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| RESEARCH ARTICLE

Engineering Crucible Pots: A Review of Kaolin-Based Composites with Functional Additives

Emmanuel I. Nwankwo[1], Swift N. K. Onyegirim[2] ✉ Kennedy C. Owuama[3] and Chris A. Ubani[4]
[1234]Department of Mechanical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli – Nigeria
Corresponding Author: Swift N. K. Onyegirim, **E-mail**: sk.onyegirim@coou.edu.ng

| ABSTRACT
This review examines the advancements in the fabrication of kaolin-based crucible pots, underscoring the significance of functional additives and processing methodologies on thermal and mechanical efficacy. Although kaolin is plentiful and exhibits thermal stability, it is characterized by brittleness and inadequate shock resistance, necessitating reinforcement for its application in industrial contexts. A comprehensive literature review spanning from 1995 to 2024 was performed utilizing Scopus and Google Scholar as primary sources. Thirteen pivotal studies were scrutinized, indicating that the inclusion of additives such as graphite, alumina, and magnesium oxide markedly enhances mechanical strength, thermal conductivity, and overall durability. Processing techniques, including slip casting and sintering, were predominantly utilized to refine microstructure and minimize porosity. Comparative evaluations demonstrated that locally sourced clays are viable for high-performance applications when appropriately combined with specific additive ratios. The review further emphasizes the criticality of achieving a balanced composition to circumvent performance compromises. It advocates for the implementation of standardized testing protocols, increased utilization of sustainable materials such as agro-waste, and the integration of computational modeling to optimize formulations. These strategies can help produce cost-effective, durable crucibles tailored for modern metallurgical operations.

| KEYWORDS
Kaolin crucible, functional additives, thermal performance, local clay, refractory materials, composite ceramics, high-temperature applications, graphite reinforcement.

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1. Introduction
Crucible pots have historically been instrumental in the domains of metallurgy and materials processing, functioning as indispensable vessels for the processes of melting, alloying, and refining metals at elevated temperatures (Krishnamurthy, 2022). The efficacy of crucibles is predominantly influenced by their material composition, with kaolin-derived ceramics emerging as a favored option owing to their exceptional thermal stability, chemical inertness, and robust mechanical strength (Chukwudi et al., 2024; Dikeogu et al., 2014; Ekpechi et al., 2023; Ekpechi et al., 2025). However, the development of sophisticated kaolin-based composites reinforced with functional additives has become necessary due to the growing demands of contemporary metallurgical processes, which include greater working temperatures, resistance to thermal shock, and extended durability (Al-Ameri et al., 2024a; Ali et al., 2025).

Kaolin, a naturally occurring aluminosilicate clay, displays remarkable refractory characteristics, rendering it a critical constituent in the fabrication of crucibles (Chakraborty, 2014). Notwithstanding its merits, pure kaolin ceramics experience drawbacks including brittleness, vulnerability to thermal shock, and diminished mechanical strength under extreme thermal cycling conditions (Bozorgkhou et al., 2022; Zawrah et al., 2024). To address these limitations, researchers have investigated the integration of various functional additives, encompassing alumina (Al_2O_3), silicon carbide (SiC), graphite, and zirconia (ZrO_2), to augment thermo-mechanical properties (Kaur et al., 2022; Prajapati et al., 2023). These additives contribute to enhanced thermal shock resistance, increased fracture toughness, and mitigated crack propagation, thereby prolonging the operational lifespan of crucibles in demanding environments (Ma et al., 2016). The choice of additives is contingent upon the specific application of the crucible (Erebugha et al., 2024; Eze et al., 2021; Ezeaku et al., 2024; Ezechukwu et al., 2025; Ikebudu et al., 2012; Ikebudu et al., 2015; Iweka et al., 2019). For example, the incorporation of graphite enhances thermal conductivity and slag resistance, rendering it suitable for the melting of non-ferrous metals (K. Kumar et al., 2019). Conversely, reinforcements with alumina and zirconia bolster high-temperature stability (Anaemeje et al., 2022; Idogho et al., 2025; Chinedu, 2019), which is pivotal for the processing of refractory metals and superalloys (Fergus & Hoffmann, 2014; Sengupta & Manna, 2022). Moreover, the utilization of nano-sized additives has garnered considerable interest due to their capacity to enhance sintering behavior and microstructural uniformity, resulting in superior mechanical properties (A. Kumar et al., 2019; Sikora et al., 2022).

