



The Effect of Partial Substitution of Feldspar with Palm Bunch Ash on the Mechanical and Electrical Properties of Porcelain Insulator Production

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Abstract

The production of electrical porcelain insulators in Nigeria relies heavily on imported materials like feldspar which increase the cost of production and purchasing price of electrical porcelain insulators. This study investigated the partial substitution of feldspar with Palm Bunch Ash (PBA), a silica-rich by-product of the palm oil industry to enhance sustainability and cost-effectiveness. Using local raw materials (kaolin, quartz, ball clay) and PBA at substitution ratios of 0%, 5%, 10%, 15%, and 20%, samples were prepared, fired at 900°C, and glazed at 1250°C. Mechanical properties (moisture content, plasticity, shrinkage, water absorption, porosity, density) and electrical properties (resistivity, dielectric strength) were evaluated. The results showed that 5% PBA substitution achieved optimal performance, with a resistivity of $2.92 \times 10^{14} \Omega\cdot\text{m}$ and dielectric strength of 9.0 kV/mm, comparable to conventional insulators, while reducing raw material costs by 20%. Higher PBA levels increased porosity, compromising insulation efficiency. This approach leverages local waste to address resource constraints, aligning with circular economy principles and supporting Nigeria's power sector. This is the first systematic evaluation of PBA as a feldspar substitute in Nigerian porcelain insulators, validating its role in circular economy-driven ceramic production.

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Keywords: Palm Bunch Ash; feldspar replacement; porcelain ceramics; dielectric strength; circular economy

Article history

Received: September 23, 2025

Received in revised form: November 13, 2025

Accepted for publication: November 11, 2025

Available online: January 16, 2026

1.0 Introduction

The growing need for electricity is driving a significant transformation in the global energy sector, especially in rapidly developing regions like Africa where industrialization and rising living standards are driving an unprecedented increase in energy demands. Power infrastructure is under tremendous strain due to this increase in demand, so stable grids require components that are dependable, effective, and sustainable. Electrical porcelain insulators, which offer insulation and mechanical support to stop undesired current flow and guarantee operational safety, are essential parts of transmission and distribution systems. These insulators have been the mainstay of high-voltage systems because of their remarkable mechanical strength, electrical stability, and resistance to environmental deterioration. Traditionally, they are made using a mixture of kaolin, quartz, and feldspar. But the use of traditional raw materials, especially feldspar, presents serious problems from an economic and environmental standpoint, which is why sustainable alternatives are being investigated. This study is the first to evaluate Palm Bunch Ash (PBA), a silica-rich agro-waste, as a partial feldspar substitute in Nigerian electrical porcelain production. The purpose of this study is to determine whether Palm Bunch Ash (PBA), a by-product of the palm oil industry, can be used in place of some of the feldspar in the manufacturing of electrical porcelain insulators. The goal is to increase sustainability without sacrificing performance. Due to its capacity to satisfy these requirements, porcelain insulators, which are mainly made of kaolin for plasticity, quartz for structural stability, and feldspar as a fluxing agent are preferred. Specifically, feldspar lowers the melting point during firing, which promotes vitrification and improves the mechanical and electrical characteristics of the insulator (Silva *et al.*, 2019). However, energy-intensive mining methods used to extract feldspar, a mineral that

makes up more than 60% of the Earth's crust, contribute to habitat destruction, deforestation, and high carbon emissions (Jones *et al.*, 2014; Warr, 2021).

A potential substitute for feldspar is Palm Bunch Ash (PBA), a byproduct produced by burning the leftovers from palm oil mills. PBA has the potential to be used as a fluxing agent in ceramic production because it is rich in silica and can aid vitrification while lowering the need for mined resources (Nelson *et al.*, 2023). Empty fruit bunches are among the large amounts of waste produced by the palm oil industry, which is a major economic driver in nations like Nigeria. These are frequently burned, producing ash that contains a lot of silica. PBA substitution converts an environmental liability into a useful resource by repurposing this waste, which is consistent with the principles of the circular economy (Oosterveer, 2015). This method lessens the ecological footprint related to feldspar extraction as well as the environmental impact of waste disposal. This study aimed to give a thorough grasp of PBA's potential by evaluating its compatibility with ceramic matrices and its effects on mechanical and electrical properties. While biomass ashes have been explored in ceramics, no prior study has systematically evaluated PBA as a flux substitute in electrical porcelain insulators. This research fills that gap.

2.0 Materials and Methods

2.1 Materials

The materials used in this study are listed below. The following were sourced from Okene Local Government Area of Kogi State:

1. Kaolin: It was used to provide whiteness, plasticity and structural strength of the porcelain insulator to be formed during firing.
2. Ball Clay: It was used to increase plasticity and workability to the mixture, allowing the porcelain insulator to be easily shape.

