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ENHANCING CERAMIC MATERIAL PROPERTIES THROUGH KAOLIN BENEFICIATION: A REVIEW

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Abstract

The ceramic industry relies heavily on kaolin, a versatile clay mineral, for its unique physical, chemical, and thermal properties. However, raw kaolin deposits often contain impurities such as quartz, feldspar, iron oxides, titanium minerals, and organic matter that degrade its performance in high-value applications. Beneficiation processes, encompassing mechanical, chemical, thermal, and biological techniques, are essential to upgrade kaolin quality for optimal use in ceramics and other industries. This review synthesizes global and Nigerian research on kaolin beneficiation, with emphasis on how these methods influence ceramic material properties, including whiteness, plasticity, sintering behavior, and mechanical strength. Special attention is given to recent advancements such as high-gradient magnetic separation, froth flotation, calcination, and eco-friendly "green beneficiation" approaches like bioleaching and enzyme-assisted treatments, which align with environmental sustainability goals. Case studies from Nigeria and other countries illustrate the economic, environmental, and technological impacts of beneficiation, highlighting its role in reducing import dependence, fostering industrial growth, and promoting local content development. The paper further examines emerging opportunities in nanotechnology, advanced ceramics, and circular economy integration, underscoring the strategic potential of kaolin beneficiation in supporting Nigeria's industrial diversification agenda.

Keywords
kaolin, beneficiation, ceramics, Nigeria, green processing, material properties, industrial applications

1. INTRODUCTION

The advancement of modern materials science and engineering has emphasized the development of high-performance materials to meet growing industrial, technological, and environmental demands (Nhiem et al., 2023). Among the key materials driving these innovations are ceramics, a class of inorganic non-metallic compounds known for their exceptional thermal stability, chemical inertness, electrical insulation, and mechanical strength. The performance of ceramic products is largely dependent on the properties and treatment of the raw materials employed in their fabrication. Kaolin, a naturally occurring clay mineral primarily composed of kaolinite ($Al_2Si_2O_5(OH)_4$), serves as one of the most important inputs in ceramic production, playing a crucial role in the formulation of porcelain, sanitary ware, floor tiles, and technical ceramics (Udhayakumar et al., 2022). However, as-mined kaolin often contains deleterious impurities such as quartz, feldspar, mica, iron oxides, titanium-bearing minerals, and organic matter. These impurities adversely impact critical ceramic properties such as whiteness, plasticity, and sintering behavior, necessitating beneficiation treatments that enhance kaolin's suitability for high-performance ceramic applications (Bhukte et al., 2022).

Beneficiation, the process of improving the physical or chemical properties of a mineral to make it more suitable for specific applications, is essential for optimizing the utility of kaolin in ceramics. Various beneficiation techniques have been developed and refined over time, ranging from simple mechanical separation methods to complex chemical, thermal, and biological processes. The primary purpose of these processes is to remove unwanted minerals, brighten the clay, adjust particles and improve the surface. All of this adds up to reinforce ceramics, making them more heat resistant, and more durable (Chandramohan et al., 2022; Dondi et al., 2025). Recent research by the likes of indicates that the refining kaolin can not only lift its quality and usability, but that processing raw materials in this way is both commercially and environmentally beneficial as it makes the production process more efficient and less wasteful.

Kaolin is present in several Nigerian states including Kogi, Ekiti, Ogun, Plateau, Katsina, and Bauchi and it is considered a vital resource. However, most ceramic industries in Nigeria depend on imported kaolin due to poor confidence in the uniformity and quality of the local kaolin supply. Research by Mamudu, et al. (2020), and the Raw Materials Research and Development Council (RMRDC) pointed out that Nigerian kaolin can meet international quality standards and can replace imported ones – provided it is processed properly. The issues preventing this opportunity are underdevelopment of infrastructure, lack of skilled technical staff and the initial costs of new investment for contemporary kaolin processing (Efavi et al., 2012; Erkan and Alp, 2024). There has been substantial advancement in kaolin processing finishing and technology by countries around the world including China, the United States, Brazil, and India and they have modernized kaolin processing. Therefore, Nigeria requires a stronger, stable and sustainable approach to kaolin beneficiation if it is to reduce its level of kaolin imports, grow the ceramic industry and improve local developments. In addition, there has been a clear shift in global trends in favor of environmentally and cost-effective beneficiation methods including biological and microwave-assisted processing, that reduce chemical application and energy consumption (Eyankware et al., 2021).

The review approached the challenges, opportunities and strategic interventions for kaolin use in the ceramic industry in relation to the local Nigeria and international contexts. The review's specific objectives were to address the important aspects of kaolin's intrinsic properties and their implications for ceramic applications and to investigate various kaolin beneficiation methods including mechanical, chemical, thermal and biological. Apart from considering the impact of the different kaolin beneficiation methods on kaolin properties upon global developments, the review included recommendations and discussion on the environmental, economic and industrial implications of kaolin beneficiation in ceramic manufacturing.

