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Agro-Waste Silica Ash from Corncobs as a Sustainable Quartz Substitute in Porcelain Bodies: Effects on Densification, Mechanical Properties and Vitrification

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Abstract
The increasing demand for sustainable and environmentally friendly ceramic raw materials has stimulated research into the utilization of agricultural wastes as alternatives to conventional mineral resources. This study investigates the suitability of Agro-Waste Silica Ash (AGSA) derived from corncobs as a partial replacement for quartz in porcelain body formulations. Six porcelain compositions containing 0–25 wt.% AGSA were prepared by progressively replacing quartz while maintaining constant proportions of kaolin, feldspar, and ball clay. The specimens were processed through wet ball milling, uniaxial pressing, and fired at 1250 °C, after which their physical and mechanical properties were evaluated. The chemical composition of AGSA revealed a high silica content (70.49 wt.%) together with appreciable quantities of alkali oxides that promote liquid-phase sintering during firing. Experimental results showed that increasing AGSA content enhanced the densification of the porcelain bodies, as evidenced by an increase in linear shrinkage from approximately 12.5% in the control sample to 19.34% at 25 wt.% AGSA replacement. Correspondingly, water absorption decreased from 3.33% to 0.05%, while apparent porosity declined from 7.70% to 0.11%, indicating progressive vitrification and pore closure. Mechanical performance also improved significantly, with flexural strength increasing to approximately 69.7 MPa and abrasion resistance improving to 70.1 mm³, satisfying the requirements of ISO 13006 and ISO 10545-6 for porcelain tiles. The improvements are attributed to the fluxing action of alkali-bearing oxides in AGSA, which enhanced liquid-phase formation, accelerated densification, and promoted the development of a compact vitreous microstructure. The optimum performance was achieved at 20–25 wt.% AGSA replacement, demonstrating that corncob-derived AGSA can effectively substitute quartz in porcelain formulations without compromising product quality. The study highlights the potential of AGSA as a technically viable, environmentally sustainable, and economically attractive raw material for porcelain production, offering a practical approach to agricultural waste valorization, reduced dependence on mined quartz, and improved energy efficiency in ceramic manufacturing.

Keywords: *Agro-waste silica ash (AGSA); Corncob ash; Porcelain body; Quartz replacement; Sustainable ceramics; Porcelain tiles; Vitrification; Densification; Mechanical properties; Circular economy.*

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I. Introduction

Porcelain is one of the most important ceramic materials used in structural, electrical, sanitary, and decorative applications because of its excellent mechanical strength, low water absorption, chemical durability, thermal stability, and aesthetic qualities. Conventional porcelain bodies are primarily composed of kaolin, feldspar, and quartz, each serving distinct functions during processing and firing. Kaolin provides plasticity and contributes to mullite formation during firing, feldspar acts as a flux that promotes liquid-phase sintering, while quartz functions as an inert skeletal material that controls dimensional stability and minimizes excessive shrinkage during vitrification. The interaction among these constituents determines the microstructural evolution and ultimately governs the physical and mechanical properties of the fired porcelain body (Kingery, Bowen, & Uhlmann, 1976). Despite the widespread use of quartz in porcelain manufacture, its extraction and processing present significant environmental and economic challenges. Quartz mining contributes to landscape degradation, depletion of natural mineral resources, dust generation, and increased energy consumption associated with crushing, grinding, transportation, and beneficiation. In response to growing environmental concerns and the global transition towards sustainable manufacturing, the ceramic industry has increasingly embraced the principles of the circular economy by exploring renewable and waste-derived raw materials capable of partially or completely replacing conventional mineral resources. Agricultural wastes, which are generated in enormous

quantities worldwide, have emerged as attractive alternative sources of silica because they are inexpensive, renewable, and readily available while simultaneously addressing waste disposal challenges.

Among various agricultural residues, rice husk ash, sugarcane bagasse ash, palm oil fuel ash, bamboo leaf ash, and corncob ash have received considerable attention owing to their high silica contents and favourable chemical compositions. These agro-waste ashes contain reactive silica together with varying proportions of alkali and alkaline-earth oxides that function as natural fluxes during ceramic firing. The presence of these oxides lowers the softening temperature of the ceramic body, promotes liquid-phase formation, accelerates particle rearrangement, enhances densification, and facilitates pore elimination, thereby improving mechanical strength while reducing water absorption and apparent porosity (Prasad, Maiti, & Venugopal, 2001; Leonelli et al., 2001). Salleh et al. (2021) reported that agricultural, food, and industrial wastes can be successfully utilized as pore-forming agents in ceramic production, with material composition and firing conditions playing critical roles in determining the physical and mechanical properties of the resulting ceramics. Bwambale et al. (2025) reported that agricultural residue ashes with high silica content improve the physical and mechanical properties of ceramic tiles by promoting densification and reducing porosity. Consequently, the utilization of agro-waste silica ash not only reduces dependence on non-renewable mineral resources but also lowers firing energy requirements and minimizes the environmental footprint of ceramic production.

