Available online www.worldscientificnews.com

World Scientific News

An International Scientific Journal

WSN 216 (2026) 31-47 EISSN 2392-2192

Pyrolysis Reactor Design and Suitability for Decentralized Waste-to-Energy Systems in Sub-Saharan Africa: A Systematic Review

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https://doi.org/10.65770/TFTF6973

ABSTRACT

Plastic waste accumulation and energy insecurity remain critical challenges in Sub-Saharan Africa, necessitating the development of decentralized waste-to-energy technologies that are adaptable to local socioeconomic and infrastructural conditions. Among the emerging thermochemical conversion technologies, plastic pyrolysis has gained attention because of its potential to convert nonbiodegradable plastic waste into valuable liquid fuels, gases, and char. However, the efficiency and scalability of pyrolysis systems are highly dependent on reactor design, feedstock compatibility, and the operational conditions. This systematic review evaluated the suitability of pyrolysis reactor configurations for decentralized waste-to-energy systems in sub-Saharan Africa. This review followed the PRISMA 2020 framework and synthesized data from 16 eligible experimental and pilot-scale studies published between 2017 and 2026. The findings indicate that batch and fixed-bed reactors dominate pyrolysis research in the region because of their low cost, operational simplicity, and adaptability to infrastructure-constrained environments. Batch reactors commonly operate at 203-500°C with longer residence times, whereas fixed-bed reactors exhibit improved thermal efficiency and reduced reaction times at 300-550°C. Polyolefin plastics, particularly LDPE and HDPE, are the predominant feedstocks owing to their abundance and high liquid-fuel-yield potential. Catalytic materials, such as zeolite-Y, bentonite clay, and silica-alumina, enhance hydrocarbon selectivity and reduce degradation temperatures, thereby improving process efficiency. Nevertheless, this review reveals major limitations, including weak processing capacity for heterogeneous plastic streams, dependence on unstable energy systems, and the absence of standardized reactor frameworks suitable for decentralized deployment. The study concludes that effective pyrolysis implementation in Sub-Saharan Africa requires integrated reactor systems that combine low-cost designs, adaptive energy sources, and catalytic optimization to improve scalability, thermal efficiency, and operational sustainability of the process.

Keywords: Plastic pyrolysis, Reactor design, Decentralized energy, Waste-to-energy, Sub-Saharan Africa, Fixed-bed reactor, Batch reactor, Energy systems

(Received 12 April 2026; Accepted 17 May 2026; Date of Publication 13 June 2026)

1. INTRODUCTION

Sub-Saharan Africa faces significant challenges in terms of plastic waste and energy insecurity. The rapid pace of urbanization, population growth, and industrial development has led to a surge in the use of plastics, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), primarily because of their affordability and durability [7],[15],[19],[39]. However, the lack of effective waste management systems has resulted in widespread mismanagement, with plastics being discarded in open areas, drainage systems, and water bodies, causing environmental harm and emissions from the uncontrolled burning of waste. Simultaneously, ongoing energy shortages caused by dependence on imported fuels, unreliable electricity, and inadequate infrastructure continue to hinder socio-economic progress. These issues have heightened interest in waste-to-energy technologies as comprehensive solutions for waste management and energy generation [1],[9]. Among these technologies, pyrolysis has attracted considerable attention due to its ability to thermally break down plastics without oxygen, yielding liquid oils, gases, and char. The oil produced is similar to traditional fossil fuels and can be used for heating and electricity production. Thus, pyrolysis presents a promising approach for resource recovery, emission reduction, and valorization of non-recyclable plastics, aligning with circular economy goals [7],[34]. However, its effectiveness depends on the interaction of operational and design factors, such as reactor configuration, temperature, heating rate, residence time, feedstock composition, and heat transfer efficiency.

The design of reactors is of paramount importance because it establishes the thermochemical environment for conversion, thereby directly affecting heat transfer, reaction kinetics, residence time distribution, product yield, and process stability. It is also instrumental in determining scalability, operational efficiency, and energy demand, making it a primary factor in assessing practical feasibility rather than a secondary design consideration. Reactor systems, including batch, fixed-bed, fluidized-bed, and continuous configurations, exhibit significant differences in complexity, cost, and thermal performance [30]. However, in sub-Saharan Africa, the selection of reactors is frequently constrained by economic and infrastructural limitations, resulting in simplified designs that compromise thermal efficiency, product consistency, and processing time [31]. These constraints are further exacerbated by heterogeneous and poorly segregated feedstock streams, which diminish process stability and product quality, and unreliable and costly energy supply systems that impede continuous operation [28]. These challenges highlight that reactor design in decentralized systems cannot be treated in isolation but must be evaluated in relation to feedstock heterogeneity and energy system reliability. Existing studies on plastic pyrolysis have focused on optimizing process parameters, such as temperature, heating rate, residence time, and catalyst addition, to improve the product yield and quality [6],[21],[23]. Additional research has examined feedstock blending and catalytic upgrading to enhance oil quality and selectivity [4],[20],[32],[38]. In sub-Saharan Africa, studies have primarily emphasized fuel characterization, catalyst performance, and oil yield, with limited attention to reactor suitability under decentralized and resource-constrained conditions [5],[18],[24],[25].

Despite advancements in pyrolysis technology, there remains a deficiency in comprehensive analyses that explore the interaction between reactor design, feedstock characteristics, catalyst systems, energy availability, and operational constraints, particularly in determining scalability and applicability in sub-Saharan Africa. Therefore, this review evaluates pyrolysis reactor designs for decentralized systems in sub-Saharan Africa by synthesizing evidence on reactor configurations, feedstock characteristics, catalyst strategies, operational parameters, and energy sources. This study further identifies technological and infrastructural gaps affecting scalability and deployment, offering insights into the development of cost-effective, efficient pyrolysis systems for sustainable waste management and energy recovery in sub-Saharan Africa.