2. KAOLIN FUNDAMENTALS

Kaolin, also known as china clay, is a naturally occurring clay mineral composed primarily of kaolinite ($Al_2Si_2O_5(OH)_4$), a hydrated aluminum silicate formed through the chemical weathering of feldspathic rocks. Kaolin is found in many parts of the world and is highly valued in industries because of its special physical and chemical qualities. It is known for its high whiteness, smooth texture, plasticity, and resistance to chemical reactions (Gaied and Gallala, 2015). These properties make it useful in a wide variety of industries, such as ceramics, paper, paints, plastics, rubber, pharmaceuticals, and even agriculture. The exact way kaolin can be used often depends on its mineral makeup, particle size, and the level of impurities it contains. These factors directly affect how plastic, bright, and strong it will be when used in final products (Eyankware et al., 2021; Gbagba et al.,2023)

In Nigeria, kaolin is available in several states, including Katsina, Delta, Ogun, Bauchi, and Plateau. But despite this abundance, the kaolin industry in the country is still underdeveloped. Most of the clay is either left raw or only partly processed, which reduces its industrial value (Ghani et al., 2025). However, with the push for local content, value addition, and sustainable industrial growth, there has been renewed interest in developing Nigeria's kaolin resources. Beneficiation plays a key role here, as it helps improve the quality of kaolin by removing impurities like quartz, feldspar, mica, iron oxides, and organic matter. These impurities can weaken its performance, especially in high-value industries such as ceramics (Gougazeh, 2020).

2.1 Historical Development of Kaolin Beneficiation

Kaolin beneficiation has evolved significantly over the centuries. The earliest recorded use of kaolin dates back to ancient China during the Tang Dynasty, where it was used in porcelain production. Initial beneficiation was limited to manual selection and water-washing to remove coarse impurities. During the 18th century in Europe, particularly in Cornwall, England, more systematic methods such as settling, decanting, and handpicking were adopted to improve kaolin quality (Efavi et al., 2012). In Nigeria, traditional beneficiation methods such as drying, crushing, sieving, and rudimentary washing remain prevalent in artisanal mining communities. These techniques, although simple, are inadequate for producing the high-purity kaolin required in ceramics and advanced industries. Recognizing these limitations, Nigerian research institutions have been exploring more advanced beneficiation techniques, including magnetic separation, flotation, and acid leaching, to improve the quality of local kaolin (Hartati et al., 2020). The integration of modern beneficiation technologies into Nigerian kaolin processing is still limited by infrastructural and financial constraints. However, recent pilot studies and university-led initiatives have shown promising results in upgrading the physicochemical characteristics of Nigerian kaolin to meet industrial standards. These efforts underscore the importance of sustained research and investment in mineral processing infrastructure (Hosseini and Ahmadi, 2025; Imran et al.,2023).

2.2 Global and Nigerian Significance of Kaolin

Globally, kaolin is a high-value industrial mineral with applications across several sectors. The leading producers of kaolin include the United States, China, Brazil, the United Kingdom, and Germany. Market projections vary: several industry reports place the global kaolin market between approximately USD 5.2 billion and USD 8.3 billion by 2030, with variations arising from differences in methodology, sectoral coverage, and regional scope (Zhang et al., 2018). These figures underscore the increasing reliance on kaolin as a strategic industrial raw material. In contrast, Nigeria is estimated to hold over 3 billion metric tons of kaolin reserves, yet it contributes minimally to global production due to limited beneficiation capacity, inadequate processing infrastructure, and a high dependence on imports (Romero et al., 2021). The low level of contribution from Nigeria's kaolin sector is mainly due to several challenges. These include the lack of modern beneficiation facilities, low investment in processing technologies, and limited awareness among manufacturers about the potential of using locally sourced kaolin. As a result, most of the kaolin used in Nigerian industry especially in ceramics is still imported, even though there are local deposits available (Romero et al., 2021).

However, efforts are being made to change this situation. Agencies like the Nigerian Geological Survey Agency (NGSA), the Raw Materials Research and Development Council (RMRDC), along with several universities, are working to map out kaolin deposits and develop better beneficiation methods that can make local kaolin more suitable for industrial use (Owino et al., 2025). Kaolin has an important role to play in Nigeria's plan to diversify its economy. If properly processed and put to use, it could help reduce imports, create new jobs, strengthen local industries, and support the growth of the non-oil minerals sector. Promoting domestic kaolin beneficiation also fits into the Federal Government's Economic Recovery and Growth Plan (ERGP), which places strong emphasis on developing local resources and boosting industrial growth. With the right policies, investments, and capacity-building initiatives, Nigeria stands to become a significant player in the global kaolin market (Lampropoulou and Papoulis, 2021; Lamidi et al., 2024).

3. KAOLIN BENEFICIATION TECHNIQUES AND ADVANCEMENTS

Kaolin, a hydrated aluminum silicate mineral ($Al_2Si_2O_5(OH)_4$), is globally recognized for its utility in numerous industrial sectors, especially ceramics. However, its performance in advanced applications is highly dependent on purity. Natural kaolin deposits are often associated with a range of undesirable minerals and chemical contaminants that adversely affect its brightness, plasticity, sintering behavior, and thermal resistance. These impurities include quartz, feldspar, iron oxides (e.g., hematite, goethite), titanium dioxide (especially anatase), mica, organic matter, and in some cases, heavy metals such as lead and chromium (Boonphan et al., 2024)..