Recent progressions in processing methodologies, including slip casting, pressureless sintering, and spark plasma sintering (SPS), have further refined the performance of kaolin-based composites (Al-Ameri et al., 2024b; Ohji & Fukushima, 2012). These techniques facilitate enhanced control over porosity, grain size, and phase distribution, which are vital for the attainment of high-performance crucibles (Mukherjee et al., 2023). Furthermore, the amalgamation of computational modeling and machine learning has streamlined the design of customized composite formulations, thereby minimizing the necessity for experimental trial-and-error (Badini et al., 2023). This review paper conducts a systematic analysis of the prevailing state of kaolin-based crucible composites (Iweka & Owuama, 2020; Iweka et al., 2021a; Jugu et al., 2025; Ikebudu et al., 2021; O. D. K. et al., 2024; Nwankwo et al., 2012; Nwankwo et al., 2011), emphasizing the significance of functional additives in improving their thermal, mechanical, and chemical attributes (Vivian et al., 2025; Madukasi et al., 2025; Mulani et al., 2022; Nnaji et al., 2024; Offodum et al., 2025; Okonkwo et al., 2012; Onyenanu & Nwigbo, 2021). It also explores recent advancements in processing techniques and future trajectories in crucible engineering, offering valuable insights for researchers and industry professionals seeking to innovate next-generation refractory materials (Onyenanu et al., 2024; Owuama & Owuama, 2021; Swift et al., 2012; Onyenanu et al., 2015; Ubani & Onyenanu, 2024; Ukwu et al., 2024; Utu et al., 2024).

2. Literature Review

The advancement of kaolin-based crucible pots has been characterized by systematic improvements in both material composition and processing methodologies, aimed at satisfying contemporary metallurgical requirements. Numerous academic investigations have scrutinized the enhancements of kaolin-based crucible pots in order to align with modern metallurgical standards. Ubani and Onyenanu (2024), in their study titled "Investigation of the Mechanical and Morphological Properties of Locally Developed Graphite Crucible Pot Using Kaolin Clay and Other Additives", illustrated the viability of utilizing indigenous Nigerian raw materials for the production of industrial-grade graphite crucibles. Adamu et al. (2015), in their publication "Production of High Temperature Refractory Crucibles from Locally Available Clays in Nigeria", confirmed the appropriateness of kaolin-white clay-quartz composites for such applications. Oluwagbenga et al. (2019) conducted an examination titled "Production of Refractory Porcelain Crucibles from Local Ceramic Raw Materials Using Slip Casting", which demonstrated significant levels of refractoriness and minimal water absorption. Adeoti et al. (2019), in their work "Suitability of Selected Nigerian Clays for Foundry Crucibles Production", performed a comparative analysis of the thermal and mechanical attributes of Tsaragi and Ipinsa clays. Likewise, V.S. et al. (2014) introduced a novel composite integrating bagasse ash in their study "Production of Alumino-Silicate Clay-Bonded Bagasse Ash Composite Crucible". These scholarly contributions provide critical foundational perspectives for subsequent inquiries.

3. Methodology

A systematic literature review methodology was employed in this investigation to analyze the evolution, material enhancements, and thermal-mechanical performance of kaolin-based crucible pots utilized in metallurgical and high-temperature contexts (Kitchenham et al., 2009; Van Dinter et al., 2021). The review synthesized empirical research pertaining to material formulation, processing methodologies, and functional additives, aiming to discern trends, performance benchmarks, and prospects for future innovations within the field of crucible engineering.

3.1 Data Collection Strategy

The Scopus and Google Scholar databases were chosen for their extensive indexing of peer-reviewed literature and conference proceedings pertinent to ceramic composites, refractory materials, and high-temperature engineering (Aromataris & Riitano, 2014; Bramer et al., 2017). A Boolean search strategy was implemented, utilizing combinations of the following terminologies:

"Kaolin crucible" OR "kaolin-based composite" OR "refractory crucible" AND ("thermal shock" OR "mechanical strength" OR "additives" OR "processing methods") AND ("alumina" OR "graphite" OR "zirconia" OR "silicon carbide")

The search encompassed publications from 1995 to 2024, thereby integrating both foundational research and pioneering advancements. An initial screening revealed 842 publications, which were evaluated based on inclusion criteria emphasizing experimental validation, materials characterization, and relevance to applications. Following the screening of titles, abstracts, and full texts, 32 articles were selected for comprehensive analysis, with 13 principal studies chosen for synthesis in the current review.