2. METHODOLOGY

2.1. Study Design and Review Framework

This systematic review adhered to the PRISMA 2020 guidelines, incorporating both the checklist of items and flow diagram of the selection process to ensure transparency and methodological rigor. This review focuses on experimental and pilot-scale studies of plastic waste pyrolysis in Sub-Saharan Africa, with particular focus on reactor design and configuration, feedstock characteristics, reactor compatibility, and the operational performance or conditions of pyrolysis reactors.

2.2. Literature Search Strategy and Eligibility Criteria

A comprehensive literature search was performed on Google Scholar, Scopus, BASE, Research4Life, and Web of Science to capture region-specific and open-access studies that may not have been indexed in the conventional databases. Moreover, the literature search via Google Scholar captured studies across multiple scientific databases, including Elsevier (ScienceDirect), Web of Science, Springer, African Journals Online (AJOL), and ResearchGate. The search strategy employed combinations of keywords such as "plastic pyrolysis," "Sub-Saharan Africa," "waste plastics," "reactor." The initial search yielded 19,300 records (Figure 1). To ensure relevance to recent advancements in waste-to-energy technologies, the search was restricted to studies published between 2017 and 2026, reducing the dataset to 16,700 records (Figure 1). The number of studies was reduced to 200 after the initial screening (title and abstract) of irrelevant studies, that were excluded because of irrelevant content on pyrolysis processes and studies outside Africa, selection based on the predefined eligibility criteria. A full-text assessment was subsequently performed against the inclusion criteria. The criteria required that studies be conducted in Sub-Saharan Africa and report experimental, pilot-scale, or semi-industrial pyrolysis processes involving plastic feedstocks such as HDPE, LDPE, PP, PS, PET, or mixed plastics. Additionally, eligible studies were required to report reactor specifications and operating conditions, including temperature and residence time. Studies conducted outside Sub-Saharan Africa, including those from North Africa in countries such as the Kingdom of Morocco, Egypt, and Algeria, were excluded, as were review articles and conference abstracts without sufficient experimental detail. Studies lacking the quantitative data necessary for synthesis were also excluded. Sixteen studies met the eligibility criteria and were included in the final synthesis (Figure 1).

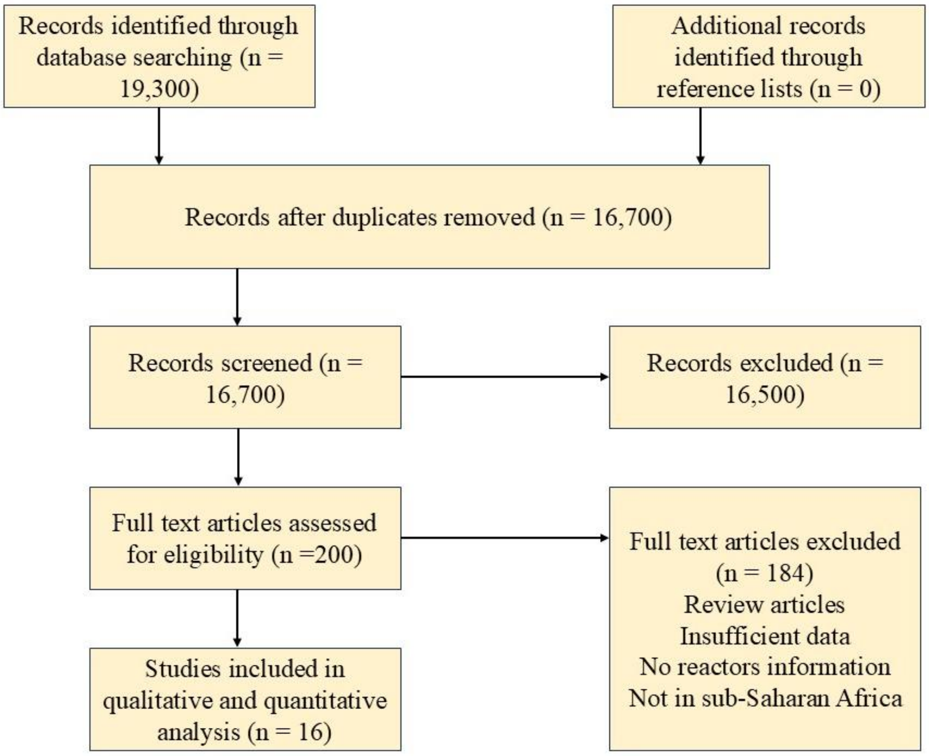

Figure 1. PRISMA flow diagram illustrating the study selection process for the systematic review of pyrolysis reactor configurations in Sub-Saharan Africa.

2.3. Data Preprocessing and Analysis

Data extraction was performed using Google NotebookLM, which allowed for the simultaneous extraction of information from multiple documents. The extracted data from 16 documents included the reactor type and configuration, feedstock composition, operating temperature (°C), residence time (h), heating rate (°C/min), catalyst type and catalyst loading. The data were tabulated and entered into Microsoft Excel. Each experimental condition reported in the study was treated as an independent observation to maintain variability in the operating parameters. The reactor parameters, specifically the internal diameter (ID) and height (H), were expressed in centimeters (cm). Temperature values were consistently expressed in degrees Celsius and residence time in hours. Qualitative information extracted from feedstock selection criteria and energy sources for pyrolysis reactors in sub-Saharan Africa was systematically analyzed using thematic coding. For feedstock selection, recurring justifications reported across studies were categorized into predefined thematic codes (T1-T6), facilitating structured tabulation and comparative analysis. In contrast, themes related to energy sources for reactor operation were synthesized and presented graphically to illustrate the distribution patterns and regional preferences. Graphs in this study were prepared using Microsoft Excel.