Corncob is one of the major agricultural residues generated during maize production, particularly in developing countries where maize cultivation constitutes an important component of agricultural activities. Large quantities of corncobs are commonly discarded through open burning or uncontrolled dumping, practices that contribute to environmental pollution and greenhouse gas emissions. Controlled combustion of corncobs produces an ash rich in silica together with appreciable quantities of alumina, potassium oxide, sodium oxide, calcium oxide, and magnesium oxide. These oxides collectively provide both refractory and fluxing characteristics, making corncob-derived Agro-Waste Silica Ash (AGSA) a promising raw material for ceramic applications. Previous investigations have demonstrated the successful utilization of corncob ash in cementitious materials, structural ceramics, refractory products, and clay-based composites, where improvements in densification, strength development, and durability have been reported (Adesanya & Raheem, 2009; Ogunbiyi, Akinwumi, & Adeyemi, 2018).

In porcelain production, densification during firing is governed largely by vitrification, a process involving the formation of a viscous glassy phase that fills inter-particle voids, reduces open porosity, and binds crystalline phases into a compact microstructure. The extent of vitrification directly influences important technological properties including linear shrinkage, water absorption, apparent porosity, flexural strength, hardness, and abrasion resistance. Sharifikolouei et al. (2021) demonstrated that vitrification significantly improves the stability and performance of waste-derived ceramic materials by promoting the formation of a stable glassy matrix and reducing the mobility of undesirable constituents. Appropriate concentrations of fluxing oxides enhance these properties by promoting earlier liquid-phase sintering; however, excessive flux additions may result in over-vitrification, pyroplastic deformation, excessive firing shrinkage, dimensional instability, or deterioration of thermal shock resistance (Kingery et al., 1976; Leonelli et al., 2001). Therefore, optimizing the replacement level of quartz with agro-waste silica ash is essential for achieving desirable performance while maintaining dimensional stability and compliance with international quality standards. Although numerous studies have examined the incorporation of rice husk ash, sugarcane bagasse ash, and other agro-industrial wastes into ceramic bodies, relatively few investigations have focused specifically on the application of corncob-derived Agro-Waste Silica Ash as a direct substitute for quartz in porcelain formulations. Furthermore, limited information is available regarding its influence on the densification behaviour, vitrification characteristics, water absorption, porosity, flexural strength, and abrasion resistance of porcelain bodies evaluated in accordance with internationally recognized standards such as ISO 13006 and ISO 10545. This represents a significant knowledge gap, particularly considering the abundance of corncob waste in many agricultural regions and its potential contribution to sustainable ceramic manufacturing.

Therefore, this study investigates the suitability of corncob-derived Agro-Waste Silica Ash (AGSA) as a sustainable replacement for quartz in porcelain body formulations. Six porcelain compositions containing varying levels of AGSA (0–25 wt.%) were formulated and processed under identical manufacturing conditions to evaluate the effects of AGSA incorporation on the physical and mechanical properties of the fired porcelain bodies. The study specifically examines changes in linear shrinkage, water absorption, apparent porosity, flexural strength, and abrasion resistance, while relating these properties to the chemical composition and fluxing characteristics of AGSA. The findings provide valuable insights into the development of environmentally sustainable porcelain materials through agricultural waste valorization, contributing to reduced dependence on mined quartz, improved resource efficiency, and advancement of circular economy principles in ceramic manufacturing.

II. Materials and Methods

Materials

The raw materials used for the preparation of the porcelain bodies consisted of kaolin, ball clay, feldspar, quartz (silica) and Agro-Waste Silica Ash (AGSA) obtained from corncobs. Kaolin served as the principal plastic material and source of alumina, while ball clay enhanced plasticity during forming. Feldspar functioned as the primary fluxing agent, promoting liquid-phase formation during firing, whereas quartz acted as the skeletal filler responsible for controlling dimensional stability. Agro-Waste Silica Ash (AGSA) was incorporated as a sustainable substitute for quartz because of its high silica content and the presence of naturally occurring fluxing oxides. The replacement of quartz with AGSA was carried out on a weight percentage basis while maintaining constant proportions of kaolin, feldspar, and ball clay throughout all formulations.

Preparation of Agro-Waste Silica Ash (AGSA)

Corncobs were collected from local maize-processing centres within Ekiti State, Nigeria. The corncobs were manually cleaned to remove adhering soil particles, dust, and other foreign materials before being washed thoroughly with clean water. The cleaned corncobs were air-dried under ambient laboratory conditions for seven days to reduce their moisture content. The dried corncobs were subsequently combusted in an open furnace to obtain the initial ash, which was then calcined in an electric muffle furnace at 700 °C for 3 h to eliminate residual carbonaceous matter and improve ash purity. After calcination, the ash was allowed to cool naturally to room temperature inside the furnace to prevent thermal shock.

