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Valorization of Coconut Shell Ash as a Partial Quartz Substitute in Sustainable Ceramic Electrical Insulators

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Abstract

This study investigates using coconut shell ash (CSA) as a sustainable partial substitute for quartz in triaxial porcelain ceramic electrical insulators. Specimens made of ceramic with 5 wt.% CSA were produced and sintered at 1250 °C. The physical, mechanical, phase, microstructural, and electrical properties were assessed using ASTM standard methods, XRD, and SEM. Including CSA encouraged mullite formation, lowered leftover quartz, and improved densification via liquid-phase sintering. As a result, the CSA-reinforced ceramic showed reduced porosity and water absorption, greater bulk density, stronger mechanical properties, better insulation resistance, and a higher flashover voltage than the reference ceramic. The enhanced performance was directly attributed to the improved phase evolution and the dense, mullite-rich microstructure. These findings show that coconut shell ash is a viable, eco-friendly source of silica for producing high-performance ceramic electrical insulators that offer enhanced mechanical and dielectric properties.

Keywords: Coconut shell ash (CSA), Ceramic electrical insulator, Mullite, Flashover and Porosity

1. Introduction

Triaxial porcelain ceramics are commonly employed as insulating materials in electrical power transmission and distribution systems due to their superior dielectric strength, mechanical reliability, thermal stability, and resistance to chemical degradation. These ceramic insulators are typically made from clay, feldspar, and quartz, with each component contributing to the phase makeup, densification process, and final performance of the ceramic material. Clay ($Al_2Si_2O_5(OH)_4$) imparts plasticity for shaping, quartz (SiO_2) serves as a filler to preserve dimensional stability during firing, and feldspar ((K_xNa_{1-x})($AlSi_3O_8$)) acts as a flux to facilitate liquid-phase sintering and vitrification [1,2].During high-temperature sintering, these raw materials experience phase changes that result in the development of mullite and a glassy phasekey contributors to the superior mechanical and electrical characteristics of porcelain insulators

In recent years, growing environmental worries and the dwindling supply of natural mineral resources have spurred the creation of sustainable ceramic materials from industrial and agricultural waste. Coconut shells, among other agro-industrial residues, are produced in large volumes by the coconut processing industry. These wastes are often discarded via open burning or landfilling, leading to environmental pollution and the waste of valuable resources. Turning coconut shells into coconut shell ash (CSA) offers an effective way to repurpose waste, yielding a silica-rich substance suitable as a substitute ceramic raw material. Due to its high silica content, CSA has drawn significant attention for enhancing vitrification, phase transformation, and mullite formation in ceramic processing [3, 4].

Various silica-containing agricultural by products such as rice husk ash, bamboo leaf ash, sugarcane bagasse ash, palm oil fuel ash, and fly ashhave been studied as partial substitutes for traditional ceramic raw materials. These studies have shown that enhanced liquid-phase sintering and mullite formation lead to improved densification, mechanical strength, and thermal stability. In comparison to these agricultural wastes, coconut shell ash is plentiful, cost-effective, and has a silica composition well-suited for use in ceramics. However, its use as a partial substitute for quartz in ceramic electrical insulators has attracted little attention, especially concerning its effects on phase transformation, microstructure formation, and dielectric behaviour [5-6].

Using coconut shell ash aligns with the principles of sustainable manufacturing and the circular economy. Substituting part of natural quartz with CSA lowers the use of non-renewable minerals and at the same time turns agricultural waste into a useful engineering material. This method helps cut down on waste disposal, lowers environmental pollution, and encourages more efficient use of resources in ceramic manufacturing [7]. In addition, utilizing locally sourced agricultural waste can lower raw material expenses and aid in creating eco-friendly ceramic insulators for electrical uses.

Outdoor ceramic insulators designed for high voltage are constantly subjected to severe environmental factors such as humidity, dust, industrial contaminants, and salt exposure. These contaminants build up on the insulator surface, boosting leakage current and ultimately causing flashover and insulation failure Thus, enhancing the electrical insulation resistance and flashover performance of ceramic insulators is crucial for maintaining the long-term reliability and safety of electrical power transmission systems [8].