3. RESULT AND DISCUSSION

3.1. Geographical Distribution of Plastic Pyrolysis Studies in Sub-Saharan Africa

The research landscape for plastic waste pyrolysis in sub-Saharan Africa is shaped by inefficient municipal waste management and energy insecurity, which drives the exploration of waste-to-energy technologies. Pyrolysis offers a versatile solution to environmental and energy challenges; however, its progress depends on local infrastructure, economics, and material conditions [7].

The reviewed studies reveal that research priorities for plastic pyrolysis at the country level are influenced by factors such as waste composition, energy access, and technological capacity. Nigeria leads research on catalyst development using local materials and decentralized systems for urban plastic waste, particularly low-density polyethylene (LDPE). Ghana emphasizes circular economy frameworks, waste segregation, and life cycle assessments to enhance fuel quality and mitigate environmental impacts. Ugandan research aligns with the concept of "appropriate technology," concentrating on low-cost biomass-powered systems that operate independently of grid electricity. Sudan prioritizes large-scale industrial systems to achieve energy self-sufficiency and reduce emissions. Cameroon and Kenya specialize in reactor optimization and the conversion of niche waste streams into high-value fuels.

As shown in Figure 2, Nigerian studies have demonstrated the efficacy of locally sourced catalysts and decentralized systems for LDPE-rich waste [2],[5],[10],[11],[12],[13],[25],[37]. Ghanaian research underscores the importance of waste segregation in achieving higher oil yields and improved environmental performance [18],[24],[36]. Ugandan studies have highlighted the feasibility of biomass-powered systems without reliance on electricity [27],[28]. Sudanese simulations illustrate the potential of large-scale systems for energy self-sufficiency and emission reduction [22]. Studies in Cameroon and Kenya have provided evidence of reactor optimization and the conversion of complex waste into high-quality fuels [8],[26]. These studies demonstrate that pyrolysis development in sub-Saharan Africa is context-dependent and lacks technological uniformity. Thus, localization enhances the relevance of reactor design but reveals a fragmented research focus and limited standardization. This poses challenges in terms of scalability and cross-regional transferability of the results. Hence, integrative frameworks are necessary to harmonize localized innovations with broader system optimizations, facilitating the coherent development of pyrolysis technology across sub-Saharan Africa.

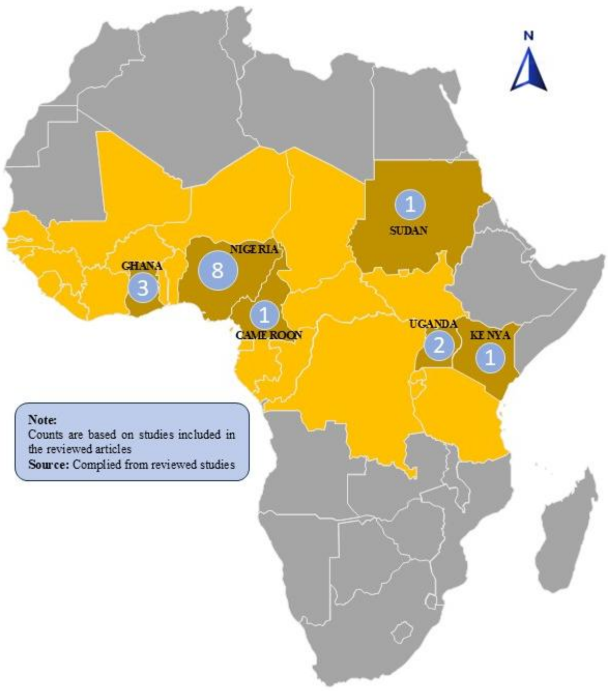

Figure 2. Geographical Distribution of Plastic Pyrolysis Studies in Sub-Saharan Africa.

3.2. Reactor Configuration and Design Characteristics

The reactor configuration critically affects the plastic pyrolysis performance, influencing heat transfer, reaction kinetics, product distribution, and scalability [7]. In sub-Saharan Africa, reactor design is limited by techno-economic factors, infrastructure, and the need for context-appropriate technologies, particularly in decentralized waste-to-energy applications. The major reactor systems used in plastic pyrolysis include batch, semi-batch, continuous, and fixed-bed configurations, each differing in operational mode, process control, production capacity, and suitability for specific applications. Batch systems ranging from 100 g to over 800 kg dominate reactors for plastic pyrolysis in sub-Saharan Africa, demonstrating their scalability and adaptability [10],[12],[18],[24],[25],[37]. Semi-batch configurations offer improved control and portability with low energy requirements, making them suitable for localized deployment [13]. Batch reactors are simple, low-cost, and flexible, making them common in laboratory-scale studies [16]. Fixed-bed reactors at smaller scales enhance cracking efficiency and hydrocarbon selectivity [2],[5],[8],[11],[36]. These fixed-bed reactors are common at the laboratory scale, and their operation is vital to parameters such as the type of feedstocks and operating conditions [29],[35]. Continuous reactors operate at higher temperatures to increase gaseous yields, which is suitable for specific objectives [28]. Industrial systems in Sudan process up to 37.5 tons per hour at 700-900°C, aiming for energy self-sufficiency.

Catalysis integration in batch systems is dominated by two approaches. The first is preloading physical mixing, where shredded plastic is manually combined with catalysts before being introduced into the reactor. For example, in Ghana, 1 kg of plastic feedstock was mixed with 100 g of Y-zeolite in a 5 kg batch reactor, while similar practices in Nigeria involved blending zeolite-Y with plastic waste prior to charging a 15-litre reactor, and LDPE was mixed with mesoporous clay composites before pyrolysis at 450°C [24],[25],[37]. This demonstrates the widespread adoption of this method. The second approach involves in-vessel contact configurations, where the feedstock and catalyst are layered or co-fed into the reactor to ensure interaction during thermal degradation. Limited evidence of mechanical enhancement exists, such as the use of agitator-controlled reactors in Nigeria to improve heat distribution and reduce feedstock particle size (2-4 mm) to facilitate more uniform mixing and reaction behavior in mixed plastic systems [10]. Batch-based systems in sub-Saharan Africa prioritize low-cost, flexible solutions, limiting the transition to advanced reactors, such as continuous systems, owing to technical and infrastructure demands. These designs are suitable for localized applications but rely on simple mixing strategies, leading to non-uniform contact and restricted mass and heat transfer, thereby reducing catalytic efficiency compared to advanced reactors. While effective for small-scale use, scaling up to high-efficiency systems requires hybrid designs that combine simplicity with improved thermal management, mixing, and catalyst delivery, enabling the efficient deployment of pyrolysis technologies across sub-Saharan Africa.