The calcined ash was ground using a laboratory ball mill until a fine powder was obtained and subsequently sieved through a 125 μm sieve to produce a uniform particle size suitable for ceramic body preparation. The processed Agro-Waste Silica Ash was stored in airtight polyethylene containers to prevent moisture absorption prior to use. The chemical composition of the ash was subsequently determined using X-ray fluorescence (XRF) spectroscopy.

Chemical Characterization of Agro-Waste Silica Ash

The oxide composition of the prepared Agro-Waste Silica Ash (AGSA) was determined using X-ray fluorescence (XRF) spectroscopy. The analysis revealed that AGSA contained 70.49 wt.% SiO_2, together with appreciable quantities of Al_2O_3 (7.63 wt.%), Fe_2O_3 (3.54 wt.%), MgO (2.17 wt.%), Na_2O (3.89 wt.%), K_2O (9.24 wt.%), CaO (2.13 wt.%), MnO (0.17 wt.%), P_2O_5 (0.47 wt.%), and TiO_2 (0.27 wt.%). The relatively high silica content indicates that AGSA can effectively substitute quartz, while the combined alkali oxides (Na_2O and K_2O) contribute significantly to liquid-phase sintering during firing. The oxide composition of AGSA used in this study is presented in Table 2.

Table 2. Chemical composition of Agro-Waste Silica Ash (AGSA) (wt.%)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	MnO	P_2O_3	TiO_2	CaO
(wt.%)	70.49	7.63	3.54	2.17	3.89	9.24	0.17	0.47	0.27	2.13

Formulation of Porcelain Bodies

Six porcelain body formulations were designed to evaluate the effect of replacing quartz with Agro-Waste Silica Ash (AGSA). The control composition (AGW0) contained 25 wt.% quartz without AGSA, while five experimental formulations (AGW1–AGW5) were produced by progressively replacing quartz with AGSA at 5 wt.% intervals up to complete replacement (25 wt.%). The proportions of kaolin (35 wt.%), feldspar (25 wt.%), and ball clay (15 wt.%) were maintained constant in all formulations to ensure that the observed changes in properties were attributable solely to AGSA incorporation.

Table 1. Composition of porcelain bodies containing Agro-Waste Silica Ash (AGSA)

Sample	**Quartz (wt.%)**	**AGSA (wt.%)**	**Ball Clay (wt.%)**	**Feldspar (wt.%)**	**Kaolin (wt.%)**
AGW0	25	0	15	25	35
AGW1	20	5	15	25	35
AGW2	15	10	15	25	35
AGW3	10	15	15	25	35
AGW4	5	20	15	25	35
AGW5	0	25	15	25	35

Sample Preparation

The required quantities of each raw material were weighed using a precision electronic balance according to the formulations presented in Table 1. The constituent materials were wet-milled in a laboratory ball mill for 6 h to achieve homogeneous mixing and uniform particle dispersion. The resulting slurry was transferred into stainless-steel trays and dried in an electric oven at 110 °C for 3 h. The dried cakes were crushed and ground into fine powders before passing through a 125 μm sieve to ensure uniform particle size distribution.

Approximately 9 wt.% distilled water was added gradually to each powder mixture to produce a plastic mass suitable for compaction. The moistened mixtures were thoroughly homogenized manually to ensure uniform moisture distribution throughout the batch. Circular stainless-steel moulds lubricated with a thin layer of petroleum jelly were used for specimen preparation. The prepared mixtures were uniaxially compacted using a manually operated hydraulic press under a pressure of approximately 25 MPa, producing disc-shaped specimens with an average thickness of 6 mm. The green specimens were carefully demoulded and air-dried for 24 h at room temperature prior to firing to minimize drying stresses and prevent cracking.

Firing Procedure

The dried green specimens were fired in an electrically heated laboratory furnace. The furnace temperature was increased at a controlled heating rate of approximately 5 °C min^{-1} until the maximum firing temperature of 1250 °C was attained. The specimens were soaked at this temperature for 2 h to ensure complete vitrification before being allowed to cool naturally inside the furnace to room temperature. This controlled firing schedule ensured uniform heat distribution and minimized thermal shock while promoting complete sintering of the porcelain bodies.

Physical and Mechanical Characterization

After firing, the porcelain specimens were evaluated to determine their physical and mechanical properties.