3. Feldspar: It was used to act as a flux, also to lower the melting temperature of the porcelain mixture as well as promote vitrification (glass-like nature) during firing.
 4. Quartz: It was used in the work to increase the strength of the porcelain insulator and also to minimize shrinkage.
 5. Palm Bunch Ash: the acquired dried palm bunches were burnt using gas furnace until they formed ash. The ashes serve as the partial replacement or substitution for feldspar in the study. While
 6. Dried Palm Bunch: Dried palm bunch was acquired from Emene community situated in Enugu East Local Government Area, Enugu State. It was converted to ash.
- Processing Equipment:
7. Grinder/Crusher: the crushing machine was used to reduce the constituents to the desired particle size in micrometers.
 8. Mortar and Pestle: This material was used to grind lesser quantities of constituents for low scale production.
 9. Mixer: Mixer was used to homogeneously mix the constituents in their rightful proportions for a large-scale production.
 10. Weighing balance: an M311L M METLAR Weighing balance was used to ascertain the weight of each individual materials in the right proportion from the formulation of the constituents.
 11. Mesh Sieves: Mesh sieves of 0.425mm and 0.18mm were used to filter the constituents to get rid of unwanted particles and plant materials.
 12. Plastic Rubber: This was used to mix the constituents and water together for proper dissolution.
 13. Water: this was used as binder to enable plasticity and formation of a workable clay mixture.
 14. Moulds: the moulds provide the shapes of porcelain insulators needed before firing.
 15. Vernier Caliper: This was used to take measurement of the porcelain insulator's length after moulding.
 16. Manual Plastometer: This was used to examine the moulded porcelain prototype after oven drying at 105⁰C before to check the relative plasticity or flexural strength.
 17. Kiln: the kiln was used to gloss fire the 100⁰C preheated porcelain to higher temperature to bisque at 900⁰C for vitrification and further harden the porcelain insulator as shown in Plate 1. It was also used to glaze fire at 1250⁰C of the vitrified porcelain insulator to form a glassy finish, smooth surface, enhance durability and to ensure a standard insulation property as well as increase resistance to moisture as shown in Plate 2.
 18. Megger Tester: this was used to test for resistivity and dielectric strength of the porcelain insulator.

2.2 Methods

2.2.1 Research Design

The study adopted an experimental research design which was carried out at the Department of Ceramic Research and Production Laboratory in Project and Research Development Institute, Emene, Enugu State.

2.2.2 Experimental Procedure

The formulation of the percentage of the constituents was the first stage. The feldspar samples were crushed with Jaw Crusher and ball milled for 24 hours to obtain a particles size of less than 25 μ m. Also, the silica sand was milled for 24 hours to obtain a particle size of 25 micrometer. The palm bunches were collected and burnt to ashes; the ashes were packed in a crucible and calcined at 700⁰C using local kiln. The Ball clay and Kaolin clay were collected separately, crushed with a Jaw crusher and ball milled also to get the required particle size. This prepared clay samples were then collected using the formulation ratios as shown in Table 1 dispersed in excess water in a pre-

treated plastic container and stirred vigorously to ensure proper dissolution. The dissolved clay was then filtered through a 0.425-millimeter mesh sieve to get rid of unwanted particles and plant materials. The filtrate was allowed to settle, after which excess water was decanted off. The clay was then sun dried and oven dried at 105°C for 3 hours, pulverized and passed through a mesh sieve of size 0.18 millimeter ready for formulation.

2.2.3 Moulding of the Test Pieces

The formulated body was then molded into three types of shapes using metallic moulds and the application of lubricants to the surface of the moulds to prevent the test pieces from sticking to the surface. The first shape is cylindrical with a width of 3.5cm and height 3cm, the second is a rectangular piece with length 8cm, width 4cm and height 1.5cm, while the third has a long rectangular shape with length 9.5cm, width 2cm and height 1.5cm.

Table 1: Batch Formulation (wt%)

Sample	Feldspar (%)	Silica (%)	Kaolin (%)	Palm Bunch Ash (%)	Ball Clay (%)
A	30	25	40	0	5
B	25	25	40	5	5
C	20	25	40	10	5
D	15	25	40	15	5
E	10	25	40	20	5

2.2.4 Making Moisture Determination

This was determined by weighing the cylindrical test pieces immediately after molding and recorded as the wet weight, W_w . The test pieces air-dried for 24hrs and then dried in an oven at 105°C until a constant weight was recorded. After drying the test pieces were weighed and the dried weight recorded as W_d . The making moisture was then calculated as shown in equation 1 (Etukudoh, Akpomie & Okereke, 2016).

$$\text{Moisture (\%)} = \frac{W_w - W_d}{W_w} \times 100 \quad (1)$$

where W_w = Wet weigh, W_d = Dry weight and 100 = percentage constant.