3.2 Publication of Journals by Ranking

Figure 1 depicts the upward trend in academic output concerning kaolin-based crucibles, especially post-2015, indicative of a heightened industrial focus on locally sourced and cost-effective refractory materials. The literature consistently underscores enhancements in fracture resistance, thermal conductivity, and chemical stability through the incorporation of alumina, graphite, and SiC additives. This increase is propelled by the demand for energy-efficient metallurgical processes and reduced reliance on imported ceramics within developing economies. The concentration of studies in high-impact journals dedicated to materials science, ceramics, and metallurgical engineering further emphasizes the interdisciplinary nature and practical significance of this research domain. The trend also aligns with global sustainability goals by promoting the use of indigenous mineral resources and environmentally friendly composite processing.

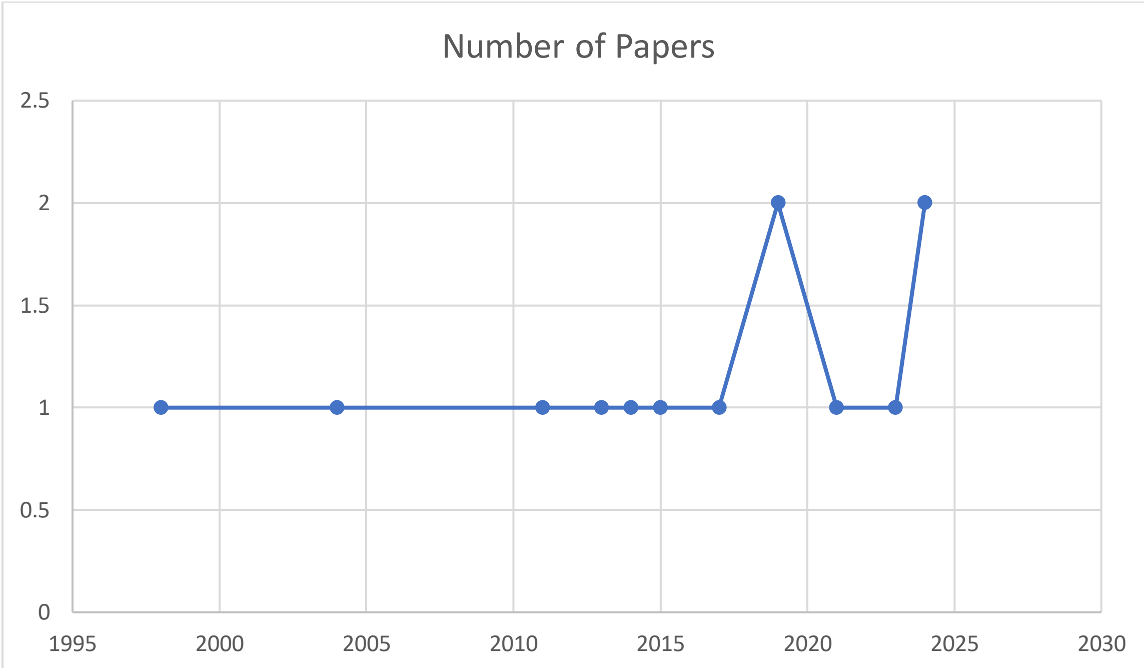

Figure 1: Graph of Journal Article by Year of Publication (Osobajo et al., 2017)

4. Review

A comparative analysis was carried out to present the advancements in kaolin-based crucible composites, with a particular focus on their raw materials, processing techniques, and performance properties. Table 1 summarizes important experimental studies, highlighting methodological approaches and results across various geographical and material contexts. This overview reveals significant efforts to optimize indigenous resources for refractory applications, particularly within West Africa.