Table 1. Reactor Configurations and Catalyst Characteristics of Plastic Pyrolysis Systems in Sub-Saharan Africa.

REACTOR TYPE	Reactor Shape and Orientation	Construction Materials of the Reactor	Capacity (kg)	ID (cm)	H (cm)	Type of catalyst	Amount of Catalyst (g)	Sources
BATCH REACTOR	Cylindrical (Tubular)	Stainless steel (sisal hemp/fiber glass insulation)	-	-	-	Mesoporous Nigerian bentonite clay	20.0	[25]
	Cylindrical (Vertical)	-	5.0	-	-	Zeolite-Y	100 (10 wt.%)	[24]
			400	-	-	-	-	
		Stainless steels	15*	-	-	Zeolite-Y **(Optional)**	(10 wt.%)	[37]
			1.0	15.0	20	Zeolite-Y (Kankara)	20.0 (10 wt.%)	[12]
			15.0	-	-	-	-	[18]
			-	-	-	Molecular sieve (for refluxing)	2.50 for 200 ml oil	[10]
			<25.0 (weight)	6.0	15.0	-	-	[13]
	Conical section	Mild steel	1.0	-	42.5	Silica-alumina	1:10 and 1:20	[28]
FIXED-BED REACTOR (Fixed Batch Reactor)	Cylindrical (Vertical)	Stainless steel (clay insulation)	1.0	-	-	-	-	[8]
	-	-	7.0	-	-	-	-	[11]
	Cylindrical	Stainless steel	0.30*	6.0	11.0	Zeolite-Y (Synthesized)	10.0 (10 wt.%)	[2]
	Vertical column	Stainless steel	10.0	74.0	92.0	-	-	[36]
			-	1.0	40.0	Mesoporous iron oxide (FeO)-alumina	0.50	[5]
REACTOR FLASK (Lab-scale Reactor)	Round-bottomed flask	Borosilicate glass	-	-	-	Acid-activated clay; Aluminum chlorides	20.0 (10:1 w/w ratio)	[27]
			0.25*	-	-	Iron-pillared calcium bentonite	(5.86-34.14 wt.%)	[26]
Continuous Reactor	Conical section	Mild steel	1.0	-	42.5	Silica-alumina	(1:10 and 1:20 ratios)	[28]
Industrial Pyrolysis Plant (Large-scale Simulation)	-	-	30,000*	-	-	-	-	[22]

*Measured in Liter (L)

3.3. Feedstocks Characteristics and Reactor Compatibility

The selection of pyrolysis feedstock in sub-Saharan Africa is influenced by the dual need to address escalating plastic waste accumulation and optimize fuel recovery from locally available materials. In this context, the polymer type is a critical determinant of process efficiency, product yield, and overall system viability. A synthesis of the reviewed literature indicates a strong regional preference for polyolefin-based plastics, particularly LDPE, HDPE, PP, and PS, driven by their abundance in municipal waste streams and favorable thermochemical behavior during pyrolysis. Quantitative evidence from the reviewed studies demonstrates that LDPE is the most dominant feedstock, accounting for approximately 71% of the usage across multiple countries, including Nigeria, Sudan, Ghana, Cameroon, and Uganda, followed by HDPE (47%) and PS (41%). PP (29%) and PET (24%) were comparatively less utilized, as shown in Figure 3 and Table 2.

This distribution aligns with the underlying selection drivers, where waste abundance and thermochemical suitability account for the largest share (44%) of the rationale for the feedstock choice. Additional drivers include environmental pollution mitigation (19%), circular economy and sustainability transition (13%), and infrastructure and preprocessing constraints (13%), whereas local resource energy recovery (6%) and emerging waste streams (6%) play relatively minor roles, as shown in Figure 4. Empirical studies further confirm that LDPE dominance is linked to its high availability in packaging waste and its efficient cracking into high liquid fuel yields [8],[10],[11],[22],[27]. Similarly, HDPE and PS are prioritized because of their persistence in the environment and contribution to solid waste burden [28],[37]. Meanwhile, PET and PP remain underutilized because of their complex structures and tendency to form waxy byproducts [33]. The findings suggest that feedstock selection in sub-Saharan Africa is pragmatically aligned with material availability and process efficiency. Nonetheless, the predominant reliance on polyolefins highlights the technological constraints in managing complex and heterogeneous plastic streams. This indicates that the advancement of pyrolysis systems in the region will necessitate the development of enhanced catalytic strategies and reactor designs capable of processing mixed plastics more efficiently. Such advancements would facilitate broader applicability and improve the overall efficacy of waste-to-energy conversion systems in the future.

