (Kenya)	Controlled at 35 °C	+30% yield vs. ambient	Up to 70% CH_4	[50, 58]
Co-digestion	Agricultural residues + MSW	C/N ratio, nutrient balance	+25–40% methane yield	0.2–0.3 $m^3 kg^{-1} VS$	[48]
Feedstock pretreatment	Agricultural and lignocellulosic residues	Mechanical/thermal pre-treatment	Enhanced biodegradability	+15–20% yield	[98]
Process monitoring	IoT-enabled control	pH, temperature, gas flow	Reduced downtime, steady CH_4 output	Improved system stability	[77]

Yield expressed as m^3 of biogas or CH_4 per kg of volatile solids (VS); methane concentration in %.Source: Compiled and adapted from the reviewed SSA case studies.

system ownership, and long-term maintenance. Ultimately, aligning biogas strategies with broader circular-economy, waste management, and climate policy objectives will not only accelerate energy access and emissions reduction but also contribute to sustainable urban and rural development across the region. A summary of the optimization strategies and observed performance improvements across Sub-Saharan Africa is presented in Table 4.

3.5 Future research directions

Future research is required to systematically evaluate the life-cycle implications and environmental trade-offs of MSW-based biogas systems in SSA. Particular attention should be given to conducting comprehensive life-cycle assessments (LCA) that quantify greenhouse gas mitigation potential, nutrient recovery efficiency, and waste-management co-benefits under varying operational contexts. Further investigation is also warranted into the techno-economic feasibility of hybrid biogas configurations, including systems that integrate plug-flow and CSTR designs or that combine anaerobic digestion with complementary technologies such as solar energy or biofertilizer production. Moreover, socio-environmental dimensions of optimization, including community employment, gender inclusion, and rural livelihood improvement, should be empirically examined to capture the wider developmental implications of biogas adoption. Future studies might also benefit from longitudinal field monitoring and cross-country comparative analysis, which could provide robust data to inform adaptive policy frameworks, enhance scalability, and guide investment priorities for sustainable biogas development across the region.

4 Conclusion

This review highlights that optimizing municipal solid waste (MSW)-based biogas systems in Sub-Saharan Africa (SSA) requires an integrated framework that couples technological innovation with financial, policy, and social dimensions. Advances in reactor design, particularly plug-flow and CSTR configurations, combined with process parameters such as temperature regulation, feedstock pretreatment, and hydraulic retention optimization, have been shown to enhance methane yield by up to 30%. Co-digestion remains the most effective approach, improving yield by 25–40% through balanced nutrient composition and enhanced microbial synergy. However, widespread implementation continues to be constrained by high capital investment, limited maintenance capacity, and weak institutional support. Addressing these constraints calls for locally adapted technologies, IoT-based monitoring, and governance mechanisms that balance cost–yield efficiency with social acceptance. Drawing on global experience, coordinated policy frameworks, fiscal incentives, and public–private partnerships are essential to stimulate innovation and scale up adoption. Future research should therefore quantify life-cycle benefits, assess the techno-economic feasibility of hybrid systems, and evaluate socio-environmental co-benefits such as employment, gender inclusion, and rural livelihoods to ensure a resilient and inclusive waste-to-energy transition across the region. Beyond energy access, biogas systems deliver co-benefits including reduced greenhouse gas emissions, improved sanitation, and nutrient recycling for agriculture. Aligning these benefits with the Sustainable Development Goals, particularly SDGs 7 (Affordable and Clean Energy), 11 (Sustainable Cities), 12 (Responsible Consumption), and 13 (Climate Action), positions optimized biogas systems as a cornerstone of SSA's sustainable development trajectory.

Author contributions
Author Contributions: Conceptualization: [E.N]Investigation (literature review and data curation): [E.N]Formal Analysis and Thematic Synthesis: [E.N]Writing Original Draft Preparation: [E.N]Writing Review & Editing: [E.N., W.D., and N.C] Visualization (figures, tables): [E.N]Supervision: [W.D and N.C]All authors have read and approved the submitted version of the manuscript.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

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