The presence of iron and titanium compounds significantly influences kaolin's coloration, transforming what should be a brilliant white mineral into a yellowish or reddish material. These color-inducing impurities hinder the aesthetic and functional performance of ceramics, especially in products requiring high whiteness like sanitary ware, porcelain, and tiles (Murray and Kogel, 2005). Iron oxides, in particular, catalyze discoloration during firing and may reduce dielectric strength when kaolin is used in electrical insulators. The removal of such compounds is essential to enhance brightness (typically measured in ISO or GE brightness scales) and reduce the risk of product failure in high-temperature environments (Lamidi et al., 2024).

In Nigeria, several kaolin deposits notably in Kogi, Ogun, Plateau, Katsina, and Bauchi states have been reported to contain considerable amounts of Fe_2O_3 (ranging from 1.5–3.2%), quartz (over 20%), and organic matter (Lampropoulou and Papoulis, 2021). These deposits, although abundant, require systematic beneficiation before they can be adopted for high-grade ceramic or industrial use. In a study conducted by Adeniyi et al. (2023), untreated kaolin from Kogi State displayed poor sintering stability and high-water absorption, limiting its applicability in wall tile production. However, after undergoing a three-stage beneficiation process involving magnetic separation, acid leaching, and calcination, its whiteness index improved by 24%, and water absorption decreased by 40%, making the processed kaolin suitable for wall tile and sanitary ware applications (Lamidi et al., 2024).

Beneficiation basically serves two purposes: it improves the natural qualities of kaolin and makes it better suited for the needs of different industries. In ceramics, this means making the clay more workable, ensuring it fires evenly, and giving it better resistance to heat. In the paper industry, the focus is on brightness and opacity, while in paints and plastics, the size of the particles and how they react on the surface are the most important factors (Adeniyi et al., 2023)]. The importance of beneficiation becomes even clearer when Nigeria's situation is considered. The country has over 3 billion metric tons of kaolin reserves, yet a large part of what's used in medicines and high-quality ceramics is still imported. This happens mainly because the quality of local kaolin is inconsistent and there aren't enough large, modern facilities to process it properly. For Nigeria, investing in better and scalable beneficiation technologies is not just about making kaolin perform well in industries. It's also about cutting down on imports, saving foreign exchange, and supporting the country's wider goal of building a stronger, more self-reliant industrial sector (Ayalew, 2023)..

3.1 Wet Processing Techniques

Wet processing is one of the most widely applied beneficiation routes for kaolin, particularly in high-grade applications such as fine ceramics, coatings, and paper production. This method is often preferred because it works well with very fine particles and removes a lot of unwanted materials. It is especially good at getting rid of coloring agents and other non-clay minerals. The general steps include slurry formation (blunging), dispersion, particle size classification (often via hydroxylamine), magnetic separation, flotation (if needed), and dewatering (Zewdie et al., 2021; Oyewo et al., 2023; 2024).

3.1.1 Blunging and slurry formation

The first step in wet beneficiation is blunging, the mechanical mixing of dry kaolin with water to form a fluid suspension or slurry. Dispersing agents like sodium silicate, sodium hexametaphosphate, or sodium polyacrylates are usually added to keep kaolin particles from clumping together. This helps loosen and separate trapped impurities such as quartz, feldspar, and organic matter from the clay. Jacob, et al. (2025) noted that the best pH level for this process, known as blunging, is usually between 6 and 8, depending on the dispersant used and the surface properties of the kaolin. Lamidi, et al. (2024) found that adding dispersants when mixing kaolin from Niger State in Nigeria helped separate particles. This then made the next sorting step about 25% better. Their work also showed that using 0.25 wt% sodium silicate was the best option. It lowered viscosity, which let the particles move easier (Mohan and Kanny, 2019).

3.1.2 Particle Size Classification via Hydrocycloning

Following dispersion, hydrocyclones separate fine kaolinite particles (typically and lt;2 µm) from bigger non-clay minerals. This separation relies on centrifugal force, which separates particles by size and density. A well-configured hydrocyclone can achieve over 80% separation, yielding high-quality kaolin with minimal quartz or mica. Many clays, mostly those with abundant impurities, need several hydrocycloning stages. For instance, in Brazil, Kohli et al. (2021) reported that a three-stage hydrocycloning process improved raw kaolin brightness from 71% to over 89%, which is adequate for sanitary ceramics and tableware. In the Nigerian context, Hartati, et al. (2020)] employed hydrocyclones to beneficiate kaolin from Kankara (Katsina State), resulting in a 60% reduction in quartz content and a 33% improvement in whiteness. The technology is currently being piloted in industrial setups in Ogun and Kogi States, albeit limited by power and infrastructure challenges.

3.1.3 Filtration and Dewatering

After classification and impurity removal, the kaolin slurry is dewatered through vacuum filters or filter presses to form filter cakes. Depending on the desired end-product characteristics, drying is carried out using flash dryers or rotary dryers to achieve a moisture content below 1% (Cavalcanti et al., 2029). While filtration systems are relatively straightforward, energy consumption during drying remains a significant operational cost. Innovations such as solar-assisted drying are being explored in Nigerian research institutes to reduce energy dependence and promote sustainable processing (Kohli et al. 2021).

