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Physical, Mechanical and Microstructural Performance Evaluation of Porcelain Wares Developed Using Groundnut Shell Ash as Novel Quartz Substitute

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Abstract— *This study investigates the physical and mechanical performance of porcelain wares fabricated using groundnut shell ash (GSA) as a partial or complete substitute for quartz. The primary objective is to explore the valorization of agricultural waste for scientific and technological applications, thereby contributing to environmental sustainability and economic efficiency. Groundnut shells were obtained as waste from a farmyard dumpsite and initially processed through thorough washing to eliminate impurities and contaminants. The cleaned shells were subsequently dried under ambient atmospheric conditions to remove residual moisture, combusted in a perforated metallic drum, and further calcined in a muffle furnace at 900°C for a soaking duration of one hour. GSA was incorporated into the porcelain formulation in varying proportions by weight, specifically in quartz-to-GSA ratios of 10:0, 4:1, 3:2, 2:3, 1:4, and 0:10, while maintaining constant amounts of kaolin and feldspar across all compositions. The resulting porcelain samples were subjected to firing at two distinct temperatures, 1200°C and 1250°C, after which their physical, mechanical, and microstructural properties were comprehensively evaluated. The results revealed notable enhancements in material properties with increasing GSA content and firing temperature. Physical characterization indicated a reduction in water absorption and apparent porosity, alongside an increase in bulk density and linear shrinkage, suggesting improved densification and vitrification. Mechanical testing showed a corresponding increase in hardness and compressive strength, with the sample designated KPG6 (10% GSA, 0% quartz) exhibiting the most significant performance metrics. X-ray diffraction (XRD) analysis confirmed that the incorporation of GSA promoted the formation of a robust glassy phase in conjunction with well-crystallized mullite. Scanning electron microscopy (SEM) images supported these findings by illustrating a transition from a relatively porous structure to a dense, homogeneous, and highly vitrified microstructure, particularly prominent in samples fired at 1250°C.*

Keywords— *Porcelain wares, Groundnut shell ash, Mullite phase, Characterization, Quartz.*

I. INTRODUCTION

Porcelain wares are advanced ceramic materials composed of a triaxial formulation typically consisting of clay (or kaolin), quartz, and feldspar. The clay or kaolin component imparts plasticity and dry mechanical strength during forming, while also contributing to the formation of mullite and a glassy phase upon firing. Feldspar serves as a fluxing agent, facilitating vitrification at relatively low temperatures and enabling near-zero open porosity (<0.5%) and minimal closed porosity (<10%). Quartz, due to its high melting point, enhances thermal and dimensional stability of the fired product [1–3].

Owing to its aesthetic appeal, chemical inertness, low water absorption, and excellent mechanical and thermal resistance, porcelain finds widespread application in both domestic and industrial sectors [4–6]. Its desirable properties such as low thermal expansion, low thermal conductivity, high strength, and superior resistance to thermal shock [3] make it suitable for uses in electrical insulators, interior and exterior tiles, sanitary ware, stoneware, and tableware [7, 8].

Porcelain has been the subject of extensive scientific investigation for decades, with researchers exploring the complexities of its raw materials, processing parameters, phase transformations, and microstructural evolution [6]. Recent efforts have focused on modifying traditional raw materials, particularly quartz, by incorporating industrial and agricultural waste products to enhance physical and mechanical properties while promoting sustainability. Materials such as fly ash, rice husk ash, waste glass, and slags have been studied as potential replacements for quartz, with encouraging results reported by several researchers including Das *et al.* [9], Marinoni *et al.* [10], Njindam *et al.* [11], Owoeye *et al.* [7], Hossain *et al.* [12], Durumin-Iya *et al.* [13], and Jamo *et al.* [14]. These studies highlight the economic and environmental benefits of using waste-derived materials, citing factors such as cost-effectiveness, energy efficiency, material availability, and low processing cost.

Groundnut shell ash (GSA), a type of agricultural solid waste, is particularly notable due to its high silica content and global abundance. Groundnut is cultivated on approximately 20 million hectares of land annually [15], generating large quantities of shells that are typically discarded. Disposal of groundnut shells in landfills not only occupies valuable land but also contributes to greenhouse gas emissions, disease spread, and environmental degradation. As such, developing recycling strategies to convert GSA into value-added materials aligns with sustainable development goals.

Nigeria ranks among the top global producers of groundnuts, with an estimated production of 2,962,760 tonnes, primarily from the northern and north-central regions, while global leaders include China (16,114,231 tonnes) and India (6,933,000 tonnes) as of 2011 [16, 17]. Several studies have

demonstrated the potential of GSA in materials development. For instance, Venkatesh *et al.,* [18] utilized GSA with B_4C in the reinforcement of aluminum-based composites, reporting improvements in mechanical properties and microstructural characteristics. Ejelikwu *et al.,* [19] employed GSA as a stabilizer in reclaimed asphalt pavement, observing a decrease in maximum dry density and an increase in optimum moisture content. Kenneth *et al.,* [20] partially or fully substituted silicon carbide with GSA in Zn-27Al composites, which led to increased fracture toughness, though hardness and tensile strength decreased with higher GSA content. Similarly, Mujedu and Adebare [21] showed that up to 15% replacement of ordinary Portland cement with GSA in concrete yielded satisfactory performance. Solomon *et al*., [22] used GSA as a filler in asbestos production and reported increased compressive strength and density with smaller GSA particle sizes, along with greater water and oil absorption as particle size increased.