Though multiple studies have documented the use of agricultural waste in ceramic materials, most have concentrated on physical and mechanical characteristics, with scant focus on how phase evolution, microstructural refinement, and electrical insulation performance are interconnected [9-10]. In particular, detailed studies on how coconut shell ash contributes to mullite formation, lowers residual quartz, boosts densification, and enhances dielectric properties remain scarce. Therefore, establishing a clear link between structure and properties is crucial for creating high-performance ceramic electrical insulators from sustainable raw materials.

In this study, coconut shell ash (CSA) was used as a 5 wt.% substitute for quartz in making triaxial porcelain ceramic electrical insulators. The impact of CSA incorporation on physical properties, mechanical strength, phase evolution, microstructural development, insulation resistance, and dry power-frequency flashover voltage was studied in a systematic manner. Special attention was given to linking mullite formation, densification behavior, and microstructural changes to the resulting electrical and mechanical performance. The study shows that coconut shell ash is a viable, eco-friendly source of silica for creating high-performance ceramic electrical insulators that are well-suited for real-world power transmission and distribution uses.

2. Materials and Methods

2.1 Raw Materials

Clay, feldspar, and quartz industrial-grade ceramic raw materials were sourced from Oriental Ceramic Industry in Viruthachalam, Tamil Nadu, India. Coconut shells were gathered from local agricultural waste processing facilities and used as the silica-containing source material for producing coconut shell ash (CSA). The gathered shells were carefully washed to remove dust and surface contaminants, then air-dried to ensure all moisture was eliminated [11-12]. Initially, the dried coconut shells were burned under controlled conditions to produce ash, which was then calcined at 650 °C for three hours, heated at a rate of 300 °C per hour, to eliminate any remaining carbon and enhance the crystallinity of the silica-rich ash. The calcined CSA was ground to a fine consistency and sieved to produce a uniform powder appropriate for ceramic applications.

The X-ray fluorescence (XRF) analysis was used to determine the chemical compositions of quartz and CSA, with the findings shown in Table 1. The CSA had a high silica content (73.75 wt.%), along with small amounts of K_2O, Fe_2O_3, Na_2O, CaO, MgO, and Al_2O_3. Its elevated silica level, combined with the presence of fluxing oxides, makes CSA a suitable alternative silica source that can enhance liquid-phase sintering and mullite formation in ceramic processing. The use of agricultural waste as a partial replacement for natural quartz represents a sustainable approach for producing environmentally friendly ceramic electrical insulators.

Table 1. Chemical Composition of Quartz and CSA (wt%)

Composition	SiO_2	Al_2O_3	K_2O	Fe_2O_3	Na_2O	TiO_2	CaO	MgO	Others
Quartz	97.55	0.97	0.41	0.27	0.35	0.04	0.23	0.08	0.10
CSA	73.75	0.48	7.98	6.16	4.12	0.08	2.52	1.63	3.26

2.2 Fabrication of Ceramic Insulators

To produce the standard ceramic insulator (RC), a conventional ternary ceramic blend consisting of 60% clay, 25% feldspar, and 15% quartz was employed. In the case of the composite ceramic insulator (CSC), 5 wt% calcined coconut shell ash was incorporated to replace quartz. To ensure a uniform mixture and fine particle dispersion, each composition's raw components were individually subjected to wet ball milling for 12 hours. Water was introduced continuously during milling to create a consistent slurry. The prepared slurry was subjected to filter pressing to eliminate excess water and yield a plastic, moldable ceramic mass [13]. The ceramic material was kept at a moisture content of 4% to 6%. Following molding, the samples were air-dried for 48 hours to eliminate any remaining moisture; afterward, the dried green bodies were sintered in a high-temperature furnace under controlled heating at 1250 °C. After sintering, the ceramic samples underwent testing for mechanical, electrical, phase, microstructural, and physical properties [14].