3.2 Dry Processing Techniques

Dry beneficiation techniques are often employed when the kaolin deposit is relatively low in impurities or when water resources are scarce or expensive to manage. In contrast to wet processing, dry methods are generally more energy-efficient at small scales and produce minimal wastewater. However, they tend to be less effective in improving brightness and removing fine-grained or chemically bound impurities, making them more suitable for coarse applications such as brick manufacturing, cement additives, or low-cost ceramics (Fakorede et al., 2025). Dry processing typically involves a sequence of physical separations including, crushing, grinding, air classification, and surface charge-based separation. The objective is to liberate kaolinite from associated silicate minerals (such as quartz and feldspar), followed by the removal of course or non-clay particles (Kohli et al., 2021).

3.2.1 Crushing and Grinding

Raw kaolin ore often contains nodular or lump formations composed of tightly bound clay and mineral impurities. To prepare the ore for further beneficiation, mechanical size reduction is performed using jaw crushers, roller mills, and ball mills. Crushing breaks down the oversized feed into smaller fragments, while grinding reduces the material to finer sizes suitable for classification. For example, Aly, et al. (2019) studied kaolin from Ogun State and found that dry grinding it in a ceramic-lined ball mill for 90 minutes reduced the particle size from 200 µm to 45 µm. This made it much easier to separate out quartz using air classification. However, if grinding goes too far, it can create too many ultra-fine particles and even damage the kaolinite structure, which may lower its performance in structural ceramics. To avoid this problem, researchers have developed hybrid methods that use controlled energy during milling. One such approach, tested by Jacob, et al. (2025), involved grinding the kaolin in steps and then dry-sieving it. This method kept the kaolinite's crystal structure intact while also removing more impurities.

3.2.2 Air Classification

Air classification, also called pneumatic sseparation, is an important step in dry processing because it separates particles by size and density using streams of air. In this process, ground kaolin is passed through a strong airflow inside a zigzag-shaped classifier or a cyclone separator. The heavier particles, like quartz and feldspar, drop down due to gravity, while the lighter kaolinite particles are carried upward by the air and collected through the cyclone system (Gougazeh, 2020). The advantage of air classifiers is that they produce kaolin with a more controlled particle size distribution, which also improves the clay's plasticity. However, they are often less effective than hydrocyclones in separating very fine impurities, such as iron oxide particles smaller than 5 µm. In Nigeria, Air classification has been successfully applied in Bauchi and Plateau states for upgrading local kaolin for cementitious and brick applications (Zewdie et al., 2021). Despite its limitations in brightness improvement, air classification is economically favorable. It requires relatively low energy, has no chemical costs, and produces no effluents, making it ideal for decentralized beneficiation plants and artisanal mining clusters.

3.3 Triboelectric and Electrostatic Separation

A more advanced dry separation method is triboelectric separation, which operates based on the differential charging of particles. When kaolinite and quartz are passed through a high-friction environment (e.g., a rotating drum), they acquire different electrostatic charges due to variations in surface chemistry and dielectric properties. The charged particles are then subjected to an electric field where oppositely charged particles are attracted to opposite electrodes, achieving separation (Zewdie et al., 2021). Triboelectric separation has been used extensively in the USA, especially in the kaolin industries of Georgia. Lamidi, et al. (Lamidi et al., 2024) reported that this method could remove up to 80% of titania and iron-bearing particles in dry kaolin samples. Although still underutilized in Nigeria, researchers at Ahmadu Bello University have conducted pilot-scale trials demonstrating that triboelectric separation can increase brightness by 15–20% in selected Nigerian clays (Zewdie et al., 2021). One significant advantage is its water-free nature, which avoids the need for drying and chemical waste management. However, triboelectric systems are capital-intensive and require careful calibration to optimize charge behavior, limiting their current deployment in low-income regions.

3.4 Magnetic Separation

Magnetic separation is one of the most effective and selective beneficiation methods for removing iron-bearing contaminants from kaolin. Iron oxides such as hematite (Fe_2O_3), goethite ($FeO(OH)$), and magnetite (Fe_3O_4), which are often present in Nigerian kaolin deposits, severely affect the whiteness and electrical insulation quality of ceramics. The method involves exploiting the magnetic properties of these contaminants and separating them from non-magnetic kaolinite under the influence of magnetic fields (Adeniyi et al., 2023). There are two main categories of magnetic separators used for kaolin:

3.4.1 Low-Intensity Magnetic Separators

Low-Intensity Magnetic Separators **(**LIMS) typically operate at magnetic field strengths below 2000 Gauss and are effective for separating strongly magnetic minerals like magnetite. However, since most kaolin-associated iron contaminants are weakly magnetic (e.g., goethite and hematite), LIMS are seldom sufficient for high-purity applications. They may be used as a preliminary step before high-gradient magnetic separation (HGMS). In some Nigerian processing facilities, LIMS has been used to remove coarse magnetite fragments from kaolin excavated in Nasarawa and Ekiti states, particularly when kaolin is sourced as a byproduct from granite-related environment (Mamudu et al., 2020).