Despite the growing body of literature on the application of GSA in various composite and construction materials, limited attention has been given to its use in porcelain production as a quartz substitute. This study therefore investigates the potential of GSA as a sustainable alternative to quartz in porcelain ware development. Groundnut shells were processed via open-air combustion, thermally conditioned, and sieved to obtain uniform particle sizes suitable for ceramic formulation. The resulting porcelain samples were then evaluated for their physical and mechanical properties to assess performance viability.

II. Materials and Method

2.1 Material

The raw materials employed in this study include kaolin, potash feldspar, silica sand, groundnut shell ash (GSA), and polyvinyl alcohol (PVA). Silica sand was sourced from the Department of Glass and Ceramics Technology, Ado-Ekiti, while kaolin was obtained from natural deposits located in Ikere-Ekiti, Ekiti State. Waste groundnut shells were from Auchi, Edo State, and subsequently transported to Ado-Ekiti for further processing. Both potash feldspar and polyvinyl alcohol were acquired through commercial means; the potash feldspar was sourced from the Government Technical College in Ado-Ekiti, and the polyvinyl alcohol was purchased from Pascal Chemical Store.

2.2 Processing of raw materials

The groundnut shells were manually sorted and thoroughly washed to remove surface contaminants and impurities. This washing procedure was repeated twice to ensure sufficient purification. The cleaned shells were subsequently air-dried under ambient atmospheric conditions for a duration of three days to eliminate residual moisture. Following the drying process, the shells were combusted in open air using a perforated metallic sheet. The resulting ash was then calcined in a muffle furnace at 900°C at 1hrs holding hours and allowed to cool gradually before removal. The silica sand used in this study was of glass-making grade. To enhance its surface area, it was initially pulverized in a porcelain-lined ball mill using porcelain grinding media to minimize contamination. The milling operation was conducted for 48 hours to achieve a homogeneously fine particle size distribution. Both the calcined groundnut shell ash and the milled silica sand were subsequently sieved using a 230-mesh sieve (125 µm) to obtain uniform particle sizes suitable for further processing.

2.3 Sample preparation

The raw materials used for the fabrication of the porcelain wares were proportioned based on the stoichiometric requirements necessary for porcelain formation. In the experimental formulations, the quartz content was systematically varied by substituting it with different proportions of the prepared groundnut shell ash (GSA). All constituent materials were accurately weighed using a digital analytical balance and thoroughly mixed manually to achieve compositional homogeneity. Polyvinyl alcohol (PVA) was incorporated into the mixture as a binding agent prior to the compaction process. The blended mixtures were then pressed into shape using a plastic mold under an applied uniaxial pressure of 200 MPa. The compacted green bodies were subsequently sintered at a temperature of 1200°C and 1250°C in a gas-fired muffle kiln with a soaking time of one hour. The resulting porcelain samples were designated as KPG_1, KPG_2, KPG_3, KPG_4, KPG_5, and KPG_6, corresponding to their respective GSA-to-quartz ratios.

TABLE 1: Sample designation for the developed porcelain wares

Samples	KPG_1	KPG_2	KPG_3	KPG4	KPG_5	KPG_6
Kaolin (%)	50	50	50	50	50	50
Potash Feldspar	40	40	40	40	40	40
Quartz	10	8	6	4	2	0
GSA	0	2	4	6	8	10

2.4 Characterization of developed porcelain ware samples

To evaluate the physical and mechanical properties of the developed porcelain samples, a series of analytical techniques were employed. Water absorption was assessed by first drying the specimens to a constant weight, followed by immersion in water for a predetermined duration. The weight gain after immersion was recorded to determine the water absorption capacity. Apparent porosity was calculated based on the measured mass and volume of the samples. Bulk density was determined using the ratio of the sample's mass to its volume, while linear shrinkage was calculated by comparing the sample lengths before and after firing. The surface morphology and microstructural features of the samples were analyzed using a Scanning Electron Microscope (JSM-6100 JEOL), enabling observation of grain structure, distribution, and porosity. Phase composition and crystallographic characteristics were identified using an X-ray diffraction spectrometer (XDS 2400H) equipped with a MiniFlex2+ goniometer and detector, providing insights into phase formation and mineralogical transformations during sintering. Mechanical performance was evaluated by measuring hardness and compressive strength. Vickers micro hardness testing was conducted using a Zwick/Roell Indented ZHV tester under a load of 19.6 g for 10 seconds to assess resistance to localized plastic deformation. Compressive strength was determined using a Form Test

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Seidner compression testing machine (Model GMBH D7940), which measured the maximum load-bearing capacity and overall structural integrity of the ceramic specimens.

III. Results and Discussions

3.1 Water absorption analysis

Figure 1 presents the water absorption characteristics of the developed porcelain wares incorporating groundnut shell ash (GSA) as an alternative substitute for quartz. The results reveal a consistent and progressive decrease in water absorption with increasing GSA content across both firing temperatures. As the proportion of GSA increases from sample KPG_1 to KPG_6 corresponding to a gradual replacement of quartz the water absorption values decline markedly, with KPG_6 (containing 10% GSA and 0% quartz) exhibiting the lowest water absorption at both 1200°C and 1250°C. This pronounced reduction in water absorption indicates that GSA functions effectively as a fluxing agent within the porcelain matrix [23]. While groundnut shell ash is primarily rich in silica, it also contains notable amounts of alkali oxides such as K_2O and Na_2O, which can significantly lower the eutectic temperature of the ceramic system [24]. The complete substitution of quartz with GSA in sample KPG_6 underscores the superior densification achieved through GSA addition, suggesting that it contributes more effectively to vitrification and porosity reduction than quartz in this composition [25]. Additionally, the rise in firing temperature from 1200°C to 1250°C causes a significant drop in water absorption. This behavior aligns with established principles in ceramic processing, wherein higher firing temperatures enhance sintering kinetics by providing greater thermal energy [26, 27]. This promotes the formation of a more extensive liquid phase, reduces melt viscosity, and facilitates better pore filling and particle rearrangement [28]. These findings collectively highlight the role of GSA and high-temperature sintering in improving densification and reducing open porosity in porcelain formulations.