2.3 Characterization Techniques

The physical properties of the sintered ceramic insulators were measured in compliance with ASTM C373-88. Linear shrinkage (LS), apparent porosity (P), water absorption (WA), and bulk density (BD) were assessed via the Archimedes method. The compressive strength (CS) was determined using a Universal Testing Machine (UTM).

The crystalline phases and their changes following sintering were analyzed via X-ray diffraction (XRD, D/ Max ULTIMA) using Cu-Kα radiation. XRD analysis was conducted to detect quartz and mullite phases and to assess how CSA affects phase transformation during sintering.

The fracture surfaces were analyzed for their microstructural features using Scanning Electron Microscopy (SEM, JEOL JSM-5610LV). SEM observations were employed to assess grain morphology, pore distribution, grain bonding, and mullite crystal formation, facilitating links between microstructural changes and the physical, mechanical, and electrical properties of the ceramic insulators.

The electrical properties were assessed by measuring insulation resistance with a 5000 V DC insulation resistance tester and the dry power-frequency flashover voltage in accordance with ASTM D149, under standard laboratory conditions. These measurements were conducted to evaluate the dielectric performance of the manufactured ceramic insulators and to determine how microstructural densification, phase development, and electrical insulation behavior are interconnected.

3. Results and Discussion

3.1 Physical and Mechanical Properties

The physical and mechanical properties of the reference ceramic (RC) and coconut shell ash reinforced ceramic insulator (CSC) are presented in Table 2.

Table 2. Physical and Mechanical Properties of Ceramic Insulators

Specimen	Shrinkage (%)	P (%)	P (%)	WA (%)	BD (g/cm³)	MS (MPa)
RC	5.410	1.405	1.405	0.678	2.050	2.480
CSC	7.550	1.201	1.201	0.589	2.062	3.050

Adding 5 wt.% coconut shell ash (CSA) had a notable effect on the sintering behavior and densification of the ceramic electrical insulator. The CSC sample showed a lower apparent porosity (1.201%) compared to the reference ceramic (1.405%), suggesting that the silica-rich CSA enhanced liquid-phase sintering and led to better particle packing during firing. As a result, water absorption dropped from 0.678% to 0.589%, indicating that a denser and less permeable ceramic structure had formed [15-16].

The improved densification is additionally backed by the small rise in bulk density from 2.050 g/ cm³ for the RC specimen to 2.062 g/ cm³ for the CSC specimen. During sintering, the reactive silica in CSA contributed to vitrification and mullite formation, resulting in a dense microstructure with fewer interconnected pores. Linear shrinkage rose from 5.410% to 7.550%, due to better particle diffusion and greater consolidation within the ceramic matrix. The measured shrinkage stayed within the acceptable limits for porcelain insulator manufacturing and did not result in any visible flaws or dimensional instability [17-18].

The mechanical strength rose from 2.48 MPa in the RC specimen to 3.05 MPa in the CSC specimen, marking an increase of about 23%. This improvement is linked to decreased porosity, stronger grain bonding, and the development of reinforcing mullite crystals during the sintering process. The dense microstructure successfully minimized crack initiation points and limited crack spread during compressive loading, thereby enhancing structural integrity. These observations show a clear link among microstructural refinement, mullite formation, and the improved physical and mechanical properties of the CSA-reinforced ceramic insulator.

Overall, the results show that 5 wt.% CSA serves as an effective partial substitute for quartz, enhancing densification, mechanical reliability, and microstructural stability while maintaining the processing properties of the ceramic insulator. The enhanced performance underscores the promise of coconut shell ash as a sustainable, silica-rich raw material suitable for advanced electrical insulation uses.