3.4.2 High-Gradient Magnetic Separation

High-Gradient Magnetic Separation (HGMS) is an advanced technique used to remove minerals that respond only weakly to magnets. It works by passing kaolin, either as a slurry or in dry form, through very strong magnetic fields often stronger than 10,000 Gauss. This is usually done with superconducting magnets or by using fine steel wool placed inside the magnetic field to trap the impurities. A well-known study by Jacob et al. (2025) showed how effective this method can be. They treated Chinese kaolin and reduced its iron oxide

(Fe_2O_3) content from 1.4% to just 0.35%, which boosted its brightness by almost 20%. In Nigeria, Adeniyi et al. (2023) reported similar success when they applied HGMS to Ifon kaolin, cutting down the iron oxide from 1.92% to 0.48%. The resulting kaolin was deemed suitable for floor tiles, and in some cases, even sanitary wares.

3.4.3 Dry Magnetic vs. Wet Magnetic Separation
While magnetic separation can be carried out on both wet and dry feeds, the efficiency is generally higher when operated in slurry form. Wet HGMS allows closer interaction between kaolinite particles and magnetic contaminants, improving capture efficiency. However, dry magnetic separation is less expensive and simpler to operate, especially in remote or off-grid areas. Dry magnetic rollers or belt separators have been deployed in pilot projects in northern Nigeria where water is scarce. Recent technological advancements include automated sensor-based magnetic sorting, which integrates real-time monitoring of feed properties to adjust magnetic intensity dynamically. Such smart systems are being developed in China and Germany and could greatly enhance kaolin beneficiation in resource-limited settings if adopted (Bhukte et al., 2022).

3.5 Froth Flotation
"Froth flotation is a surface-chemistry-based separation technique that has become a central method in the beneficiation of kaolin clays, particularly where gangue minerals like quartz, feldspar, and titania need to be selectively removed. It involves the preferential attachment of certain particles to air bubbles within a flotation cell, allowing for physical separation based on surface hydrophobicity or affinity for air (Hartati et al., 2020). The process is particularly effective for ultrafine particles and is increasingly utilized to produce high-purity kaolin required for applications such as fine ceramics, whiteware, paints, plastics, and advanced composites. The basic process includes mixing the clay slurry with various reagents (collectors, depressants, pH modifiers, and frothers) and introducing air bubbles. The hydrophobic particles (typically impurities like quartz or iron-titania compounds) adhere to the bubbles and float, while the hydrophilic kaolinite remains in suspension and is collected as the underflow or concentrate (Hartati et al., 2020).

3.6 Thermal Processing and Calcination
Thermal processing, particularly calcination, is one of the most transformative and industrially significant routes for upgrading kaolin. Unlike purification-focused methods, calcination alters the kaolinite lattice to form metakaolin, an amorphous aluminosilicate with distinctive pozzolanic, optical, and thermal properties enabling use in ceramics, refractories, paints, rubber, and cementitious composites. Calcination conditions govern reactivity and phase evolution (dehydroxylation to metakaolin and, if overheated, onset of spinel/mullite), so process control is critical for target applications (Romero et al., 2021). Attrition scrubbing sits between basic classification and intensive chemical beneficiation and is widely used to deagglomerate particles and liberate surface-bound impurities before or alongside flotation/magnetics. As summarized in recent process studies, while leaching and flotation can deliver higher brightness/iron removal, attrition scrubbing offers a cost-effective, lower-chemical option for producers aiming at moderate-grade ceramic or filler kaolin (Bhukte et al., 2022). Table 1 presents the summary of beneficiation methods.

Table 1: Summary of beneficiation methods (Lampropoulou and Papoulis, 2021)

Method	Environmental Impact	Brightness Gain	Complexity	Reagent Use
Water Washing	Low	Low (3–5%)	Low	None
Magnetic Separation	Moderate	Moderate (5–10%)	Moderate	None
Attrition Scrubbing	Low	Moderate (10–15%)	Moderate	Low
Froth Flotation	Moderate	High (15–20%)	High	High
Chemical Leaching	High	Very High (20–30%)	High	Very High

3.7 Overview of Green Beneficiation
"Green beneficiation" refers to methods that prioritize low environmental impact, resource efficiency, and ecological balance in the extraction and processing of minerals. In kaolin beneficiation, such approaches aim to reduce or eliminate the use of toxic chemicals such as HCl, H_2SO_4, and NaOH, minimize water and energy consumption, generate less hazardous waste, and utilize natural, biodegradable materials. Techniques under this umbrella include bioleaching, phytoremediation, enzyme-assisted beneficiation, the use of biodegradable

chelators or surfactants, and microwave or solar-assisted methods often hybridized with biological processes (Ayalew, 2023). Green beneficiation is particularly suitable for kaolin because many of its impurities, especially iron and titanium oxides, occur as surface stains or weakly bonded coatings that can be removed without highly aggressive processing.

3.8 Bioleaching

Bioleaching involves the use of microorganisms, primarily bacteria and fungi, to mobilize and solubilize mineral impurities from ores. This technique exploits the ability of certain microbes to produce organic acids, siderophores, or other chelating agents that dissolve undesirable elements such as Fe^{3+}, Mn^{2+}, or Ti^{4+} from kaolin. Table 2 presents the pro and cons of bio beneficiation process. While not yet industrialized, phytoremediation shows promise in small-scale kaolin depots in Osun, Ekiti, and Niger states. In addition, to reinforce understanding, a consolidated table that summarises the beneficiation process focusing on the target and kaolin property improvement is presented in Table 3.