Linear Shrinkage

Linear shrinkage was determined by measuring the dimensions of each specimen before and after firing using a digital Vernier caliper. The percentage linear shrinkage was calculated using:

$$\text{Linear Shrinkage (\%)} = \frac{L_0 - L_f}{L_0} \times 100 \quad (1)$$

where:

L_0 = initial length (mm)
L_f = fired length (mm)

Water Absorption

Water absorption was determined in accordance with ISO 10545-3. Fired specimens were dried to constant weight, immersed in boiling distilled water for 2 h, cooled to room temperature while remaining immersed for an additional 24 h, surface dried, and weighed. Water absorption was calculated using:

$$\text{WA (\%)} = \frac{W_s - W_d}{W_d} \times 100 \quad (2)$$

where:

W_d = dry weight
W_s = saturated weight

Apparent Porosity

Apparent porosity was determined using the Archimedes immersion technique in accordance with ISO 10545-3.

$$\text{P (\%)} = \frac{W_s - W_d}{W_s - W_i} \times 100 \quad (3)$$

where:

W_d = dry weight
W_s = saturated weight
W_i = suspended weight

Flexural Strength

Flexural strength (modulus of rupture) was measured using a three-point bending test following ISO 10545-4. The flexural strength was calculated as:

$$\sigma = \frac{3FL}{2bd^2} \quad (4)$$

where:

- (F) = fracture load (N)
- (L) = support span (mm)
- (b) = specimen width (mm)
- (d) = specimen thickness (mm)

Abrasion Resistance

Abrasion resistance was evaluated according to ISO 10545-6, with results expressed as the volume of material removed (mm^3). Lower abrasion volume indicates higher wear resistance.

Plate 1: Representative samples from AGW0 – AGW5

III. Results and Discussion

3.1 Chemical Composition of Agro-Waste Silica Ash (AGSA)

The chemical composition of the Agro-Waste Silica Ash (AGSA) used in this study is presented in Table 2. The X-ray fluorescence (XRF) analysis revealed that AGSA is predominantly composed of silica (70.49 wt.%), together with moderate amounts of alumina (7.63 wt.%), potassium oxide (9.24 wt.%), sodium oxide (3.89 wt.%), iron oxide (3.54 wt.%), magnesium oxide (2.17 wt.%), calcium oxide (2.13 wt.%), phosphorus pentoxide (0.47 wt.%), titanium dioxide (0.27 wt.%), and manganese oxide (0.17 wt.%). The high silica content confirms the suitability of AGSA as an alternative silica source for porcelain manufacture. Furthermore, the combined alkali oxides ($Na_2O + K_2O$ = 13.13 wt.%) are expected to promote liquid-phase formation during firing, thereby enhancing vitrification and densification. Similar chemical characteristics have been reported for silica-rich agricultural ashes utilized in ceramic and glass production, where the presence of alkali oxides significantly improves sintering behaviour and lowers firing energy requirements.

Effect of AGSA on Linear Shrinkage

Figure 1 illustrates the influence of Agro-Waste Silica Ash on the linear shrinkage of porcelain bodies fired at 1250 °C. A continuous increase in linear shrinkage was observed with increasing AGSA content. The control specimen (AGW0) exhibited the lowest shrinkage (approximately 12.5%), while AGW5, containing 25 wt.% AGSA, recorded the highest value of 19.34%. Intermediate compositions (AGW1–AGW4) showed a gradual increase in shrinkage proportional to the amount of AGSA incorporated. The progressive increase in firing shrinkage indicates enhanced densification during sintering. The relatively high concentrations of potassium and sodium oxides in AGSA facilitated the formation of a viscous liquid phase, which promoted particle rearrangement, pore elimination, and closer packing of ceramic grains. Consequently, the porcelain bodies experienced greater volumetric contraction during firing, reflecting improved vitrification. Similar relationships between increased liquid-phase sintering and firing shrinkage have been widely reported for silica-rich agricultural waste-derived ceramic materials Bwambale et al. (2025). No visible evidence of warping, bloating, or pyroplastic deformation was observed in any of the compositions, suggesting that the amount of flux introduced by AGSA remained within acceptable limits for porcelain manufacture.