2.2.5 Determination of Relative Plasticity

The relative plasticity was determined using the cylindrical test pieces. The original height, H_o of the test pieces were obtained by the use of the Vernier caliper by taking the average of three sides. Afterwards, a manual plastometer machine was used to deform the test pieces. The deformation height, H_i was recorded taking the

average of three sides. The relative plasticity was then calculated by the method by Hill (2023) as shown in equation 2.

$$\text{Relative Plasticity} = \left(\frac{H_o}{H_i} - 1 \right) \times 100 \quad (2)$$

where H_o = Original height and H_i = Deformation height

2.2.6 Shrinkage Determination

Immediately after molding of the cylindrical porcelain samples, a Vernier caliper was used to measure the length; this was recorded as the original length L_o (cm). The porcelain samples were then air dried for 7 days and then dried in an oven at 105°C until no further weight loss was obtained. After which the length was measured labeled dried length L_d (cm). Afterwards, the five of the dried samples were fired to a bisque state at 900°C and also glazed at 1250°C. The lengths after glazed firing were determined and recorded as the fired length, L_f (cm). The shrinkage was then calculated as shown in equation 3, equation 4 and equation 5 below (Abuh *et al.*, 2014).

$$\text{Wet – Dry Shrinkage (\%)} = \frac{100 (L_o - L_d)}{L_o} \quad (3)$$

where L_d = Dried length, L_o = Original length
100 = constant term for percentage shrinkage.

$$\text{Dry – Fired Shrinkage (\%)} = \frac{100 (L_d - L_f)}{L_d} \quad (4)$$

where L_d = Dried length, L_f = Fired length
100 = constant term for percentage.

$$\text{Total Shrinkage (\%)} = \frac{100 (L_o - L_f)}{L_o} \quad (5)$$

where L_d = Fired length, L_o = Original length
100 = constant term for percentage

2.2.7 Determination of Water of Absorption

The fired test pieces obtained after firing were then weighed and the weight recorded as dry weight, M_1 (g). Thereafter, the test pieces were soaked in water for one hour, then removed, cleaned and weighed immediately and recorded as soaked weight, M_2 (g). The water absorption was then calculated as shown in equation 6 (Etukudoh *et al.*, 2016):

$$\text{Water of Absorption (\%)} = \frac{100 (M_2 - M_1)}{M_1} \quad (6)$$

where M_1 = Dry weight in grams, M_2 = Soaked weight in grams and 100 = constant term for percentage.

2.2.8 Porosity and Density Determination

After the procedure described above was completed. The suspended weight of the test pieces was then determined by the use of a lever balance and recorded as M_3 (g). The apparent density of the sample is dependent on the external volume of the sample; it is defined as the weight of a given volume divided by the volume while the bulk density is dependent on the overall space occupied by the materials of the samples (Etukudoh *et al.*, 2016). It is based on how the samples are packed that is, a closely packed sample of a material would have a higher bulk density than a normally poured sample. Density is a concept defined for any substance, while bulk density is only used in cases where the particles of matter are packed with space for air within, Bulk density of a substance varies with the state the sample is in.

Therefore, it is not an intrinsic property of a material, whereas density is an intrinsic property. The apparent porosity, apparent density and bulk density were then calculated as shown in equation 7, equation 8 and equation 9 respectively (Etukudoh *et al.*, 2016):

$$\text{Apparent Porosity (\%)} = \left(1 - \frac{M_1 - M_3}{M_2 - M_3} \right) \times 100 \quad (7)$$

$$\text{Apparent Density (\%)} = \frac{M_1}{M_1 - M_3} \quad (8)$$

$$\text{Bulk Density (\%)} = \frac{M_1}{M_2 - M_3} \quad (9)$$

where M_1 = Dry weight in gram, M_2 = Soaked weight and M_3 = Suspended weight in grams.

2.2.9 Testing Procedures

Comprehensive testing was conducted on the fired samples to evaluate various properties, including:

- i. Mechanical Properties: Tensile strength, compressive strength, and flexural strength were measured to assess the structural integrity of the insulators.
- ii. Electrical Properties: Dielectric strength, electrical resistivity, and leakage current were evaluated to determine the electrical performance.

2.2.10 Data Collection and Analysis

Quantitative data from the testing procedures was collected and subjected to statistical analysis. Comparative studies between the control group (feldspar-based insulators) and the experimental groups (PBA-substituted insulators) were conducted to identify any significant differences in performance. The results were interpreted to draw conclusions about the feasibility and effectiveness of partial substitution with PBA. This experimental design ensures a systematic and controlled investigation into the impact of Palm Bunch Ash substitution on the properties of electrical porcelain insulators, providing valuable insights for both industry application and future research endeavors.

3.0 Results

This section presents the findings from laboratory experiments and tests conducted on the completed porcelain insulator prototype.

3.1 Mechanical properties of the PBA based porcelain insulators

3.1.1 Moisture Content of Porcelain Insulator

By entering the dry weight (g) and wet weight (g) values into equation 1, the moisture contents

of the glazed porcelain samples were ascertained. The results are displayed in Table 2 below. According to the results, Sample A had the lowest moisture content (1.40% with 0.00% PBA), followed by Sample B (2.57% with 5.0% PBA), Sample C (1.79% with 10.0% PBA), Sample D (2.18% with 15.0% PBA), and Sample E (2.36% with 20.0% PBA). Figure 1's findings demonstrated that the porcelain samples' moisture content increased with the PBA content.