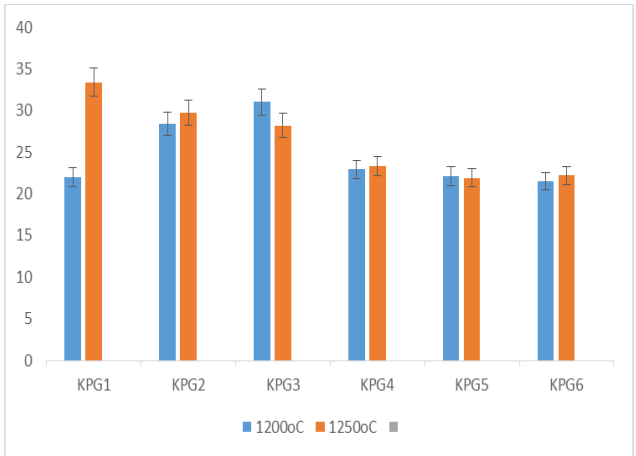


Fig. 1. Water absorption analysis of developed porcelain wares

3.2 Estimated porosity analysis (%)

Figure 2 presents the estimated porosity values of the developed porcelain wares incorporating groundnut shell ash (GSA) as an alternative to quartz. The observed trend reveals that porosity exhibits an inverse relationship with water absorption, which is consistent with established ceramic principles namely, that reduced water absorption corresponds to lower levels of open porosity [29] Given that water absorption reflects the presence of interconnected open pores, and the alignment of these two measurements reinforces the reliability and validity of the experimental data. Across both firing temperatures, a systematic decrease in porosity is observed with increasing GSA content [30]. As the substitution of quartz with GSA progresses from sample KPG_1 to KPG_6, porosity values steadily decline, with KPG_6 (10% GSA, 0% quartz) displaying the lowest porosity at both 1200°C and 1250°C. At the higher firing temperature of 1250°C, the porosity approaches near-zero values, particularly for samples with high GSA content. This trend further substantiates findings from the water absorption analysis and supports the conclusion that GSA serves as an effective fluxing or densifying agent within the porcelain matrix [23]. The complete substitution of quartz with GSA appears to significantly enhance the elimination of pores, likely due to the presence of fluxing oxides such as K_2O and Na_2O in GSA, which promote early liquid-phase formation during sintering. Additionally, increasing the firing temperature from 1200°C to 1250°C leads to a marked reduction in porosity across all compositions. For high-GSA samples, especially KPG_5 and KPG_6, the porosity values at 1250°C are exceptionally low, indicating near-theoretical density. [27, 29].

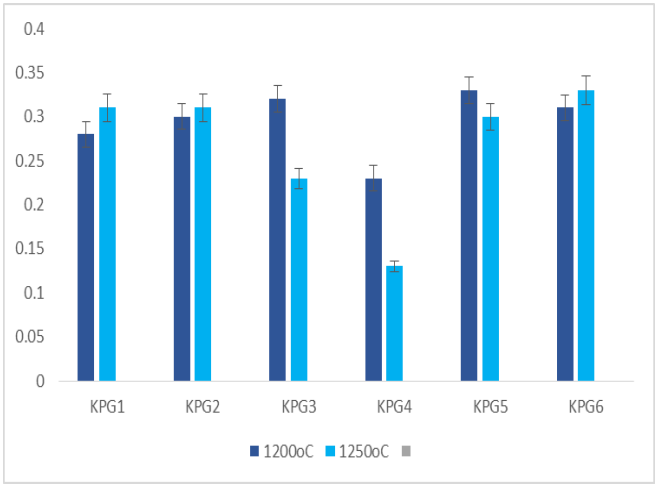


Fig. 2. Estimated porosity analysis of developed porcelain wares

3.3 Bulk density analysis (g/cm3)

Figure 3 presents the bulk density results of the developed porcelain wares incorporating groundnut shell ash (GSA) as a partial or complete substitute for quartz. The results indicate a consistent increase in bulk density with increasing GSA content and corresponding reduction in quartz, progressing from sample KPG_1 to KPG_6. Notably, sample KPG_6 (containing 10% GSA and 0% quartz) exhibited the highest bulk density at both firing temperatures, 1200°C and 1250°C. This trend suggests that GSA significantly enhances densification, likely due to its ability to promote liquid-phase formation during firing [23, 31]. The presence of alkali oxides in GSA may facilitate viscous flow, encourage particle rearrangement, and effectively fill

residual pore spaces, resulting in a denser ceramic matrix [32]. The progressive increase in bulk density with GSA addition further implies that GSA is more efficient than quartz in promoting densification within the tested compositional range. Importantly, the bulk density results exhibit a strong inverse correlation with both water absorption and estimated porosity, reinforcing the consistency and validity of the physical characterization data. The convergence of trends across all three parameters bulk density, water absorption, and porosity provides robust and mutually supportive evidence for the enhanced densification achieved with higher GSA content and elevated firing temperatures. These findings underscore the effectiveness of GSA as a fluxing and densifying agent in porcelain formulations.