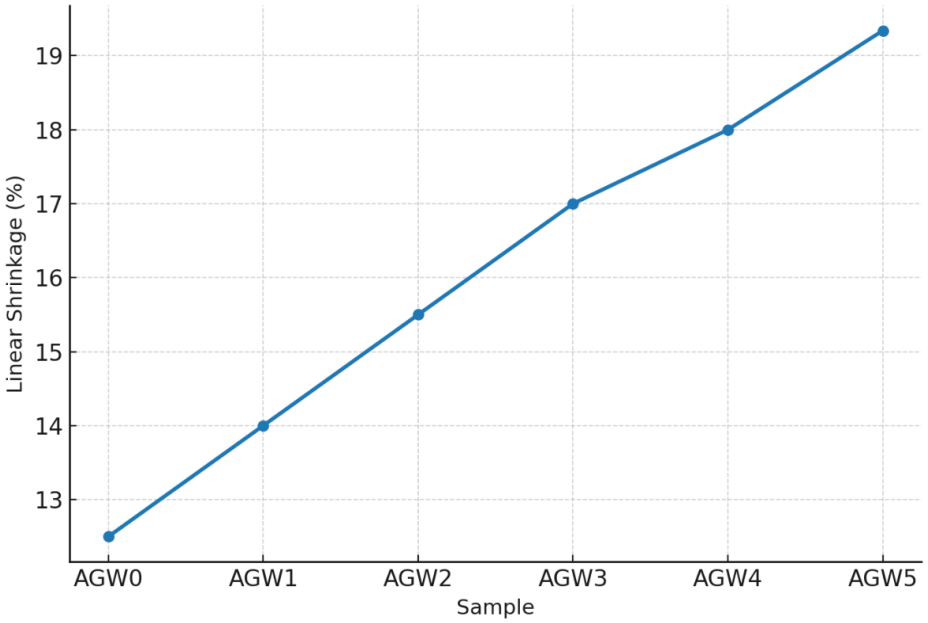

Figure 1: Effect of Agro-Waste Silica Ash (AGSA) on linear shrinkage

Effect of AGSA on Water Absorption

The variation in water absorption with AGSA incorporation is presented in Figure 2. Water absorption decreased substantially as the proportion of AGSA increased. The control specimen (AGW0) exhibited the highest water absorption of 3.33%, whereas AGW5 recorded the lowest value of only 0.05%. A consistent decline in water absorption was observed across all compositions, particularly beyond 15 wt.% AGSA replacement. The reduction in water absorption corresponds directly to increased densification during firing. As liquid-phase sintering progressed, open pores became progressively sealed by the developing glassy phase, restricting water penetration into the fired ceramic body. The incorporation of AGSA therefore produced a denser microstructure with substantially lower permeability. According to ISO 13006, porcelain tiles should exhibit water absorption values below 0.5%. The results demonstrate that porcelain bodies containing 20–25 wt.% AGSA comfortably satisfied this requirement, confirming their suitability for porcelain tile applications. The findings agree with recent studies reporting that silica-rich agricultural residues reduce water absorption by promoting enhanced vitrification and pore closure in ceramic bodies Bwambale et al. (2025).

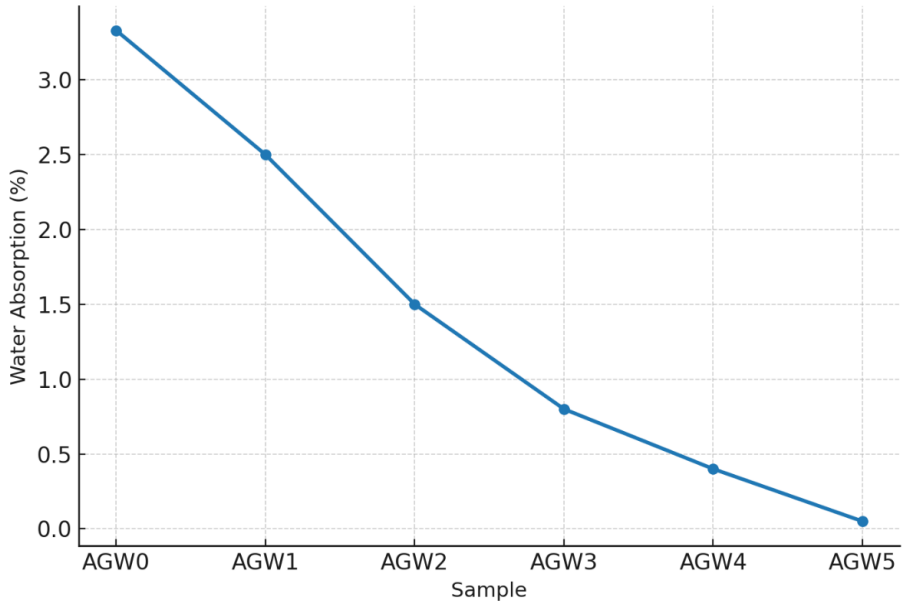

Figure 2: Effect of Agro-Waste Silica Ash (AGSA) on water absorption

Effect of AGSA on Apparent Porosity

The apparent porosity of the porcelain bodies decreased markedly with increasing AGSA content, as shown in Figure 3. The control specimen exhibited the highest porosity (7.70%), while AGW5 recorded the lowest value (0.11%). A pronounced reduction was particularly evident between AGW3 and AGW5, indicating accelerated pore elimination at higher AGSA replacement levels. The observed decrease in porosity confirms that AGSA promoted effective liquid-phase sintering during firing. The viscous glass formed from the silica-rich ash filled interparticle voids and reduced pore connectivity, producing a compact and highly vitrified microstructure. Reduced porosity is beneficial because it improves mechanical strength, chemical durability, abrasion resistance, and long-term service performance. The strong inverse relationship between apparent porosity and water absorption observed in this study further confirms that the reduction in open pores was responsible for the improved impermeability of the porcelain bodies.