Table 2: Moisture Contents of Porcelain Samples

Samples	Wet weight W _w (g)	Dry weight W _d (g)	$W_w - W_d / W_d$ (g)	Moisture (%)
A	408.0	402.4	0.0147	1.40
B	573.2	558.8	0.0265	2.57
C	420.8	408.5	0.0292	1.79
D	400.5	386.7	0.0344	2.18
E	303.2	291.8	0.0402	2.36

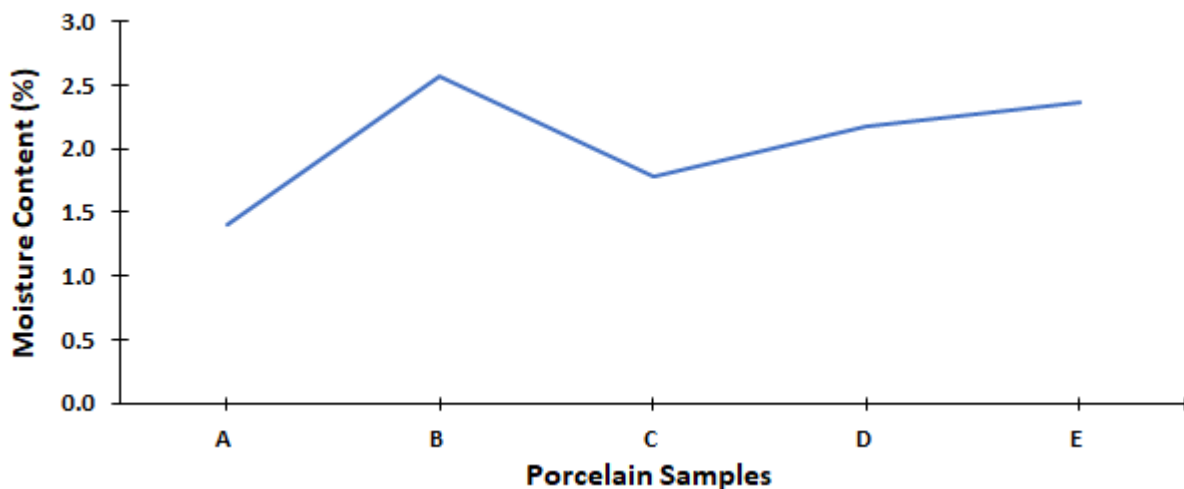


Figure 1: Graph showing moisture contents of the different samples

3.1.2 Determination of Relative Plasticity

Equation 2's formula was used to calculate the porcelain samples' relative plasticity. Changing the initial height (H₀) prior to firing and the deformation height (H_i) values. According to Table 3's results, Sample A had the lowest relative plasticity at 1.20% with 0.00% PBA, followed by Sample B at 1.89% with 5.0% PBA, Sample C at 5.04% with 10.0% PBA, Sample D at 5.44% with 15.0% PBA, and

Sample E at 6.05% with 20.0% PBA. Figure 2's findings demonstrated that the porcelain samples' relative plasticity increased with the PBA content.

3.1.3 Shrinkage of the Porcelain Samples

Equations 3, 4, and 5 were used to calculate the total shrinkage of the porcelain samples. The original length L₀ (cm), dried length L_d (cm), and length at gloze L_f (cm) at 900°C were substituted. Following glazed firing at 1250 °C,

the lengths were measured and recorded as the fired length, L_f (cm). According to the results, Sample A had a total shrinkage of 8.88% with 0.00% PBA, a wet-dry shrinkage of 10.56%, and a dry-fired shrinkage of 2.04%. Wet-dry shrinkage of 3.86%, dry-fired shrinkage of 4.14%, and total shrinkage of 13.04% with 5.0% PBA were found in Sample B; wet-dry shrinkage of 2.73%, dry-fired shrinkage of 5.50%, and total shrinkage of 10.6% with 10.0% PBA were found in Sample C; wet-dry shrinkage of 4.51%, dry-fired shrinkage of 4.51%, and total shrinkage of 9.33% with 15.0% PBA; and wet-dry shrinkage of 5.17%, dry-fired shrinkage of 5.20%, and total shrinkage of 11.34% with 20.0% PBA were found in Sample E. According to the results in Figure 3 and Table 4, the porcelain samples shrank less wet-dryly but more dry-fired and overall, when the PBA content increased.

10.0% PBA were found in Sample C; wet-dry shrinkage of 4.51%, dry-fired shrinkage of 4.51%, and total shrinkage of 9.33% with 15.0% PBA; and wet-dry shrinkage of 5.17%, dry-fired shrinkage of 5.20%, and total shrinkage of 11.34% with 20.0% PBA were found in Sample E. According to the results in Figure 3 and Table 4, the porcelain samples shrank less wet-dryly but more dry-fired and overall, when the PBA content increased.