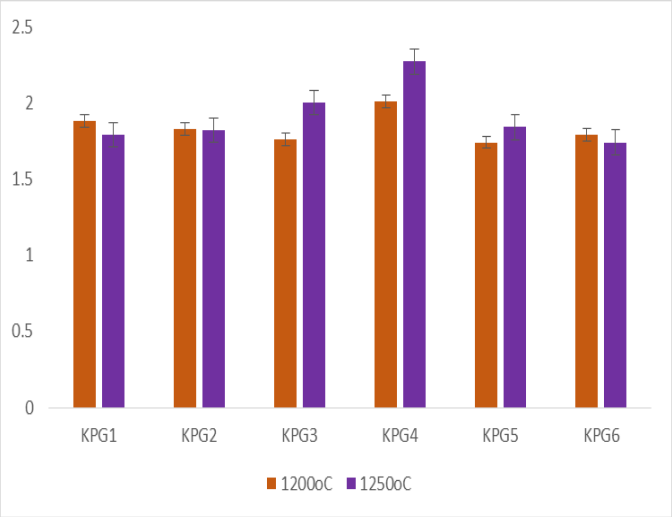


Fig. 3. Bulk density analysis of developed porcelain wares

3.4 Percentage linear shrinkage analysis

Figure 4 presents the percentage linear shrinkage results of the developed porcelain wares incorporating groundnut shell ash (GSA) as an alternative substitute for quartz. Linear shrinkage reflects the dimensional reduction of the ceramic body during firing, typically resulting from particle rearrangement, densification, and vitrification [33, 34]. A higher shrinkage value generally signifies a greater extent of densification and the formation of a continuous glassy phase [35]. The results indicate that for all sample compositions (KPG_1 to KPG_6), an increase in firing temperature from 1200°C to 1250°C results in a notable increase in linear shrinkage. This trend aligns well with established ceramic processing principles, wherein higher thermal energy enhances mass transport mechanisms such as viscous flow and solid-state diffusion, thereby promoting shrinkage and microstructural consolidation [36]. Moreover, the observed increase in linear shrinkage with rising GSA content corresponds inversely with the reductions in both water absorption and porosity. This consistency across all physical properties linear shrinkage, water absorption, and porosity provides compelling evidence of effective and predictable densification behavior. The data clearly demonstrate that increasing GSA content, in conjunction with elevated firing temperature, results in a more vitrified and densely packed ceramic structure.

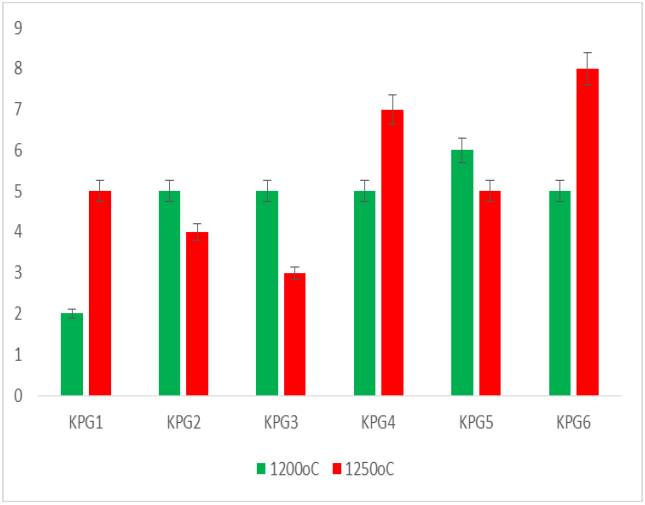


Fig. 4. Percentage linear shrinkage of developed porcelain wares

3.5 Hardness evaluation (Gpa)

Figure 5 presents the hardness results of the developed porcelain wares produced with groundnut shell ash (GSA) as a substitute for quartz. The data exhibit a strong positive correlation with previously discussed physical properties such as bulk density and linear shrinkage, and an inverse correlation with water absorption and porosity. Across both firing temperatures (1200°C and 1250°C), a consistent and notable increase in hardness is observed as the GSA content increases and quartz content decreases from sample KPG_1 to KPG_6. Notably, KPG_6 (10% GSA, 0% quartz) demonstrated the highest hardness values at both firing temperatures. This trend provides compelling evidence that GSA contributes significantly to the development of a harder ceramic matrix, functioning effectively as a quartz substitute.