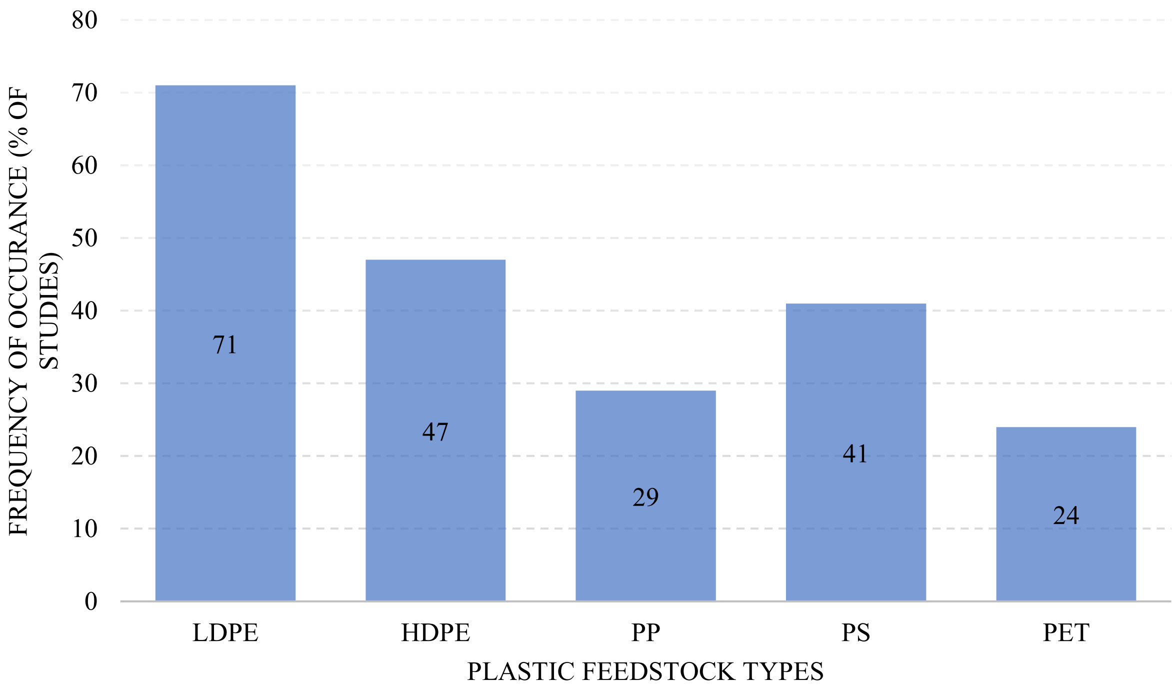

Figure 3. Distribution of Plastic Feedstock Used in Pyrolysis Studies in Sub-Saharan Africa.

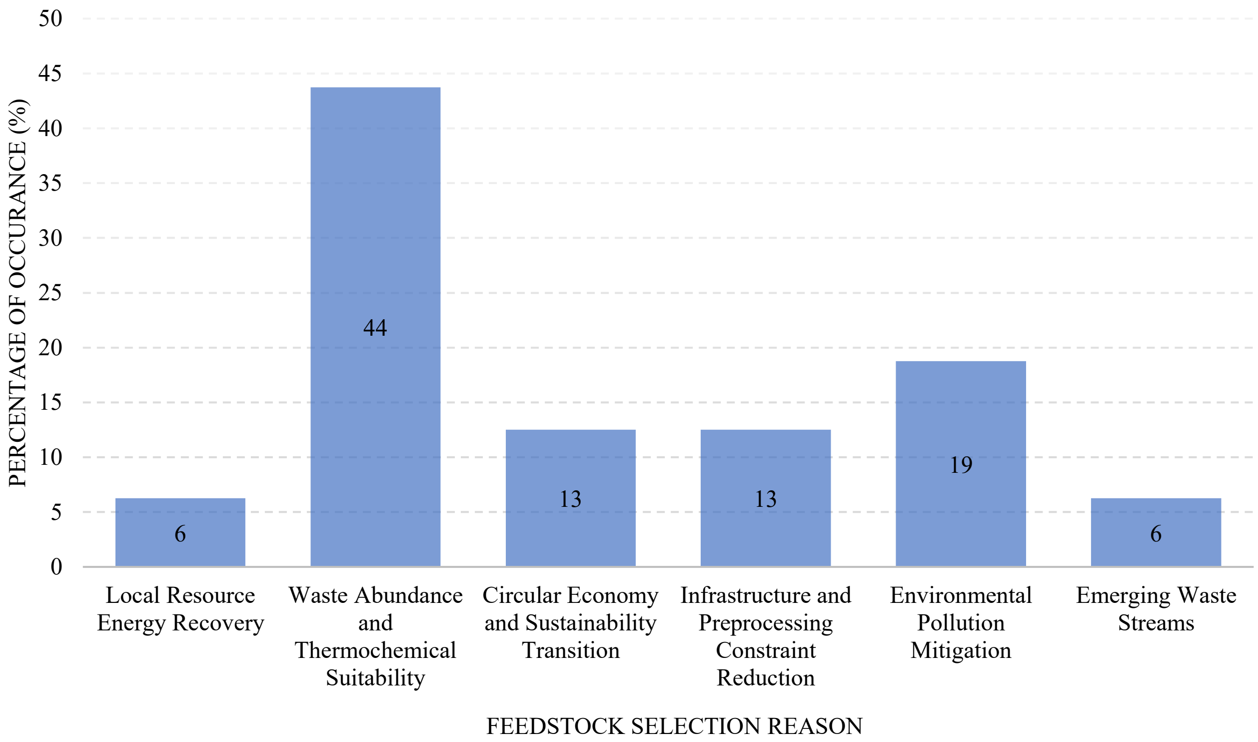

Figure 4. Thematic Drivers for Feedstock Selection in Plastic Pyrolysis Studies in Sub-Saharan Africa.

Table 2. Feedstock Types, Selection Criteria, and Feedstock Loading in Plastic Pyrolysis Studies across Sub-Saharan Africa.