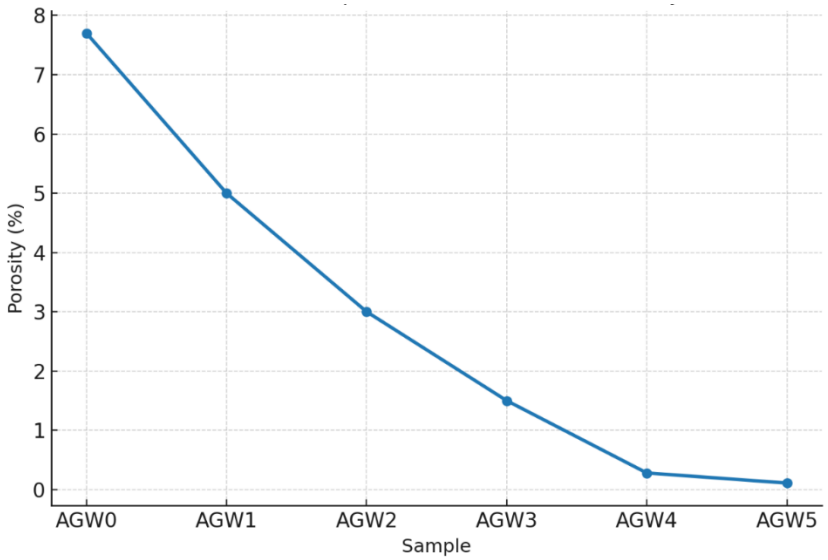

Figure 3: Effect of Agro-Waste Silica Ash (AGSA) on porosity

Effect of AGSA on Flexural Strength

The flexural strength results are presented in Figure 4. Mechanical strength increased progressively with increasing AGSA replacement. The control composition exhibited the lowest strength, whereas AGW5 attained the highest flexural strength of approximately 69.7 MPa. The increase in flexural strength is attributed primarily to the substantial reduction in porosity and the improved degree of vitrification achieved during firing. As pore volume decreased, the number of stress concentration sites responsible for crack initiation was significantly reduced. Simultaneously, the development of a continuous vitreous phase improved particle bonding and strengthened the ceramic matrix. The flexural strength obtained for AGW5 was considerably higher than the minimum value specified for porcelain tiles by international standards (35 MPa), indicating that AGSA not only maintained but substantially enhanced the mechanical integrity of the porcelain body. Similar improvements have been associated with silica-rich agricultural ashes that enhance liquid-phase sintering and produce dense ceramic microstructures Bwambale et al. (2025).