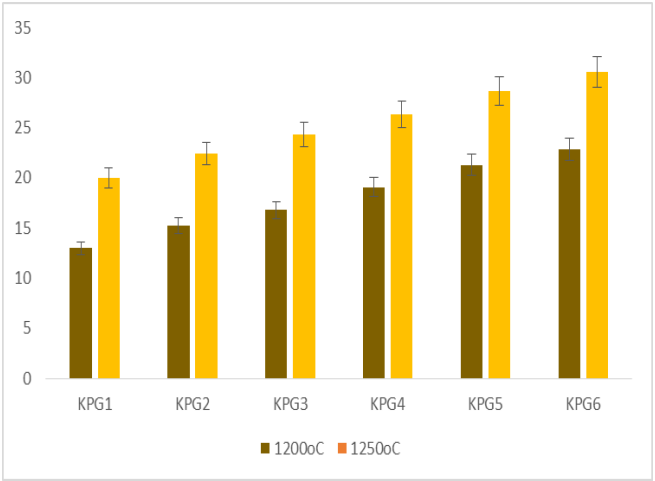


Fig. 5. Hardness evaluation of developed porcelain wares

The increased hardness is attributable to GSA's fluxing characteristics, which promote the formation of a continuous and robust glassy phase [37-38]. This vitrified matrix enhances the bonding among particles, leading to reduced porosity and improved microstructural cohesion. The elevated firing temperature of 1250°C further amplifies these effects by facilitating greater liquid-phase formation, enhancing viscous

flow, and promoting atomic diffusion. Additionally, changes in the quantity and morphology of crystalline phases formed during sintering may contribute to the observed enhancement in hardness [39]. Overall, the hardness results clearly demonstrate that groundnut shell ash serves as an effective and functional substitute for quartz in porcelain formulations, significantly improving the mechanical performance of the final product.

3.6 Compressive strength evaluation (Mpa)

Figure 6 illustrates the compressive strength results of the developed porcelain wares incorporating groundnut shell ash (GSA) as a substitute for quartz. The data indicate a marked improvement in the structural integrity and mechanical load-bearing capacity of the samples, aligning with the trends observed in the previously discussed physical and mechanical properties. At both firing temperatures (1200°C and 1250°C), compressive strength increases progressively with rising GSA content from KPG_1 to KPG_6. Notably, sample KPG_6 (comprising 10% GSA and 0% quartz) exhibited the highest compressive strength values at both temperatures. This consistent increase supports the conclusion that GSA functions as an effective fluxing agent, significantly enhancing densification and vitrification processes during sintering [30-31].

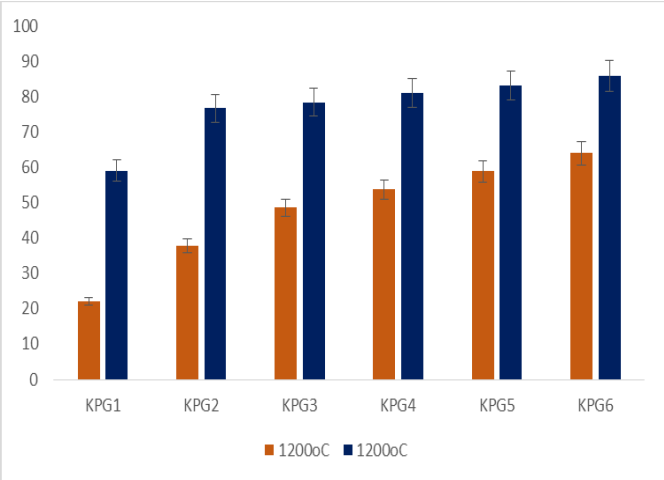


Fig. 6. Compressive strength evaluation of developed porcelain wares

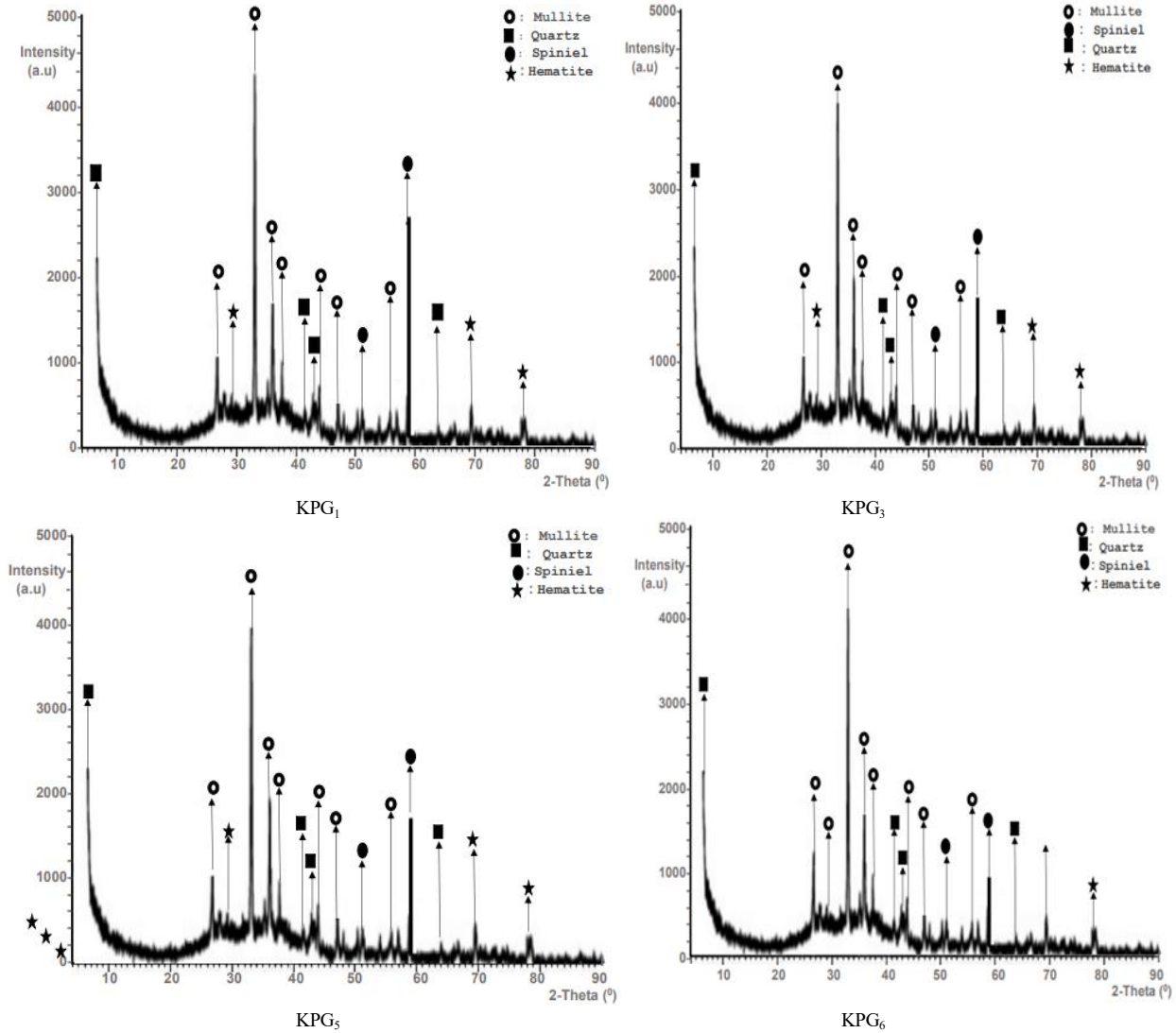
The development of a more extensive and continuous glassy phase, alongside efficient pore elimination, contributes to a denser and more cohesive ceramic microstructure capable of withstanding greater mechanical stress [39]. The superior performance of GSA over quartz in this context suggests that GSA introduces active components such as alkali oxides that facilitate the formation of strength-contributing phases and promote improved matrix densification, unlike the relatively inert quartz [24, 32]. Furthermore, the elevated firing temperature of 1250°C amplifies these effects by accelerating sintering kinetics and enhancing microstructural consolidation [40]. The combined influence of increased GSA content and higher firing temperature leads to optimized densification and a substantial improvement in mechanical strength. These findings affirm that groundnut shell ash is not only a viable but a superior alternative to quartz in porcelain formulations, offering significant improvements in compressive strength and overall mechanical performance.