REACTOR TYPE	**Feedstock Type**	**Feedstock Load (kg)**	**Reason of Selection of Feedstock (Thematic code)**	**Descriptions**	**Sources**
BATCH REACTOR	LDPE	0.1	T5	Pollution control (drainage blockage and environmental littering mitigation)	[25]
	Mixed Plastics (PET, PE, PP, PS)	1.0	T3	Circular economy and SDG-driven waste-to-energy transition	[24]
		5.0			
	PP, PE, and PS	1.0	T5	Urban pollution control and fuel substitution under energy cost pressure	[37]
	Mixed waste plastics (PE, PP, PS, and PET)	0.2	T4	High consumption and very low recycling rate driving recovery need	[12]
	LDPE	3.0	T4	Technology adaptation for mixed waste under weak sorting infrastructure	[18]
	LDPE	3.8	T2	High availability and high conversion efficiency due to polymer structure	[10]
	PS and Cashew nut shell	-	T1	Local resource utilization for decentralized energy recovery under energy insecurity conditions	[13]
	HDPE, PP and PS	1.0	T5	Environmental hazard mitigation (livestock deaths, pollution control)	[28]
FIXED-BED REACTOR (Fixed Batch Reactor) [b]	LDPE and PS	1.0	T2	High waste prevalence and resistance to natural degradation requiring thermal treatment	[8]
	PE	7.0	T2	Dominant in dumpsites and suitable for thermochemical conversion	[11]
	LDPE	0.1	T2	High volatility and high liquid fuel yield potential	[2]

	PP, PET, PE, and mixed-plastic wastes	4-10	T3	Circular economy response under poor waste collection systems	[36]
	PET	0.2	T2	High consumption and very low recycling rate driving recovery need	[5]
REACTOR FLASK (Lab-scale Reactor)	PE (1:1 w/w)	0.2	T2	Dominant municipal waste fraction with environmentally unsustainable disposal practices	[27]
	Automotive Plastic Wastes (APW)	-	T6	Anticipatory waste management from end-of-life vehicle plastics	[26]
Continuous Reactor	HDPE, PP and PS	1.0	T5	Environmental hazard mitigation (livestock deaths, pollution control)	[28]
Industrial Pyrolysis Plant (Large-scale Simulation)	LDPE	37.5 ton.h^{-1}	T2	High abundance and ease of thermal degradation due to polymer structure	[22]

PE (HDPE+LDPE)**; Thematic codes:** T1-Local Resource Energy Recovery; T2-Waste Abundance and Thermochemical Suitability; T3-Circular Economy and Sustainability Transition; T4-Infrastructure and Preprocessing Constraint Reduction; T5-Environmental Pollution Mitigation; and T6-Emerging Waste Streams.

3.4. Energy Sources and Reactor Operability in Sub-Saharan Africa

The selection of energy sources for plastic pyrolysis reactors in sub-Saharan Africa is influenced by the need to balance experimental control, techno-economic feasibility, and resource accessibility within infrastructure-constrained environments. Considering the fluctuations in electricity reliability and fuel supply throughout the region, the operability of reactors is largely determined by the type of heating system chosen, which plays a crucial role in ensuring process stability, scalability, and practical application. A synthesis of the reviewed studies, supported by the thematic distribution in Figure 5, indicates a hierarchy among the drivers of energy-source selection. Experimental control and precision were the dominant factors (46%), followed by techno-economic feasibility and scalability (31%), resource availability and accessibility (15%), and energy integration and process efficiency (8%). This hierarchy elucidates the technological pattern, where energy system selection transitions from precision-oriented laboratory configurations to context-adapted and self-sufficient solutions as the scale increases and infrastructural constraints intensify.

Approximately 46% of the studies, predominantly from Nigeria, employed electrical heating systems, reflecting the priority given to experimental precision. These systems utilize resistance coils and PID controllers to achieve accurate and reproducible thermal conditions, enabling detailed kinetic studies and polymer degradation analyses at temperatures exceeding 600°C [2],[10],[13]. The 31% contribution of techno-economic considerations is reflected in the adoption of LPG-based systems, particularly in Ghana, where higher heat flux and operational practicality support pilot-scale applications despite reduced control resolution [18],[24],[36]. Resource-driven decisions (15%) are evident in Uganda and Cameroon, where biomass-based systems, such as wood-fired reactors and the recirculation of non-condensable gases, are implemented to overcome grid limitations and ensure operational continuity [8],[28]. The least represented driver, energy integration and process efficiency (8%), corresponds to industrial-scale systems, such as those modeled in Sudan, where Total Site Heat Integration (TSHI) is employed to achieve energy self-sufficiency and reduce CO_2 emissions [22]. The alignment between the thematic drivers and the observed technological choices reveals a structural imbalance. The dominance of precision-driven electrical systems indicates that current research is oriented toward controlled experimental conditions rather than real-world deployment.

In contrast, the low emphasis on resource-based and energy-integrated systems suggests that solutions suited to decentralized and infrastructure-limited contexts remain underdeveloped. This divergence highlights the need to prioritize the development of hybrid and adaptive energy systems that integrate process control with local energy availability to enhance the practical operability and scalability of pyrolysis technologies in Sub-Saharan Africa.