3.2 XRD Phase Analysis

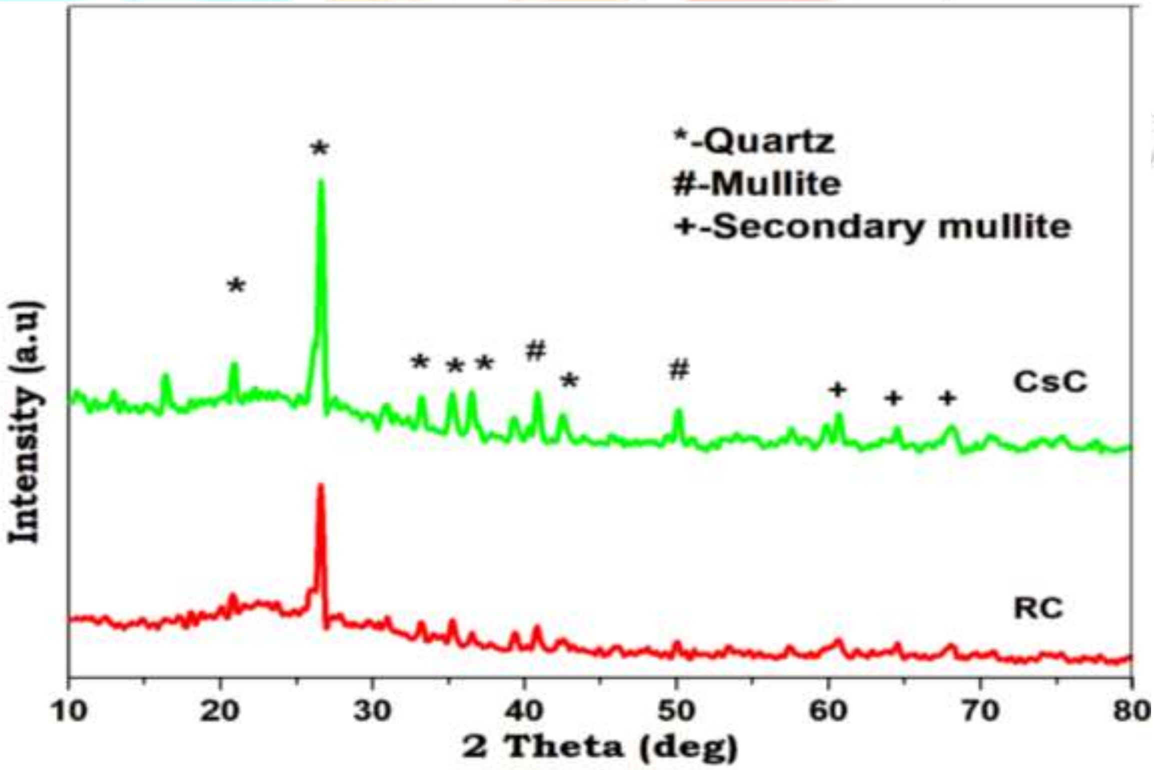

Fig.1. XRD Patterns of Experimental Insualtors

Figure 1 shows the X-ray diffraction (XRD) patterns of the reference ceramic (RC) and the coconut shell ash-reinforced ceramic (CSC), both sintered at 1250 °C. Both samples primarily consisted of quartz (SiO_2) and mullite ($3Al_2O_3 \cdot 2SiO_2$) as their main crystalline components. The RC specimen exhibited a prominent quartz diffraction peak at $2\theta \approx 26.6°$ (011), suggesting the persistence of unreacted free silica following the sintering process. By contrast, the CSC sample showed weaker quartz peaks and stronger mullite diffraction peaks at $2\theta \approx 40.8°$, 50.2°, 54.0°, and 60.6°, indicating greater mullite formation. The silica-rich CSA provided reactive silica that took part in the high-temperature reaction

[($3Al_2O_3+2SiO_2$)→($3Al_2O_3•2SiO_2$(Mullite)], aiding the transformation of free quartz into mullite during sintering.