Table 2: Pros and Cons of beneficiation process (Zewdie et al., 2021; Adeniyi et al., 2023)

Advantage	Limitation
Cost-effective and natural	Requires space and time
Simultaneous carbon sequestration	May not reach deeper impurities
Enhances soil health	Low metal recovery rate

Table 3: Summary of Beneficiation Techniques, Target Impurities, and Resulting Improvements in Kaolin Properties (Adeniyi et al., 2023; Ayalew, 2023)

Target Impurity	Primary Technique	Support Method	Brightness Gain	Remarks
Iron Oxides	Magnetic Separation	Bioleaching	10–20%	Effective for Fe-rich clays
Organic Matter	Enzyme-assisted	Scrubbing	5–10%	Mild conditions
Quartz/Mica	Flotation	Screening	10–15%	Depends on particle size
Titanium Oxides	Acid Leaching	Scrubbing	20–30%	High chemical input
Coated Impurities	Attrition Scrubbing	Magnetic Separation	10–15%	Eco-friendly

4. INDUSTRIAL APPLICATIONS AND IMPACTS OF BENEFICIATED KAOLIN

The beneficiation of kaolin significantly improves its mineralogical purity, particle size distribution, and surface properties, thereby expanding its range of industrial applications. By removing impurities such as iron oxides, titanium minerals, quartz, and organic matter, beneficiated kaolin exhibits higher brightness, improved plasticity, and enhanced thermal stability, making it suitable for high-value products in ceramics, paper, paints, plastics, pharmaceuticals, and cosmetics. In the ceramics industry, for example, enhanced whiteness and reduced impurity levels improve sintering behavior, mechanical strength, and aesthetic quality of the final product (Ayalew, 2023). In non-ceramic sectors, beneficiated kaolin serves as a functional filler, pigment extender, rheology modifier, and reinforcing agent, contributing to cost reduction and improved product performance Beneficiation also has a big economic benefit. By making locally sourced kaolin good enough to replace imports, it helps support local industries, creates jobs, and cuts down on the money spent on foreign exchange (Ayalew, 2023).

4.1 Industrial Applications of Kaolin

Beneficiation greatly improves the physical, chemical, and mineral properties of kaolin, which makes it more useful for many industries. One of the most important users of high-quality kaolin is the ceramic industry. For ceramics, kaolin needs to be very pure, bright, and stable under heat. Its natural features, such as structural strength, whiteness, and low iron content directly affect the final product's strength, ability to fire evenly, heat resistance, and overall appearance. In this study, different beneficiation methods whether physical, chemical, or biological affect kaolin's suitability for ceramic production, with special focus on the Nigerian context Adeniyi et al. (2023).

4.2 Kaolin in Ceramic Manufacturing

Kaolin is an essential raw material for making many ceramic products. These include sanitary wares like toilets, basins, and sinks; ceramic tiles for floors and walls; electrical insulators; porcelain and tableware; as well as refractory linings and fire bricks. For kaolin to be suitable for these uses, it must meet strict quality standards. Typically, this means having a high alumina content of at least 30%, very low levels of impurities such as iron oxide (Fe_2O_3) and titanium dioxide (TiO_2) below 1%, a whiteness level of 85% or more, a well-controlled particle size distri bution, and good plasticity with reliable firing behavior (Zewdie et al.,2021). However, raw kaolin deposits frequently fall short of these standards due to the presence of mineral impurities such as quartz, feldspar, iron oxides, titanium-bearing minerals, and organic matter, all of which can compromise the mechanical strength, aesthetic appearance, and thermal stability of ceramic products. Beneficiation helps overcome these limitations by making the kaolin brighter, increasing its alumina-to-silica ratio, and reducing the presence of oxides that cause discoloration. This upgrades the clay so it can meet the strict standards needed for high-performance ceramic applications (Zewdie et al., 2021). Figure 1 presents the typical application of Kaolin in Ceramic Applications (pot).

Figure 1: Kaolin in Ceramic Application (Efavi et al., 2012)

4.3 Applications in Nigeria Ceramic Sector

In 2020, Kwara Ceramic Works in Ilorin produced a pilot project focused at upgrading ceramic tile production by bringing beneficiated kaolin from Plateau State. The kaolin was improved using flotation and scrubbing, processes known for their effectiveness in dispersing iron-rich impurities, quartz, and other unwanted minerals (Erkan and Alp, 2024). The refined material upgraded particle packing and sintering efficiency, leading to a 28% upgrade in tile yield. Additionally, the enhanced mineral purity contribtted to better thermal shock resistance, reducing defect rates during firing. Export-grade output also rose significantly from 62% to 84% which positionedthe company to compete in higher-value international markets. This case illustrates how targeted beneficiation can directly boost both operational performance and market competitiveness (Ayalew, 2023).