Table 1: Comparative Summary of Key Studies on Engineering Crucible Pots Using Kaolin-Based Composites

Study Topic	Focus Area	Key Findings	Reference
Investigation of the mechanical and Morphological properties of locally Developed a graphite crucible pot using Kaolin clay and other additives	Aimed to develop an indigenous method for producing graphite crucibles using raw materials sourced within Nigeria.	"Optimized compositions achieved hardness strength of over 4 MPa, and density of 2.48 g/cm^3. Results demonstrate the feasibility of manufacturing graphite crucibles locally that meet industrial standards, utilizing readily available Nigerian raw materials."	(Ubani & Onyenanu, 2024)
Production of Refractory Porcelain Crucibles from Local Ceramic Raw Materials using Slip Casting	"Refractory porcelain crucibles were produced from indigenous ceramic raw materials from Ikere Ekiti and Awo (locations in South Western Nigeria). Chemical analysis was carried out on the raw materials using X-ray Fluorescence Spectrometer (XRF) to determine their chemical compositions."	"The result of the standard tests carried out on the locally produced porcelain crucibles showed total shrinkage of 10%-15%, water absorption of 0.36%-0.72%, compressive strength of 1.43N/mm^2-1.65 N/mm^2, and refractoriness of 1680.2^{0}C-1717.5^{0}C. The result showed that ceramic raw materials sourced from the selected deposits in South Western Nigeria are suitable for the production of porcelain crucibles with good refractory properties."	(Oluwagbenga et al., 2019)
Suitability of selected Nigerian clays for foundry crucibles production	Investigation and characterization of selected Nigerian clays for Foundry Crucible production	"The results obtained showed that the refractoriness of Tsaragi clay was 1600°C and that of Ipinsa clay was 1370°C. The overall results showed that both samples can be used for crucible production, but it was discovered that samples from Tsaragi were found to be more suitable concerning the value obtained in terms of Refractoriness, thermal conductivity (2.32 W/m/k), and cold crushing strength (7.5MPa) than the Ipinsa sample."	(Adeoti et al., 2019)
Production of alumino-silicate clay-bonded bagasse ash composite crucible by slip casting	This research work developed a new material for the production of crucibles using alumino-silicate clay (Kankara) and bagasse ash.	"The results obtained showed that density, porosity, crushing strength, and thermal shock resistance are within the recommended standard. The developed crucible has a high stability to the contamination of crucible materials (Al2O3 and SiO2) on the cast aluminium."	(V.S et al., 2014)
Local raw material exploration for the production of refractory pots for melting glass.	"An attempt is made to develop five containers for molten glass from local refractory clay materials comprising Kaolin from Kankara, Katsina State, whose deposit is of economic value, and ball clay from Bomo-village, Zaria, Kaduna State."	"All pots made were able to withstand high temperatures without crumbling, although some showed higher crack formation. The refractory pots were able to withstand the chemical action of the molten glass of lead crystal and soda-lime silica glass batches. The composite body of 60% grog and 40% Kaolin was found to be the most suitable for the production of pots that would be used for melting glass, having shown the	(Garkida, 1998)

		best results of the tests that were carried out."	
Production of High Temperature Refractory Crucibles from Locally Available Clays in Nigeria.	"The study experimented with using local ceramic raw materials (white clay, kaolin, and silica or quartz) found in AssinFosu in the Central Region of Ghana to manufacture crucibles for melting metals and other precious minerals."	"The results revealed that the composition of Cruc, containing 70% of white clay, 20% of kaolin, 8% of quartz, and 2% of white grog, sintered at 1500˚C, was very successful and therefore used to develop the recipe to manufacture the proposed crucibles. The "throwing" technique was employed to fabricate the crucibles. A test for thermal expansion was conducted for the manufactured crucibles at 1000˚C for thermal shock and microcracking tests. It was found out, among others, that the recipe developed had very good physical and chemical properties of alumina silicate refractory materials and was fit for use at any high-temperature application."	(Adamu et al., 2015)
Effect of aluminum powder on the synthesis of corundum-mullite composites	"The effect of aluminum powder content on the synthesis and densification of the corundum-mullite was studied. Bulk density, apparent porosity, phase composition, and microstructure of final sintered (1100°C to 1500°C) products were analyzed."	"The results indicated that aluminum powder can promote the densification and mullitization of corundum-mullite composites. At the same time, aluminum powder promoted the formation of columnar mullite. Among materials sintered at 1500°C for 3 h, samples with 8 % aluminum powder had the highest bulk density."	(Ruan et al., 2013)
Solid mineral resource development in sustaining Nigeria's economic and Environmental realities of the 21st century	"This study attempts to take a general over view of ceramic raw materials based on the researcher's field exploration, exploitation, and studio experimentation on these materials that were accessed to produce products that satisfy aesthetic, functional, and technical purposes which have a direct or indirect impact on the sustainability of the environment."	The manufacturing of structural ceramic products such as clay roof tiles, sanitary wares, wall and floor tiles, electrical insulators, sewage pipes, and burnt bricks, are basic components that contribute significantly to housing provisions in the built environment. The mineral exploitations and industrial establishments that are solid minerals-based, in no small way, contribute to the socio-economic transformation of the environment through job creation."	(Kashim, 2011)
Influence of Firing Temperature on the Ceramic Properties of Clays from Campos dos Goytacazes, Brazil.	This study aims to evaluate the potential suitability of Tetouan and Meknes (central Morocco) clay material as raw materials in various ceramic applications by investigating their textural, chemical, thermal, and firing characteristics.	"The Tetouan clays have medium to low CEC and medium SSA values. The main oxides in the clayey samples are SiO2 (35 - 54.3 wt%), Al2O3 (20.6 - 43.9 wt%), and Fe2O3 (9.7 - 22.4 wt%). The amount of CaO in Meknes clays ranges from 8 to 12 wt%, whereas CaO is only present in some Tetouan clay (TE4, TE7, TN4, and TN5). A significant densification of ceramic behaviour could be noticed for most of the Tetouan clays at firing temperatures above 1000℃. Meknes clays show earlier	(Monteiro and Vieira, 2004)