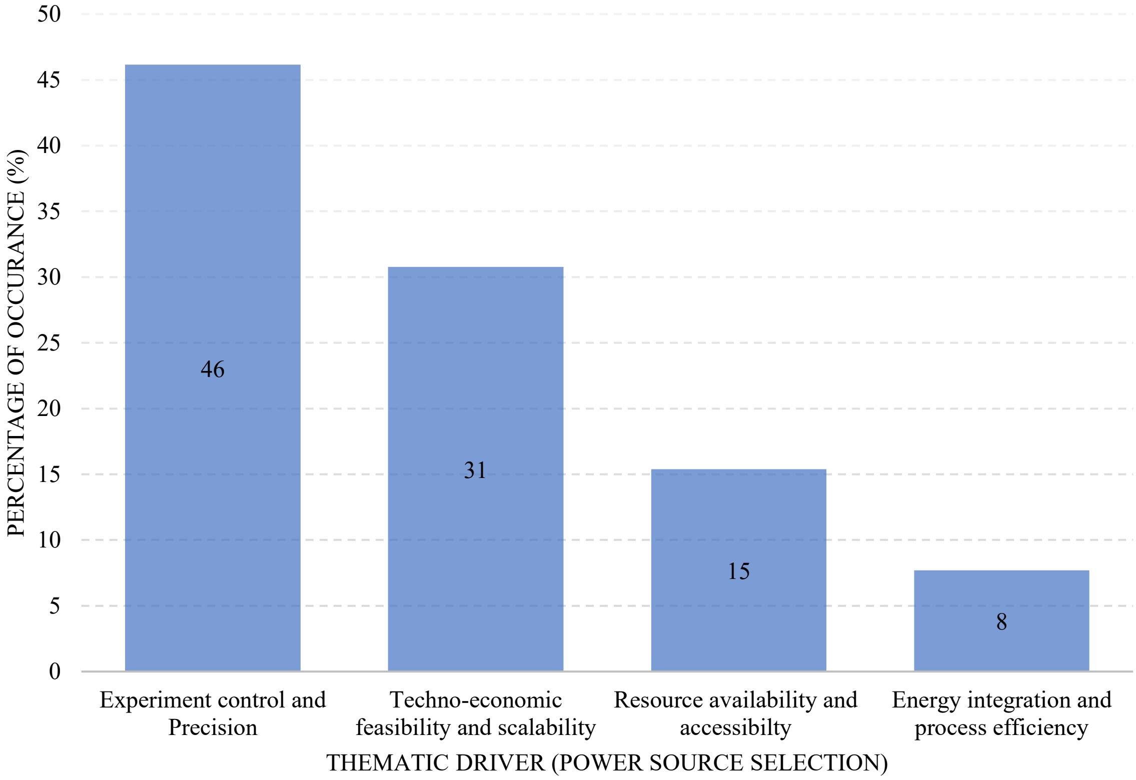

Figure 5. Thematic Drivers Influencing Energy Source Selection for Pyrolysis Reactors in Sub- Saharan Africa.

3.5. Operational Performance of Reactors

Pyrolysis is a thermochemical decomposition process performed in the absence of oxygen, where temperature and residence time serve as the primary operational determinants of the yield and quality of liquid oil, gas, and char [3],[40]. A systematic analysis of the reviewed literature revealed a definitive relationship between reactor configuration and thermal intensity within sub-Saharan Africa. Batch reactors predominantly operate within a broad low-to-mid temperature range of 203-500 °C as shown in Table 3, necessitating extended residence times of 1-6 h owing to inherent kinetic limitations and inefficient heat transfer across larger feedstock masses [10],[12],[13],[18],[24],[25],[28],[37]. In contrast, fixed-bed reactors, as indicated in Table 3, exhibit a more optimized operating window of 300-550 °C with reduced residence times, while large-scale industrial simulations in the Sudan model extreme thermal intensification at 700-900 °C to prioritize rapid thermal cracking and high gaseous yields [2],[5],[8],[11],[22],[26],[27],[36]. However, the introduction of catalysts shifts these parameters by lowering the activation energy of polymer chain scission [14]. For instance, [28] reported that the use of silica-alumina catalysts in Uganda reduced the degradation temperatures of HDPE, PP, and PS by 17-33% compared to purely thermal processes. Similarly, [27] demonstrated that introducing aluminum chloride reduced the reaction time from 4 h in a thermal run to 3 h 10 min.

These findings suggest that reactor configuration transcends mere design choice and serves as a pivotal factor in determining process efficiency and scalability. Although batch systems are adaptable and suitable for decentralized applications, they are characterized by thermal inefficiency and time-intensive operations. Fixed-bed reactors demonstrate enhanced performance but require greater design precision and meticulous catalyst management. Although industrial systems can achieve high throughput and energy recovery, they rely heavily on advanced infrastructure and thermal integration. Therefore, optimizing pyrolysis in sub-Saharan Africa necessitates a balance between thermal efficiency and technological simplicity, with catalytic integration emerging as a crucial strategy for enhancing the performance without significantly increasing the system complexity.

Table 3. Operational Parameters and Energy Sources of Plastic Pyrolysis Reactors in Sub-Saharan Africa.

REACTOR TYPE	Operating Temperature (°C)	Residence Time (hrs.)	Heating Rate (°C/min)	Power Source	Study Location	Sources
BATCH REACTOR	450	4.0	-	Electrical	Uyo, Nigeria	[25]
	250-500*	3.0	-			
	400-500*	2.0	-	Gas burner	Kumasi, Ghana	[24]
	600	4.0-6.0	-			
	350-500*	0.75-1.5	-	Electrical	Ibadan, Lagos, Nigeria	[37]
	350*	1.5	-	Gas burner	Zaria (Kaduna State), Nigeria	[12]
	450-490	2.0	-			
	300-450	2.0	10.0	Gas burner	Accra, Ghana	[18]
	203-400*	1.0	-	Electrical	Ilorin, Nigeria	[10]
	500-800	-	100	Electrical (2.5kW)	Nsukka, Nigeria	[13]
	300-450*	4.0	15.0	Wood fuel	Kabanyolo, Uganda	[28]
FIXED-BED REACTOR (Fixed Batch Reactor)	450-550	3.7-4.0	-	Biomass combustion	Dschang, Cameroon	[8]
	350-450	2.0	-	Gas burner	Port Harcourt, Nigeria	[11]
	300*	0.5	8.0	Electrical (2.0kW)	Ota, Nigeria	[2]
	350-450	3.0-6.0	-	Liquefied Petroleum Gas (LPG) burner	Cape Coast Technical University, Ghana	[36]
	350-500*	1.5	10.0	-	Zaria, Nigeria	[5]
	340-400*	3.5	10.5	Electrical	Gulu, Uganda	[27]
		3.2	15.5			
		4.0	12.5			
	350-521*	-	10-20	Electrical (modified brick furnance)	Eldoret, Kenya	[26]
Continuous Reactor	300-450*	4.0	15.0	Wood fuel	Kabanyolo, Uganda	[28]
Industrial Pyrolysis Plant	700-900	8000 h/yr operation	-	Integrated thermal utilities	Khartoum, Sudan	[22]

*Catalytic condition.