3.7 Phase evaluation of developed porcelain wares fired at 1200°C

Figure 7 presents the X-ray diffraction (XRD) phase analysis of the developed porcelain wares fired at 1200°C, incorporating groundnut shell ash (GSA) as an alternative substitute for quartz. The diffraction patterns reveal prominent peaks corresponding to quartz, consistent with its presence in the initial formulations. Additionally, characteristic mullite peaks typical of porcelain ceramics at this firing temperature are also observed, indicating the reaction between kaolin and other constituents during sintering [41-42]. Secondary peaks corresponding to spinel and hematite phases were also identified, likely originating from impurities or complex reactions among the raw materials. As the proportion of quartz decreases and GSA content increases across samples KPG_2 to KPG_6, a progressive reduction in the intensity of quartz peaks is observed. In the case of sample KPG_6 (comprising 0% quartz and 10% GSA), the quartz peaks are either significantly diminished or entirely absent, confirming the successful replacement of quartz with GSA in the ceramic matrix. Mullite peaks remain visible in all compositions, though some variations in their intensity may be attributed to the influence of GSA-derived silica on mullite formation or its crystallographic stability. Additionally, a notable increase in the amorphous phase is inferred from the broad hump in the baseline of the XRD patterns, particularly at lower 2θ angles [43]. This diffuse background signal is indicative of an enhanced glassy phase formation, which is consistent with the fluxing behavior of GSA. The increased presence of this glassy phase supports the observed improvements in densification, as it facilitates pore filling and contributes to the formation of a more cohesive microstructure [44-46] These results confirm that GSA not only acts as an effective fluxing agent but also promotes the formation of desirable crystalline and amorphous phases that enhance the structural and mechanical properties of the porcelain wares.