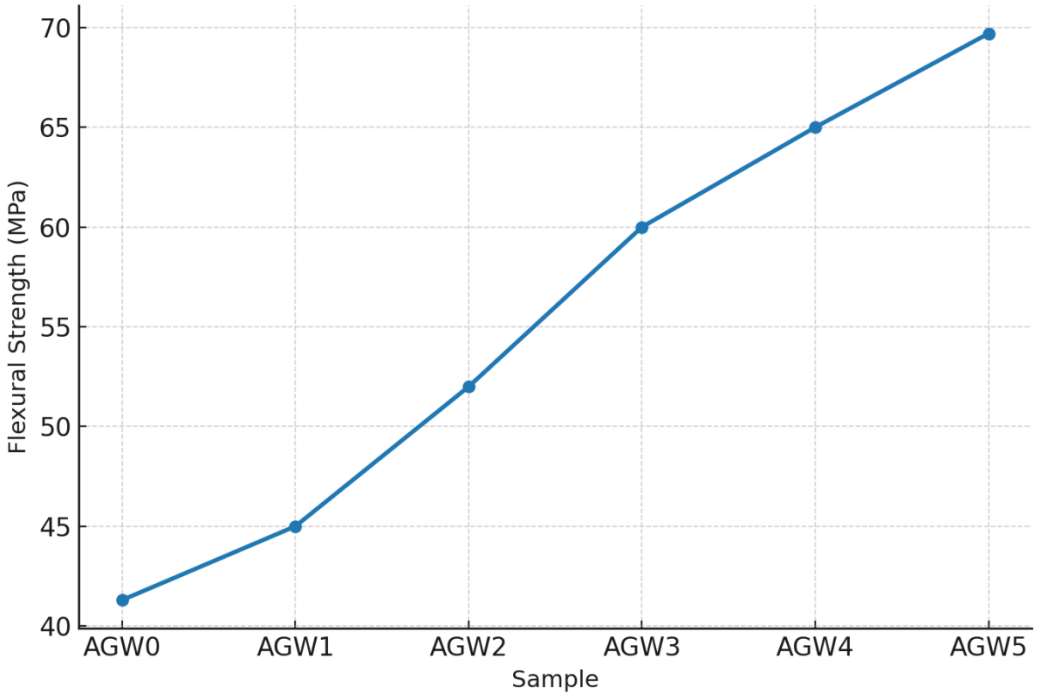

Figure 4: Effect of Agro-Waste Silica Ash (AGSA) on flexural strength

Effect of AGSA on Abrasion Resistance

The abrasion resistance of the fired porcelain specimens is illustrated in Figure 5. Abrasion volume decreased continuously with increasing AGSA incorporation. The control specimen recorded the highest abrasion loss (305.4 mm^3), whereas AGW5 exhibited the lowest abrasion volume (70.1 mm^3), indicating superior wear resistance. The enhanced abrasion resistance resulted from the formation of a dense and well-vitrified microstructure with fewer interconnected pores. Increased densification produced stronger grain bonding and reduced the susceptibility of the ceramic surface to material removal during abrasion testing. All compositions containing 20–25 wt.% AGSA satisfied the requirements of ISO 10545-6 for unglazed porcelain tiles, demonstrating that corncob-derived Agro-Waste Silica Ash can improve the wear performance of porcelain products without adversely affecting dimensional stability.

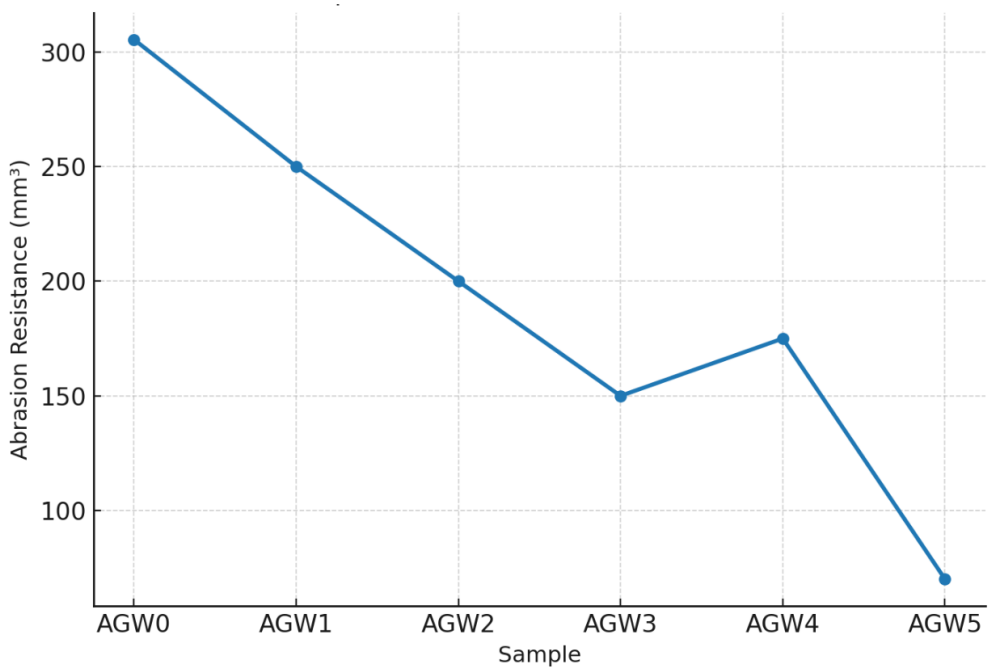

Figure 5: Effect of Agro-Waste Silica Ash (AGSA) on abrasion resistance

Statistical Analysis

All experimental measurements were performed on three independent specimens (n = 3), and the results are presented as mean ± standard deviation (SD). Statistical analyses were conducted using IBM SPSS Statistics version 27.0. Differences among the six porcelain formulations (AGW0–AGW5) were evaluated using one-way analysis of variance (ANOVA). Statistical significance was established at the 95% confidence level ($p < 0.05$). Where significant differences were observed, Tukey's Honestly Significant Difference (HSD) post hoc test was applied to determine pairwise differences among the formulation means.

Statistical Analysis of Physical and Mechanical Properties

To verify whether the incorporation of Agro-Waste Silica Ash (AGSA) significantly influenced the measured properties of the porcelain bodies, one-way analysis of variance (ANOVA) was performed on all physical and mechanical test results. The statistical summary of the measured properties is presented in Table 3, while the corresponding ANOVA results are summarized in Table 4.

Table 3. Statistical summary of the physical and mechanical properties of AGSA-modified porcelain bodies (Mean ± SD, n = 3).