4. DISCUSSION OF THE RESULTS

The findings suggest that the optimization of plastic pyrolysis for decentralized waste-to-energy systems in Sub-Saharan Africa is constrained by both technical and infrastructural limitations, rather than by reactor design alone. This indicates that performance outcomes are shaped by system-level constraints that extend beyond the operations of individual units. The development of pyrolysis in the region has been significantly influenced by the need to manage municipal plastic waste while simultaneously addressing energy insecurity. This has resulted in the emergence of reactor configurations tailored to specific contexts rather than standardized designs. Analysis of reactors indicates that batch systems predominate due to their low cost, operational simplicity, and suitability for decentralized deployment. These systems typically operate at temperatures ranging from 203-500°C and are widely applied in Nigeria, Ghana, and Uganda for the conversion of LDPE and mixed plastics [10],[25],[28]. However, their limited heat transfer efficiency and long residence times constrain the consistency of the oil yield. Additionally, these batch systems are disadvantaged by high labor costs and are unsuitable for the mass production of pyrolysis oil, with varying byproducts in each batch [17].

Fixed-bed reactors demonstrate improved thermal contact and narrower operating ranges (300-550°C), enhancing cracking efficiency and product selectivity [8],[36]. In contrast, industrial-scale systems (700-900°C) exhibit high throughput potential but require centralized infrastructure and advanced energy integration, limiting their applicability in decentralized contexts [22]. Across reactor types, a clear scalability gradient was observed, where increases in performance were associated with proportional increases in infrastructural and energy demands. This confirms that scalability is primarily limited by infrastructure rather than by technology. Feedstock selection further influences oil yield performance, with a strong regional preference for polyolefins, particularly LDPE, HDPE, and PP, due to their abundance and high liquid fuel yield potential [8],[10]. However, the limited processing of mixed plastics and PET highlights the poor alignment between reactor design and real-world heterogeneous waste streams, thereby reducing the overall system efficiency in decentralized settings. This mismatch suggests a structural inefficiency between the realities of waste composition and existing conversion technologies.

Moreover, the choice of energy source significantly affects the reactor operability and oil yield stability. Electrical heating is predominant in laboratory studies due to precise temperature control, whereas LPG and biomass-based systems are increasingly utilized in Ghana, Uganda, and Cameroon to address grid instability [24],[28]. These variations indicate that process efficiency is strongly dependent on energy reliability, which directly influences thermal stability and product quality. Catalytic integration has emerged as a key optimization strategy, with zeolite-Y, bentonite, and silica-alumina catalysts improving hydrocarbon selectivity and reducing degradation temperatures by up to 30% [28]. This demonstrates that oil yield enhancement in decentralized systems is achieved more effectively through catalytic and operational optimization than through reactor complexity alone. This shifts the optimization focus from mechanical design to process intensification strategies. Overall, the study indicates that the effective optimization of pyrolysis oil production in Sub-Saharan Africa requires an integrated system design that combines simple reactor configurations, adaptable energy sources, and low-cost catalytic enhancement. The results confirm that the viability of decentralized waste-to-energy systems depends on system integration rather than isolated improvements in reactor engineering alone. This reinforces a systems-level interpretation in which performance is determined by the interaction of reactor design, feedstock heterogeneity, and energy infrastructure, rather than any single technological component.

5. KNOWLEDGE GAP AND AREAS FOR FURTHER RESEARCH

Despite the increasing interest in plastic pyrolysis throughout sub-Saharan Africa, several critical gaps hinder the transition from laboratory-scale demonstrations to scalable and decentralized waste-to-energy systems. This includes the lack of standardized reactor design frameworks tailored to African waste and infrastructure. Existing studies are highly fragmented, with batch, fixed-bed, and continuous systems developed independently and failing to converge toward optimized hybrid designs. This fragmentation limits the comparability of the results and restricts knowledge transfer across different contexts. Insufficient scale-up validation remains a significant constraint. Most reported systems operate at the laboratory or pilot scale, with limited empirical evidence from semi-industrial or decentralized community-scale applications. Consequently, the performance of reactors under real municipal waste variability and operational stress is poorly understood. There is also weak integration between the reactor design and feedstock heterogeneity. Most systems are optimized for homogeneous polyolefins, despite real waste streams being mixed and contaminated. This mismatch leads to reduced thermal efficiency, unstable product yields, and poor catalytic performance. Moreover, energy system integration remains underdeveloped in this region. Although some studies have explored electrical, liquefied petroleum gas (LPG), and biomass heating, there is limited research on hybrid or self-sustaining energy systems that integrate waste-derived syngas or heat recovery for reactor operation. Finally, there is a lack of techno-economic and environmental optimization frameworks linking reactor configurations to life cycle emissions, cost efficiency, and decentralized deployment feasibility. This weakens policy relevance and slows down technology adoption.

6. CONCLUSION

This study demonstrates that plastic pyrolysis in sub-Saharan Africa is technically feasible but is structurally constrained by reactor design limitations and contextual misalignment. Batch and fixed-bed reactors dominate because of their simplicity and low cost; however, they are thermally inefficient and poorly suited for heterogeneous waste streams. Continuous and industrial systems show superior performance but remain largely theoretical in sub-Saharan Africa contexts due to infrastructure and capital limitations. The findings confirmed that the reactor configuration is a decisive factor influencing the conversion efficiency, product distribution, and scalability. However, the absence of standardized hybrid, and context-adapted reactor systems limits the transition toward decentralized waste-to-energy deployment. To advance this field, future research must prioritize scalable hybrid reactor designs, the integration of heterogeneous feedstock processing capabilities, and energy self-sufficient reactor systems that utilize waste-derived energy streams. Without these advancements, pyrolysis technology will remain confined to experimental validation rather than practical deployment in Sub-Saharan Africa.

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