densification from 800℃. The chemical, textural, and ceramic properties of Tetouan and Meknes clays indicate their suitability as raw materials for the production of structural ceramics."

To compare kaolin composite compositions, including their performance characteristics and additives, a more thorough synthesis was carried out. Material compositions, manufacturing variables, and the resulting thermal-mechanical performance are recorded in Table 2.

Table 2: Summary of Previous Works on Kaolin-Based Crucible Materials

Citation	Title of Study	Additives Used	Processing Technique	Key Findings
(Ibekwe & Aramide, 2023)	Development of Mullite-Carbon-Refractory Ceramic Composite from Locally Sourced Materials	Graphite, magnesium oxide, and calcium oxide	Sintering at 1300–1500 °C	"Findings indicated that additive inclusion spurred mullite phase development between 1300°C and 1500°C, enhancing their physico-mechanical properties. Among the samples, Sample R, composed of 15% MgO, 65% kaolin, and 20% graphite, fired at 1500°C, displayed optimal physico-mechanical properties (95.8%), and favorable mullite formation (46.0%) was achieved."
(Odewole, 2019)	Production of Refractory Porcelain Crucibles from Local Ceramic Raw Materials Using Slip Casting	White clay, kaolin, and silica or quartz	Slip casting, firing at 1300 °C	"The results revealed that the composition of Cruc containing 70% of white clay, 20% of kaolin, 8% of quartz, and 2% of white grog, sintered at 1500˚C, was very successful and therefore used to develop the recipe to manufacture the proposed crucibles."
(Gounden et al., 2024)	Improving the performance properties of plastic-sand bricks with Kaolin Clay	Kaolin clay	Thermoset composite fabrication	"The key findings indicate that the lowest water absorption rate of 0.39% was achieved with a 60s:40p ratio, attributed to the addition of 10% Kaolin Clay. Scanning Electron Microscopy (SEM) analysis revealed that Kaolin Clay effectively fills voids between particles, enhancing the structural integrity and reducing water absorption of the brick samples."
(García-Ten et al., 2010)	Thermal conductivity of traditional ceramics: Part II: Influence of mineralogical composition	Various mineralogical compositions	Ceramic processing	"The findings suggest that to manufacture traditional ceramics with high thermal insulation and appropriate mechanical properties, it is advisable to use illitic-kaolinitic clays. Large-sized potassium feldspar and quartz particles adversely affect fired mechanical strength. In addition, quartz has high thermal conductivity."
(Awad et al., 2020)	Flow and Tableting Behaviors of Some Egyptian Kaolin Powders as Potential Pharmaceutical Excipients	___	Powder characterization	"The obtained tablets exhibited hardness between 33 and 44 N only from the dehydrated powders at 400 °C, with elastic recovery (ER) between 21.74% and 25.61%, ejection stress (ES) between 7.85 and 11.45 MPa and tensile fracture stress (TFS) between 1.85 and 2.32 MPa, which are strongly correlated with crystallinity (HI) and flowability (HR) parameters."