Table 3: Relative Plasticity of Porcelain Samples

Samples	Wet-Dry Shrinkage (%)	Dry-Fired Shrinkage (%)	Total shrinkage (%)
A	10.56	2.04	8.88
B	3.86	4.14	13.04
C	2.73	5.50	10.6
D	4.51	4.51	9.33
E	5.17	5.20	11.34

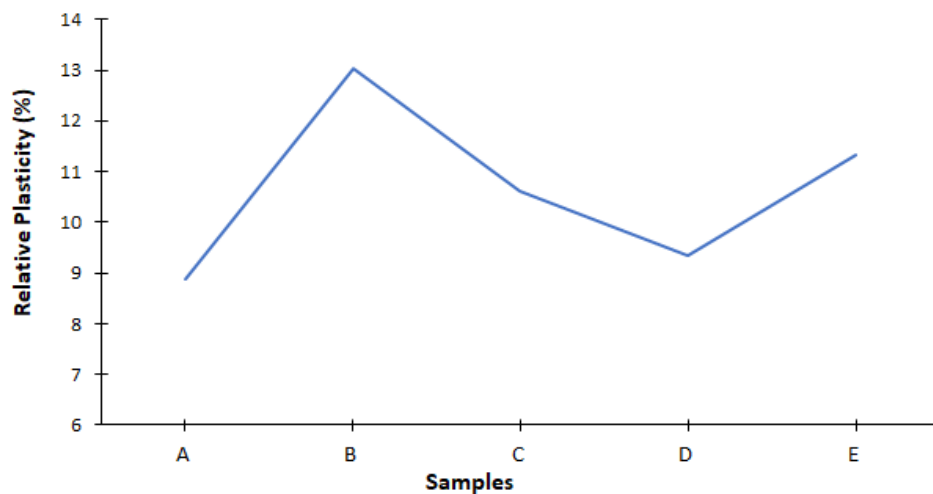


Figure 2: Relative Plasticity of Porcelain Samples

Table 4: Shrinkage Level of Porcelain Samples

Samples	Wet-Dry Shrinkage (%)	Dry-Fired Shrinkage (%)	Total shrinkage (%)
A	10.56	2.04	8.88
B	3.86	4.14	13.04
C	2.73	5.50	10.6
D	4.51	4.51	9.33
E	5.17	5.20	11.34

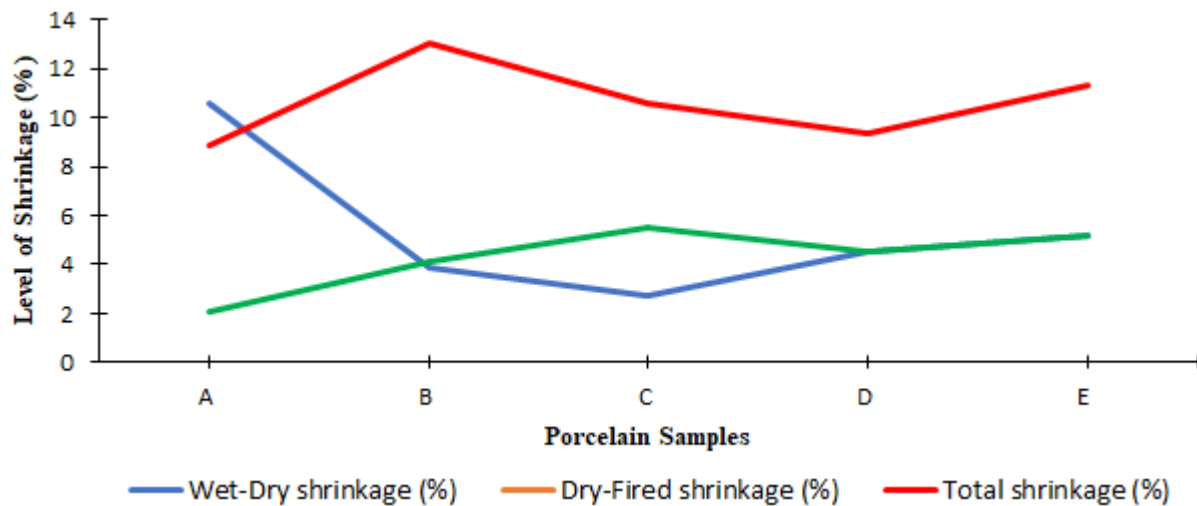


Figure 3: Shrinkage Levels of Porcelain Samples

3.1.4 Water of Absorption of Porcelain Samples

Equation 6's formula was used to calculate the porcelain samples' water absorption. As indicated in Table 5, different values in the percentage of water absorption were obtained by substituting the dry weights W_1 (grams) and soaked weights W_2 (grams) of the samples for different samples. Figure 4 demonstrated that water absorption rises with PBA levels.

3.1.5 Apparent Porosity of Porcelain Samples

Equation 7 from Archimedes' principle was used to calculate the porcelain samples' apparent porosity. Different percentages of water absorption were obtained by substituting the dry weights M_1 (grams), wet weight M_2 , and subtended weights M_3 (grams) for different samples. The results are shown in Figure 5 below.