A similar outcome was observed at Dangote's ceramic division in Katsina State, where chemically purified kaolin underwent controlled acid leaching followed by fine particle classification. This multi-stage approach reduced Fe_2O_3 content from 1.5% to 0.38%, a substantial improvement given that even trace amounts of iron can cause discoloration and weaken dielectric properties in ceramic products (Erkan and Alp, 2024). The whiteness level increased from 69% to 91%, allowing the kaolin to meet the demanding standards for high-grade tableware and electrical insulators. These improvements not only enhanced aesthetic and functional qualities but also reduced the company's reliance on imported raw materials, demonstrating that industrial-scale beneficiation can deliver both technical and economic advantages (Erkan and Alp, 2024).

At the local level, small-scale potters in Abeokuta, Ogun State, have also seen the benefits of kaolin beneficiation. By using simple methods like scrubbing and sieving, they were able to remove coarse particles and make their clay blends easier to work with. Although these techniques are not as advanced as flotation or acid leaching, they still brought noticeable improvements. The treated clay produced smoother finishes, had lower porosity, and dried faster reducing the chances of cracking during production (Adeniyi et al., 2023). For the artisans, this meant stronger, elongated lasting products and less waste, which allowed them to sell their goods at better prices in local markets. The positive results seen in both large-scale industries and small community workshops highlight the flexibility of kaolin beneficiation. No matter the scale or level of technology used, it consistently improves raw material quality, enhances product performance, and delivers better economic value (Adeniyi et al., 2023)

4.4 Green Beneficiation for Health Applications

Bioleaching and enzyme-based treatments are emerging as eco-friendly ways to process kaolin, especially when very high purity is required, such as in pharmaceutical products. Unlike traditional acid leaching, which often leaves behind chemical residues that need extra cleaning, bioleaching makes use of microorganisms or the substances they produce to dissolve and remove unwanted metals like iron, manganese, and titanium (Prasad et al., 1991). This method keeps the kaolinite structure intact, cuts down hazardous waste, and fits well with the goals of sustainable mineral processing. Enzyme assisted treatments work in a similar "green" way. Instead of harsh chemicals, they use enzymes to break down organic coatings or free up mineral impurities on the clay surface. This boosts brightness and purity without affecting kaolin's natural properties (Prasad et al., 1991).

In Nigeria, progress has already been made in this area. Fungal bio-leaching with Penicillium oxalicumto purify kaolin from Jos, Plateau State, for use in oral medicines was well documented Hosseini and Ahmadi (2025). The fungi released organic acids, like oxalic and citric acid, which bonded with heavy metals and dissolved them, all while leaving the kaolin structure untouched. This reduced iron oxide (Fe_2O_3) and other contaminants to levels that met pharmacopeia standards for pharmaceutical use. Other studies have also shown that fungal and bacterialstrains such as Aspergillus niger and Bacillus subtilis can achieve similar results, showing strong potential for these biotechnological methods to be scaled up in Nigeria's kaolin industry (Oyelami et al., 2023). The growing body of researchon bioleaching and enzyme-based beneficiation supports their adoption as eco-friendly alternatives to conventional chemical purification, particularly for sensitive applications in pharmaceuticals, cosmetics, and food packaging.

4.5 Global Applications and Technological Integration

In Europe, particularly in Spain and Germany, kaolin beneficiation for porcelain production is carried out using advanced flotation and leaching techniques. These processes are designed to selectively remove iron oxides, titanium minerals, and other coloring impurities that would otherwise compromise the whiteness and translucency of high-grade porcelain. Companies such as Imerys Ceramics, a global leader in the sector, have optimized these beneficiation steps to consistently produce kaolin with Fe_2O_3 levels below 0.4%, brightness values exceeding 92%, and particle sizes of less than 2 microns specifications that are essential for enhanced glaze formulation and smooth surface finishes (Lopes et al., 2018). The precision of these processes allows European producers to maintain tight control over quality, enabling them to meet the demanding standards of luxury porcelain manufacturers and high-performance ceramic applications (Lopes et al., 2018).

In Brazil, companies like CADAM and Caulisa have become major players in the global ceramic tile industry by combining several beneficiation steps such as centrifugation, magnetic separation, and particle size classification. Centrifugation helps remove coarse impurities and ensures finer, more uniform particle sizes, while magnetic separation gets rid of iron-rich minerals that can affect brightness and color (Lopes et al., 2018). This step by step approach enables Brazilian producers to deliver high-quality kaolin both at home and abroad, especially for ceramic wall and floor tile production. China, the world's leading ceramic manufacturer, makes extensive use of calcined kaolin, particularly in combination with high-alumina mixes to produce premium porcelain and refractory bricks. This mix improves strength, resistance to sudden temperature changes, and glaze bonding. According to Jacob, et al. (2025), China's advanced calcination technologies not only increase whiteness and firing performance but also yield metakaolin, which is suitable for both structural and decorative ceramic uses. India, which has some of the world's largest kaolin reserves, has been paying more attention to sustainable beneficiation practices, largely due to stricter environmental regulations and local community concerns. In kaolin-rich states like Kerala and Rajasthan, pilot projects have tested bio-beneficiation and phytoremediation methods. Bio-beneficiation uses microorganisms to clean out metallic and organic impurities without harsh chemicals, while phytoremediation relies on plants to absorb or stabilize pollutants in mining areas. Together, these eco-friendly methods lower the environmental impact of kaolin mining and processing, while also supporting India's wider push for greener industrial and mining practices [28].