Furthermore, the specific effects of functional additives on kaolin composites were examined. The composition range and property enhancements, including strength, stability, and thermal resistance, are shown in Table 3. For the majority of mechanical improvements, a kaolin content of 10–15 weight percent was ideal.

Table 3: Effect of Functional Additives on Properties of Kaolin Composites

Additive	Composition (%)	Property Enhanced	Experimental Outcome	Reference(s)
Kaolin Powder	0 to 14 wt.%	Tensile strength, hardness	Increased tensile strength and hardness; decreased impact strength with higher kaolin content	(Hong, 2019)
Raw and Calcined Kaolin	(0, 1, 3,5, 10, 14) wt.%	Tensile strength, modulus	Calcined kaolin composites showed higher tensile strength and modulus compared to raw kaolin composites.	(Mustafa, 2012)
Kaolin Powder	1–14 wt%	Impact strength, hardness	Improved impact strength and hardness up to 10 wt% kaolin; properties declined beyond this point	(Mustafa, 2012)
Kaolin Particulate & Luffa cylindrica Fiber	5, 10, and 15%wt	Tensile strength, flexural strength	Enhanced mechanical properties with optimal fiber and kaolin content	(Yaro et al., 2021)
Kaolinite	12wt. %	Thermal stability, flammability	Increased thermal stability and reduced flammability with higher kaolinite content	(Majeed & Sabar, 2017)
Kaolin	10–30 wt%	Wear resistance, water absorption	Enhanced wear resistance and reduced water absorption with increased kaolin content	(Bati et al., 2025)

5. Discussion

The reviewed studies clearly show that kaolin-based crucible pots have evolved significantly through the integration of various additives and processing methods to meet the demanding needs of high-temperature applications. While kaolin is valued for its thermal stability and abundance, it has limitations, which are mainly its brittleness and poor resistance to thermal shock. To address these challenges, researchers have adopted different strategies, often depending on local material availability and specific performance goals. For instance, Ubani and Onyenanu (2024) successfully developed a graphite-reinforced kaolin crucible using Nigerian raw materials, achieving industrial-grade strength and thermal properties. This aligns with the findings of Adamu et al. (2015), who used kaolin, white clay, and quartz to create crucibles that withstood high temperatures and showed excellent thermal expansion behavior. Both studies confirm the potential of local resources but differ in their additive approaches—graphite for thermal conductivity in Ubani's case and multi-mineral blending in Adamu's. Likewise, Oluwagbenga et al. (2019) and V.S. et al. (2014) both applied slip casting but focused on different materials. Oluwagbenga's crucibles, made from Ikere and Awo clays, showed excellent shrinkage and refractoriness, while V.S. incorporated bagasse ash, highlighting a sustainable method that enhanced thermal shock resistance. This comparison underlines how material choice plays a key role in determining final crucible performance. Adeoti et al. (2019) added a valuable dimension by comparing clays from Tsaragi and Ipinsa, showing that Tsaragi clay offered better thermal conductivity and compressive strength. Their results echo those of Monteiro and Vieira (2004), who found that clays with higher alumina and silica content tend to perform better at elevated temperatures. Further insights come from Ibekwe and Aramide (2023), who optimized a kaolin-based composite using graphite, magnesium oxide, and calcium oxide. Their formulation achieved nearly 96% improvement in performance metrics, thanks to the formation of mullite—a high-strength ceramic phase. Their work aligns with trends reported by Mustafa (2012) and Bati et al. (2025), who also emphasized the need for precise additive balance. Too much kaolin or reinforcement, they noted, can reduce impact resistance or cause internal stress. These studies demonstrate clear progress in kaolin-based crucible engineering. They collectively show that with the right formulation, kaolin composites can meet and even exceed industrial requirements.

6. Conclusion

This review demonstrates that kaolin-based crucibles when reinforced with additives like graphite, alumina, and MgO, provide improved thermal and mechanical performance suitable for high-temperature applications. Local clays, particularly in Nigeria, are valuable raw materials that can be handled effectively. Slip casting and sintering remain viable fabrication techniques. Future work should adopt standardized testing, explore sustainable additives, and utilize computational modeling for optimized formulations. Collaboration with industry stakeholders is essential to align crucible performance with real-world demands. Emphasizing local resource use and eco-friendly innovations will promote cost-effective, durable crucibles for advanced metallurgical processes.

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