Table 5: Water of Absorption of Porcelain Samples

Sample	Dry Weight M_1 (g)	Soaked Weight M_2 (g)	Water Absorption (%)
A	405.4	406.3	0.22
B	568.8	570.1	0.23
C	411.5	414.2	0.65
D	396.5	400.1	0.90
E	296.2	299.3	1.04

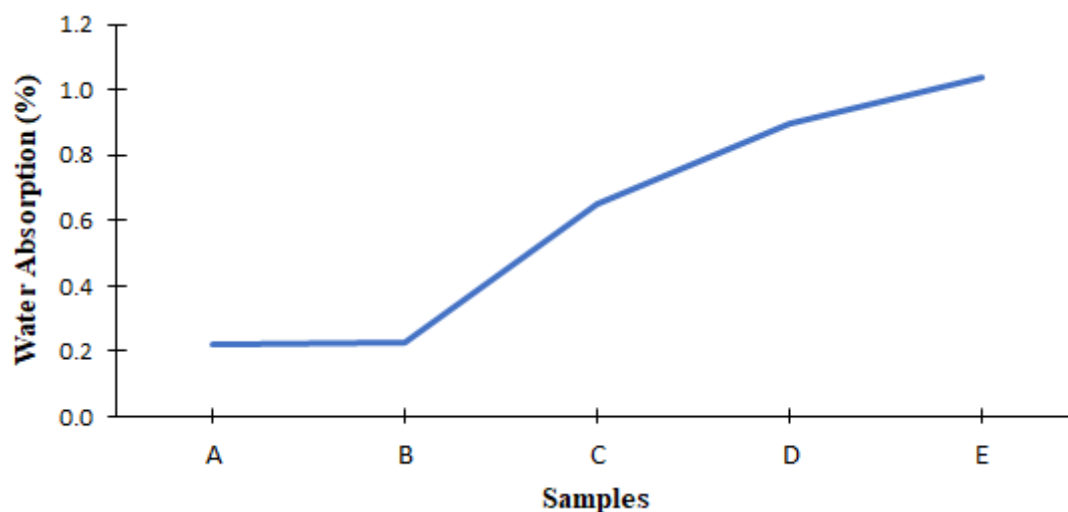
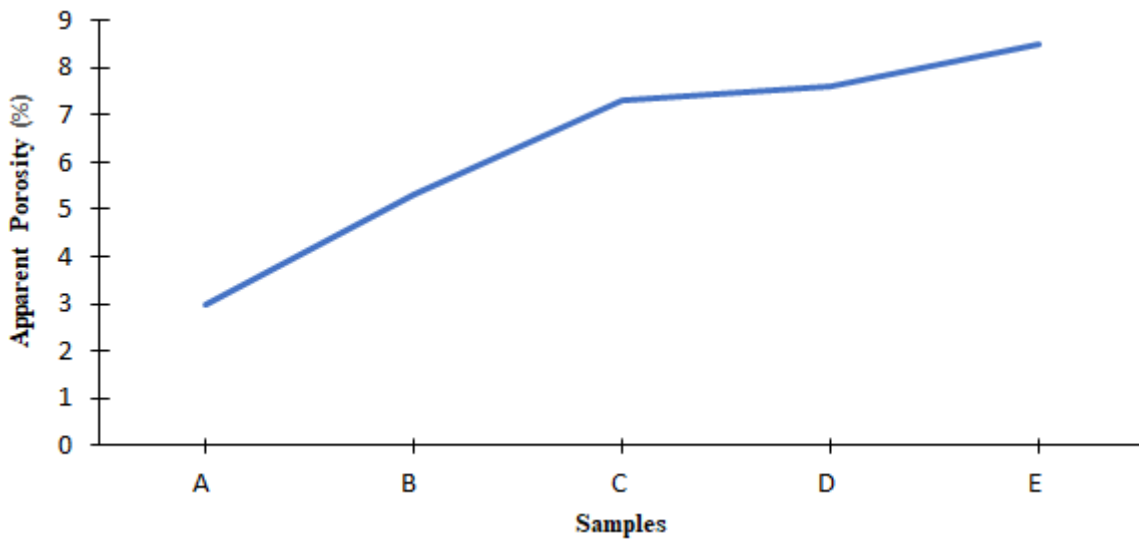


Figure 4: Water Absorption of Porcelain Samples

Table 6: Porcelain Samples' Apparent Porosity

Sample	Dry M_1 Weight (g)	Wet Weight M_2 (g)	Weight Suspended M_3 (g)	Apparent Porosity (%)
A	405.4	408.0	310.7	3.00
B	568.8	573.2	390.3	5.30
C	411.5	418.8	318.9	7.30
D	388.5	396.5	291.4	7.61
E	296.2	305.0	201.7	8.51

**Figure 5:** Apparent Porosity of Porcelain Samples

3.16 Apparent Density Determination

The weight of a specific volume divided by its volume is the sample's apparent density, which depends on its external volume. While bulk density is only used when the matter particles are densely packed with air space inside, density is a concept that can be applied to any substance. A substance's bulk density changes depending on the sample's condition. As a result, while density is an intrinsic property of a material, it is not. Equation 8 was used to determine the sample's apparent densities.

Figure 6 displays the mechanical characteristics of the PBA-based porcelain insulators for Samples A, B, C, D, and E. Sample A, which contains 30% feldspar, 25% quartz, 40% kaolin, 0.0% PBA, and 5% ball clay, is used for water absorption. Sample B, which has variable PBA and feldspar of 5% and 25%, respectively, displayed more

porosity than Sample A. With a composition of 30% feldspar, 25% quartz, 40% kaolin, 0% PBA, and 5% ball clay, Sample A had the lowest porosity and water absorption rate for water absorption, which was consistent with its low PBA content. Increased porosity and water absorption rates were shown by samples with increasing PBA contents (B through E), indicating that PBA addition promotes the development of open pores and lessens the compactness of the porcelain matrix. Crucially, the reduction of open porosities and the increase in the glassy phase within the porcelain body caused the overall water absorption to decrease across all samples as the firing temperature rose. Because high-voltage insulators should ideally have zero water absorption to maintain insulation efficiency, these decrease in porosity and increase in vitrification leads to a decrease in water absorption.