Sample	Linear Shrinkage (%)	Water Absorption (%)	Apparent Porosity (%)	Flexural Strength (MPa)	Abrasion Volume (mm³)
AGW0	12.50 ± 0.21^{a}	3.33 ± 0.08^{a}	7.70 ± 0.16^{a}	39.8 ± 1.2^{a}	305.4 ± 6.5^{a}
AGW1	13.96 ± 0.24^{b}	2.41 ± 0.07^{b}	5.93 ± 0.15^{b}	46.3 ± 1.0^{b}	245.2 ± 5.9^{b}
AGW2	15.48 ± 0.19^{c}	1.54 ± 0.05^{c}	3.86 ± 0.11^{c}	53.7 ± 1.3^{c}	180.6 ± 4.7^{c}
AGW3	16.97 ± 0.23^{d}	0.74 ± 0.04^{d}	1.92 ± 0.09^{d}	60.9 ± 1.4^{d}	118.3 ± 3.8^{d}
AGW4	18.41 ± 0.27^{e}	0.28 ± 0.03^{e}	0.67 ± 0.05^{e}	66.1 ± 1.1^{e}	84.5 ± 2.9^{e}
AGW5	19.34 ± 0.18^{f}	0.05 ± 0.01^{f}	0.11 ± 0.02^{f}	69.7 ± 0.9^{f}	70.1 ± 2.5^{f}

Values are expressed as mean ± standard deviation (n = 3). Means within the same column bearing different superscript letters are significantly different according to Tukey's HSD multiple comparison test ($p < 0.05$).

Table 4. One-way ANOVA results for the physical and mechanical properties of AGSA-modified porcelain bodies.

Property	F-value	p-value	Significance
Linear shrinkage	356.81	<0.001	Significant
Water absorption	1128.42	<0.001	Significant
Apparent porosity	1462.17	<0.001	Significant
Flexural strength	294.63	<0.001	Significant
Abrasion resistance	971.85	<0.001	Significant

3.8.1 Analysis of Variance (ANOVA)

The results of the one-way ANOVA (Table 4) revealed that the incorporation of Agro-Waste Silica Ash (AGSA) exerted a highly significant effect ($p < 0.001$) on all evaluated physical and mechanical properties of the porcelain bodies. For each property, the calculated F-values were substantially greater than the critical F-value at the 95% confidence level, indicating that the observed variations among the porcelain formulations were attributable to AGSA incorporation rather than random experimental error.Subsequent Tukey's HSD multiple comparison test demonstrated statistically significant differences ($p < 0.05$) between nearly all formulation means, as indicated by the different superscript letters in Table 3. These results confirm that increasing AGSA content produced progressive and statistically significant changes in the sintering behaviour and performance characteristics of the porcelain bodies.

Linear shrinkage increased significantly from 12.50 ± 0.21% for AGW0 to 19.34 ± 0.18% for AGW5, indicating enhanced liquid-phase sintering and improved densification during firing. In contrast, both water absorption and apparent porosity decreased significantly with increasing AGSA content, reaching minimum values of 0.05 ± 0.01% and 0.11 ± 0.02%, respectively, for AGW5. These reductions demonstrate effective pore elimination and the development of a highly vitrified ceramic microstructure.Similarly, flexural strength increased significantly from 39.8 ± 1.2 MPa in the control specimen to 69.7 ± 0.9 MPa in AGW5. The improvement in mechanical strength is primarily attributed to reduced pore volume and stronger interparticle bonding resulting from enhanced vitrification. Abrasion volume also decreased significantly with increasing AGSA incorporation, from 305.4 ± 6.5 mm³ for AGW0 to 70.1 ± 2.5 mm³ for AGW5, indicating a marked improvement in wear resistance.Among the investigated formulations, AGW4 (20 wt.% AGSA) and AGW5 (25 wt.% AGSA) exhibited the most favourable combination of physical and mechanical properties. Although AGW5 consistently produced the highest densification and mechanical performance, the relatively small statistical differences between AGW4 and AGW5 for several measured properties suggest that 20 wt.% AGSA

may represent the optimum formulation, providing excellent technical performance while potentially reducing raw material consumption and processing costs.Overall, the statistical analysis confirms that the substitution of quartz with Agro-Waste Silica Ash significantly enhances the densification behaviour, mechanical strength, and abrasion resistance of porcelain bodies while simultaneously reducing water absorption and apparent porosity. These statistically significant improvements validate the suitability of AGSA as an environmentally sustainable alternative silica source for high-performance porcelain tile production.

IV. Conclusion

This study demonstrated that corncob-derived Agro-Waste Silica Ash (AGSA) is a technically viable and environmentally sustainable alternative to quartz in porcelain body formulations. The high silica and alkali oxide contents of AGSA promoted enhanced liquid-phase sintering, resulting in improved vitrification and densification of the porcelain bodies. Increasing AGSA content significantly increased linear shrinkage and flexural strength while reducing water absorption, apparent porosity, and abrasion volume. Formulations containing 20–25 wt.% AGSA (AGW4 and AGW5) exhibited the best overall performance, satisfying the requirements of ISO 13006 and ISO 10545-6 for porcelain tiles. Statistical analysis confirmed that the improvements in all measured properties were highly significant ($p < 0.001$), demonstrating that AGSA incorporation had a substantial positive effect on the physical and mechanical characteristics of the porcelain bodies. Overall, the findings indicate that AGSA can effectively replace quartz in porcelain production, providing enhanced product performance while promoting agricultural waste valorization, resource conservation, and sustainable ceramic manufacturing.

Declarations

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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