3.8 Phase evaluation of developed porcelain wares fired at 1250°C

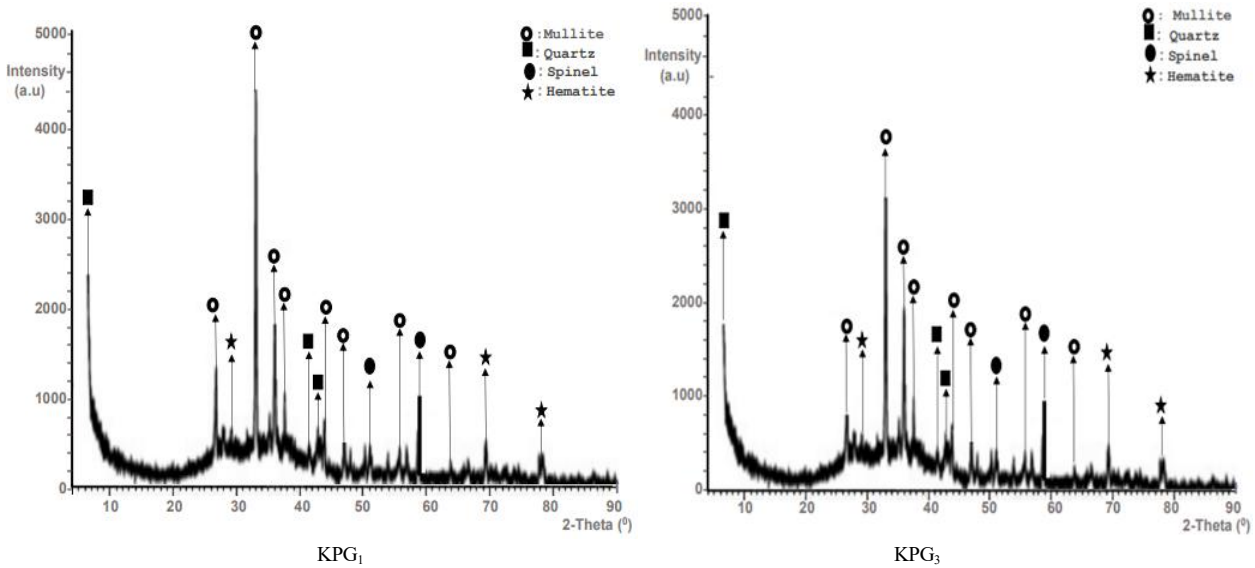
Figure 8 presents the X-ray diffraction (XRD) phase analysis of the developed porcelain wares fired at 1250°C, with groundnut shell ash (GSA) as an alternative substitute for quartz. The XRD patterns at this elevated firing temperature exhibit sharper and more intense peaks for crystalline phases, indicative of improved crystallinity, alongside a noticeable attenuation or disappearance of peaks corresponding to phases undergoing dissolution [45]. Furthermore, the presence of a broader amorphous hump in the diffraction baseline suggests a substantial increase in the vitrified (glassy) phase, pointing to enhanced vitrification at this higher sintering temperature [47]. The trend observed at 1200°C, in which quartz peaks decreased with increasing GSA content, becomes even more pronounced at 1250°C. The higher thermal energy at 1250°C facilitates the reaction of quartz with the surrounding amorphous matrix and other components, contributing to a more homogeneous and dense microstructure.



KPG$_1$ KPG$_3$

KPG$_5$ KPG$_6$

Fig. 7. XRD images of developed porcelain wares fired at 1200°C



KPG$_1$ KPG$_3$

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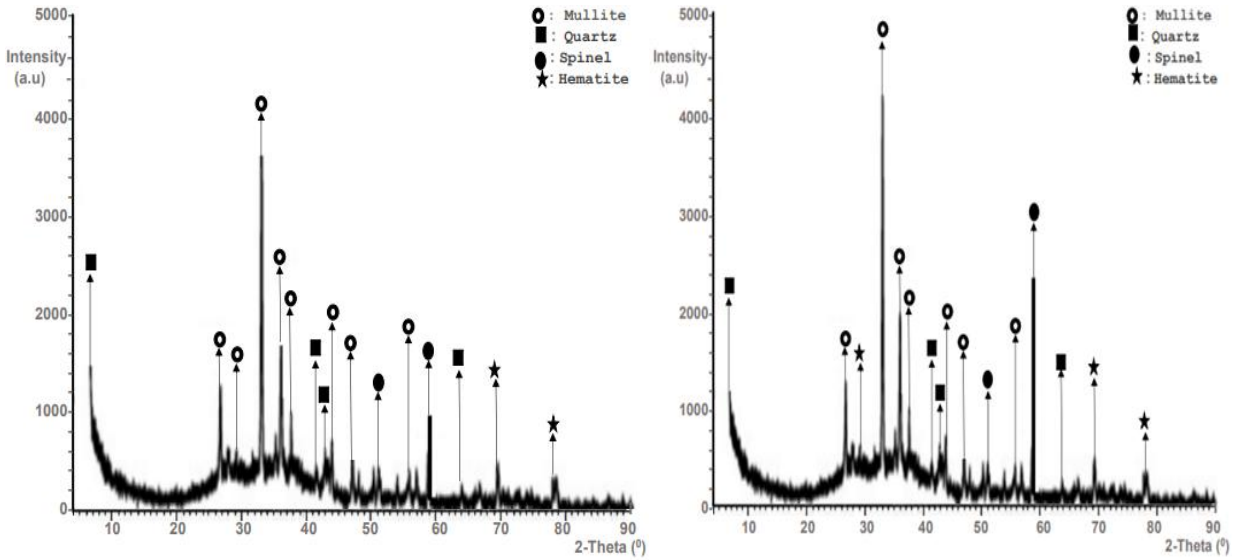
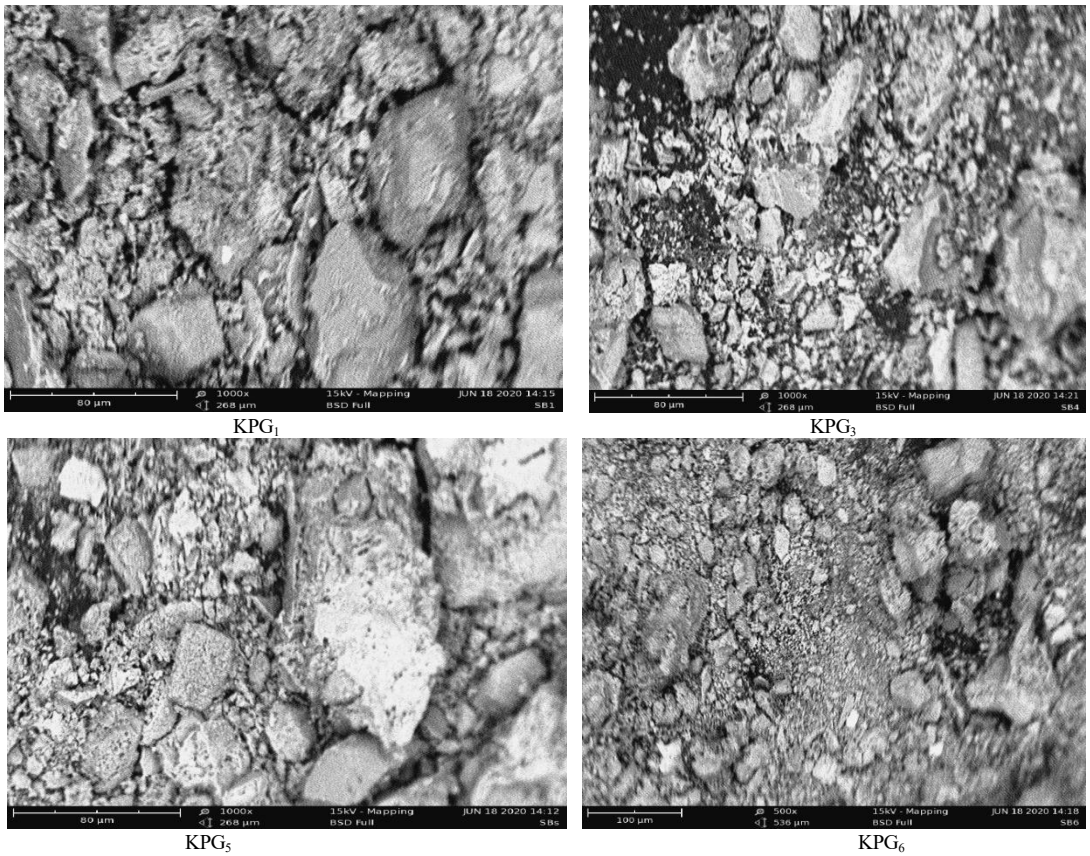