Samples A (4.28 g/cm³), B (7.25 g/cm³), C (4.44 g/cm³), D (4.00 g/cm³), and E (3.13 g/cm³) showed a trend of increasing apparent density in both apparent and bulk density, as shown in Table 7 and Figure 7. The gradual addition of PBA, which could add more filler material but might also result in increased porosity and decreased mechanical integrity, is responsible for this density increase. However, bulk density decreased slightly in all samples, with Sample A showing a bulk density of 4.17 g/cm², B 6.86 g/cm², C 4.12 g/cm², D 3.70 g/cm², and Sample E showing a bulk density of 2.87 g/cm². This is probably because of

increased porosity brought on by a higher PBA content. Although PBA addition may increase the material's mass, it also decreases structural cohesion and compactness, according to the inverse relationship between bulk density and PBA concentration. Because of its low porosity and water absorption, which are critical for high-voltage insulator performance, Sample A offered the best qualities for insulation. Samples B and C, however, retained the recognized physical characteristics of porcelain insulators. The structural compactness and insulating capacity of the porcelain insulators are clearly compromised as the PBA content increases.

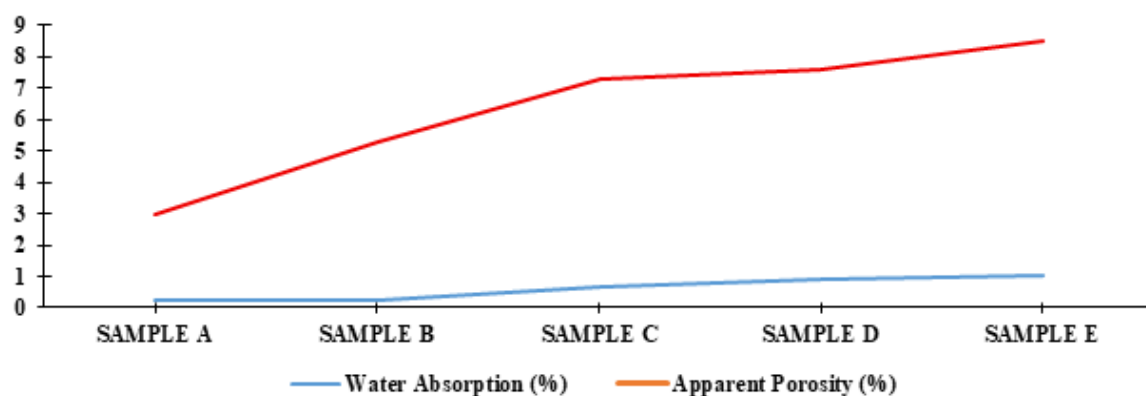


Figure 6: Apparent porosity and water absorption content of PBA porcelain insulator

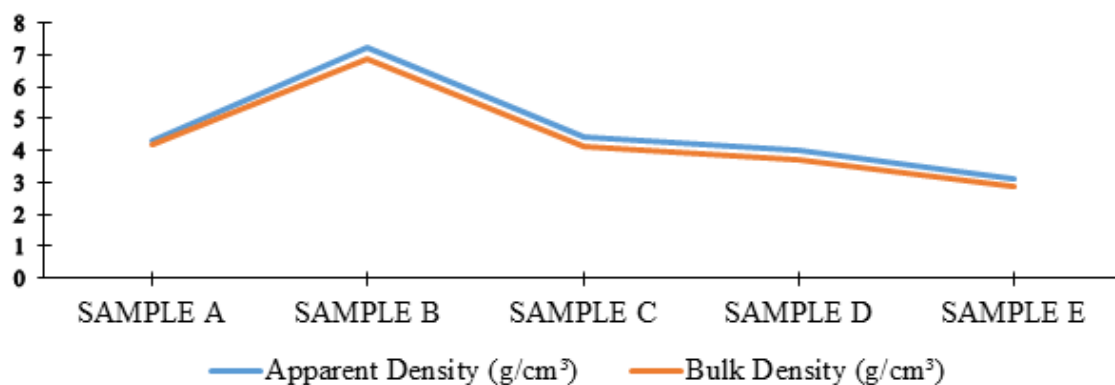


Figure 7: PBA porcelain insulator's apparent density and bulk density content

3.2 The insulators' electrical characteristics after PBA substitution

Table 8 shows that Samples A and C have the highest dielectric strength (9.0 kV/mm) and resistivity ($2.92 \times 10^{14} \Omega\cdot\text{m}$), indicating better insulation qualities than the other samples. These high numbers imply that Samples A and

C are especially well-suited for uses where strong electrical insulation is necessary. Their capacity to tolerate high voltages without breaking down is improved by Sample A's higher resistivity and dielectric strength (30%) and Sample C's 10%.