4.6 Applications in Paints, Plastics, Rubber, Paper and Pharmaceuticals

Beyond its well-known use in ceramics, treated (beneficiated) kaolin is becoming more important in many other industries. It's very fine particle size, chemical stability, bright white color, and smooth flow properties make it a highly useful material. In the paper industry, high-quality kaolin is used both as a coating and as a filler. It improves how well paper prints, increases opacity, and gives it a smoother surface. Through beneficiation methods like magnetic separation, flotation, and chemical leaching, impurities such as iron and titanium are removed. This boosts the brightness of kaolin to over 90%, which is especially important for top-grade printing and writing papers (Magliano et al., 2024). In paints and coatings, kaolin is used as an extender pigment. It improves coverage, helps paint keep its color, and makes coatings more durable. Because kaolin particles are flat and plate-like, they also add barrier properties slowing down water absorption and iimproving resistance to sunlight damage. In plastics and rubber, kaolin works as a reinforcing filler, making products stronger, stiffer, and more dimensionally stable. The controlled particle sizes achieved through beneficiation also improve mixing and dispersion in polymers, leading to consistent performance (Murad and Fabris, 2010; Pruett, 2016).

Kaolin also has a valuable role in cosmetics and pharmaceuticals. In beauty products, its whiteness, smooth feel, and ability to absorb oil make it ideal for powders, foundations, and skincare items (Lamidi et al., 2024). In medicine, purified kaolin is used as an excipient, an antidiarrheal, and a tablet filler, where purity and low heavy-metal content are essential. Newer beneficiation methods like bioleaching and enzyme-based treatments are now being applied to meet strict medical standards for pharmaceutical-grade kaolin. By improving kaolin to meet strict technical and safety requirements, beneficiation raisees its value in traditional markets while also opening doors to advanced uses in packaging, composite materialals, and even nanotechnology. This shows how vital beneficiation technologies are for expanding the uses of kaolin and strengthening the global competitiveness of countries that produce it (Prasad, 1991).

4.7 Functional Role of Kaolin in Paints

In the paint and coatings industry, kaolin serves several purposes at once. It works as a pigment extender, flow (rheology) modifier, matting agent, and even helps strengthen the paint film. When used as a pigment extender, refined kaolin can replace part of the titaniumdioxide (TiO_2), cutting production costs without reducing opacity, brightness, or coverage (Yang, 2021). Its flat, plate-like particle shape also improves how pigments spread out in the mixture, keeping the paint stable during storage and giving a smoother, more consistent finish. In matte or flat finishes, kaolin functions as a matting agent by diffusing light to reduce surface gloss, while its inert mineral structure contributes to improved film integrity and resistance to cracking. For these functions to be effectively realized, kaolin must exhibit high whiteness (typically above 85%), fine particle size (less than 2 μm), low abrasiveness to avoid damaging milling equipment, and near-neutral pH to prevent adverse reactions with other formulation components (Pruett, 2016).

4.8 Recommendations

Achieving this transformation calls for a multi-faceted strategy anchored in geological mapping, infrastructure development, market expansion, and capacity building. Nationwide digital surveys of kaolin deposits should inform targeted investment and guide the optimal location of beneficiation facilities. Public private partnerships must prioritize the deployment of modular, scalable processing plants capable of meeting varied industrial demands. In parallel, national training schemes such as N-Power and NYSC can be leveraged to develop a workforce proficient in advanced mineral processing and quality control. On the commercial front, the Nigerian Export Promotion Council should streamline export documentation, establish dedicated kaolin trade desks, and cultivate strategic market linkages across Africa, Asia, and the Middle East. Finally, a cross-sectoral oversight body should monitor compliance with environmental standards, enforce product quality benchmarks, and ensure that all beneficiation efforts align with the broader objectives of the National Industrial Revolution Plan. By combining technological innovation, market-oriented policy, and sustainable development principles, Nigeria can position itself as a global hub for beneficiated kaolin production and export.

5. CONCLUSION

The beneficiation of kaolin presents a strategic pathway for Nigeria to enhance its industrial capacity by transforming abundant but underutilized low-grade deposits into high-value raw materials suitable for a broad spectrum of applications. These range from traditional sectors such as ceramics, pharmaceuticals, paints, plastics and paper to emerging fields in advanced technologies. By applying physical, chemical, thermal, and biological beneficiation techniques, kaolin can be upgraded to meet the stringent quality standards required in both domestic industries and international markets, thereby strengthening Nigeria's position within the global kaolin value chain. Innovations in nanotechnology, hybrid ceramic–polymer composites, and AI-assisted process control are expanding its utility, while sustainable approaches such as life cycle assessment and circular economy integration are aligning industrial growth with environmental preservation. Evidence from local and global case studies confirms that, with well-coordinated policy, technological investment, and stakeholder collaboration, Nigeria can transition from an exporter of raw kaolin to a competitive supplier of high-performance, value-added kaolin products stimulating innovation, creating skilled jobs, and strengthening economic resilience.

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