KPG5 KPG6

Fig. 8. XRD images of developed porcelain wares fired at 1250°C



KPG_1 KPG_3

KPG_5 KPG_6

Fig. 9. SEM images of developed porcelain wares fired at 1250°C

Additionally, peaks corresponding to mullite ($3Al_2O_3 \cdot 2SiO_2$) become more prominent and well-defined at 1250°C, indicating the formation of larger, well-crystallized mullite needles. This is as a result of the complete reaction of kaolin and other alumino-silicate components at higher temperatures. The combination of reduced quartz content, enhanced mullite formation, and a substantially expanded glassy phase at 1250°C explains the observed improvements in the physical properties of the samples. These include a significant reduction in water absorption and porosity, as well as increased bulk density and linear shrinkage. The phase evolution at this temperature clearly demonstrates the effectiveness of GSA in promoting vitrification, densification, and structural integrity in the developed porcelain wares [46]

3.9 Microstructural evolution of developed porcelain wares fired at 1250°C

Figure 9 presents the (SEM) images of the developed porcelain wares fired at 1250°C, utilizing groundnut shell ash (GSA) as an alternative substitute for quartz. The microstructural analysis reveals notable differences in morphology across the samples, correlating strongly with the varying GSA content. The SEM image for sample KPG_1 displays a relatively dense microstructure; however, residual porosity is still evident. In addition, some unreacted or partially dissolved quartz particles remain embedded within the glassy matrix. Although the presence of mullite crystals is observed, they appear less uniformly distributed and less abundant compared to samples with higher GSA content. Moreover, well-developed, elongated, or needle-like mullite crystals are distinctly observed across the samples, particularly embedded within the glassy matrix [48-49]. The formation of these acicular mullite structures is indicative of enhanced mullite crystallization at higher firing temperatures and GSA levels. As the GSA content increases, the microstructure becomes increasingly homogeneous and uniform, with fewer visible pores and more continuous glassy regions [50-51]. This progression strongly suggests a more complete and efficient sintering process facilitated by GSA, particularly at 1250°C. The SEM observations provide compelling visual evidence supporting the previously discussed physical and mechanical property results. The marked reduction in visible porosity from KPG_1 to KPG_6 aligns with the observed decreases in water absorption and porosity, and the corresponding increases in bulk density and linear shrinkage.

IV. Conclusions

This study successfully explored the development of porcelain wares using groundnut shell ash (GSA) as a partial to complete replacement for quartz, presenting a sustainable and resource-efficient approach to ceramic material production. The results consistently demonstrate that GSA is an effective fluxing agent and a viable alternative to quartz in porcelain formulations, significantly enhancing both the densification process and the mechanical performance of the material. The progressive substitution of quartz with GSA led to a marked reduction in water absorption and porosity, accompanied by corresponding increases in bulk density and linear shrinkage. Optimal densification was achieved in samples with higher GSA content, particularly in KPG_6 (10% GSA, 0% quartz). Additionally, mechanical properties including hardness and compressive strength improved steadily with increasing GSA content. The increase in firing temperature from 1200°C to 1250°C further amplified these effects, resulting in substantial improvements across all measured properties. X-ray diffraction (XRD) analysis confirmed the gradual dissolution of quartz and the enhanced formation of both an amorphous glassy phase and well-crystallized mullite as GSA content and firing temperature increased. Complementary scanning electron microscopy (SEM) revealed highly dense and homogeneous microstructures with minimal or no visible residual porosity, further validating the effectiveness of GSA in promoting vitrification and structural integrity. Overall, the findings underscore the potential of groundnut shell ash as a sustainable and performance-enhancing material in the fabrication of high-quality porcelain wares.

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