Palm Bunch Ash (PBA) content. Samples B, D, and E, on the other hand, offer adequate but marginally less effective insulation due to their lower resistivity values ($1.47\text{--}1.52 \times 10^{14} \Omega\text{-m}$) and dielectric strengths (7.7–7.8 kV/mm).

Therefore, Samples A and C's composition make them perfect for premium porcelain insulators where the highest level of insulation strength is essential.

Table 7: Apparent density and bulk density contents of porcelain samples

Property	Sample A	Sample B	Sample C	Sample D	Sample E
Apparent Density (g/cm ³)	4.28	7.25	4.44	4.00	3.13
Bulk Density (g/cm ³)	4.17	6.86	4.12	3.70	2.87

Table 8: Porcelain Insulator Resistivity and Dielectric Strength according to Formulation

Sample	Resistivity ($\Omega\text{-m}$) $\times 10^{14}$	Dielectric Strength (kV/mm)
A	2.92	9.0
B	1.52	7.8
C	2.92	9.0
D	1.47	7.7
E	1.47	7.7

4.0 Discussion of Findings

With the lowest porosity and water absorption, Sample A demonstrated the best physical attributes for porcelain insulators in terms of mechanical properties. The open-pore structures created by PBA are demonstrated by Samples B through E's increased porosity and water absorption with increasing PBA content. Increased silica from PBA enhances glassy phase formation up to 10%, explaining why Sample C matches control (A) in electrical performance. Beyond 10%, excess flux creates open pores, reducing density and insulation efficiency (Ismail et al., 2021). On the other hand, all samples showed a decrease in overall water absorption when the firing temperature was raised. This suggests that higher firing temperatures led to reduced porosity and improved vitrification, which is a widely accepted conclusion in ceramics research (Almeida et al., 2020). Sample A was the most compact and best suited for insulating because it had the lowest apparent porosity (3.00%) and a significant bulk density (1.77 g/cm³). On the

other hand, Sample E, which contained the most PBA, had the highest lowest apparent density (2.66 g/cm³), but because of its increased porosity, its bulk density dropped dramatically to 2.87 g/cm³. Higher porosity tends to lower the material's bulk density and reduce its mechanical integrity, a well-documented phenomenon in ceramic materials (Olugbade et al., 2018). Because of their improved balance and moderate porosity and density, samples B and C are suitable for use as high-voltage insulators. According to the electrical properties analysis, Samples A and C perform better as electrical insulators because they have the highest resistivity ($2.92 \times 10^{14} \Omega\text{-m}$) and dielectric strength (9.0 kV/mm). The optimal silica-to-flux ratio at 10% PBA explains Sample C performance. These findings are in line with those of Liu et al. (2019), who discovered that the chemical makeup and microstructure of porcelain insulators can have a substantial impact on their resistivity and dielectric strength.



Plate 1: Bisque-fired porcelain insulator prototype



Plate 2: Glaze-fired porcelain insulator with smooth glassy surface

However, Samples B, D, and E displayed somewhat reduced resistivity and dielectric strength, suggesting that these characteristics decline with increasing PBA content. Nonetheless, the dielectric strengths and resistivity values remained within reasonable bounds for insulation applications, indicating that these formulations might still be useful albeit marginally less effective substitutes (Wang *et al.*, 2020). According to a study on porcelain insulators that substitute Palm Bunch Ash (PBA), 5% is the ideal amount of PBA. It was discovered that Sample B, which contains 5% PBA, effectively balances increased mechanical strength and thermal stability without sacrificing the structural integrity of the insulator. By adding PBA at this moderate level, porcelain's mechanical qualities are improved while still being suitable for high-voltage insulation. Nevertheless, porosity and water absorption rates increase with increasing PBA content, as demonstrated in Samples C, D, and E, which lowers the overall insulation performance. Increased porosity brought on by higher PBA concentrations has an adverse effect on the material's compactness and structural cohesiveness. Consequently, Sample B seems to be the best formulation, providing good insulation performance while reducing the adverse effects of too much PBA.

5.0 Conclusion and Recommendations

5.1 Conclusion

This study demonstrated for the first time partial substitution of feldspar with Palm Bunch Ash

(PBA) at 5% yields porcelain insulators with comparable dielectric strength and resistivity to conventional materials, while reducing cost and environmental burden. This validates PBA as a viable flux substitute in sustainable ceramic production.

5.2 Recommendations

1. PBA should only be used in small amounts (5%) to maximize the trade-off between environmental advantages and mechanical strength, particularly in applications that call for high electrical insulation qualities.
2. To evaluate the durability and potential for more frequent replacements, more research should examine the long-term performance of insulators with higher PBA levels under actual conditions.
3. Alternative firing methods that might permit a higher PBA content without sacrificing the mechanical integrity of the porcelain insulators should be investigated.

Disclaimer

The products used in this study are mostly and extensively utilized in our country and field of study. There are no manufacturers of the products at all because our objective is to further knowledge rather than use them as a legal tool. Furthermore, rather than being funded by the production company, the research was funded by the authors themselves.

Competing Interests

The authors have stated that they have no conflicting interests.

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