The development of secondary mullite enhanced ceramic densification and lowered the amount of residual quartz. Because mullite has high thermal stability, low thermal expansion, and strong mechanical rigidity, its greater formation improved the structural integrity of the ceramic body. Additionally, the alkali oxides in CSA enhanced liquid-phase sintering, which supported atomic diffusion and grain reorganization. As a result, the CSC specimen showed better phase development, leading directly to reduced porosity, higher bulk density, greater mechanical strength, improved insulation resistance, and a higher flashover voltage [19-21].

3.3 Morphological Analysis

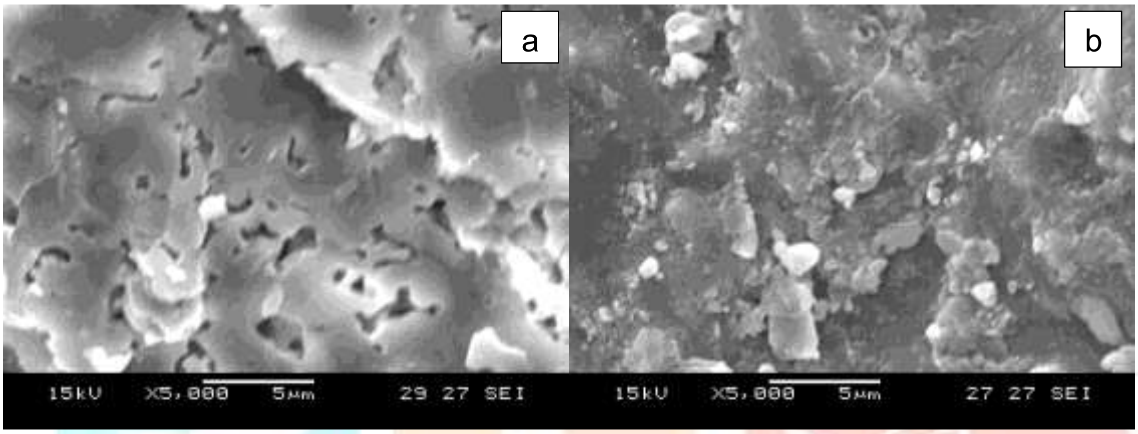

Fig.2. SEM Photograph (a) RC and (b) CSC of the Reinforced Insulators

Figure 2 shows the SEM micrographs of the fracture surfaces of the RC and CSC specimens sintered at 1250 °C. The RC specimen showed a relatively coarse microstructure featuring irregularly shaped quartz grains, many interconnected pores, and poor grain bonding, suggesting incomplete densification. These structural flaws serve as starting points for cracks and enhance moisture ingress, which in turn diminishes both mechanical strength and dielectric performance. By contrast, the CSC specimen exhibited a dense and uniform microstructure with considerably fewer pores, attributed to improved liquid-phase sintering [22-23].

The addition of CSA led to better particle packing and enhanced grain-to-grain bonding during firing. Fine, interlocking mullite crystals were evenly dispersed throughout the glassy matrix, creating a reinforcing structure that successfully slowed crack growth and improved resistance to fracture. The glassy phase occupied the spaces between grains, resulting in a denser ceramic with fewer pores and higher density. This refined microstructure limited moisture uptake and reduced leakage current paths, leading to greater insulation resistance and enhanced flashover voltage. Thus, the SEM observations strongly corroborate the XRD findings, confirming that CSA enhances mullite formation, microstructural densification, and improved mechanical and electrical performance of the fabricated ceramic electrical insulators [24].

3.4 Electrical Properties

3.4.1 Insulation Resistance

Measurements of insulation resistance at 5000 V DC showed a clear enhancement in the electrical performance of the ceramic insulators after incorporating coconut shell ash (CSA). In comparison to the reference ceramic (RC) sample, which had an insulation resistance of 12.8 GΩ, the CSA-incorporated ceramic (CSC) sample showed a higher insulation resistance of 22.3 GΩ [25]. This improvement is due to the creation of a denser ceramic microstructure with less interconnected porosity. The movement of charge carriers through the ceramic material is limited, and moisture uptake is reduced because of the lower porosity.

Moreover, the sintering process promoted the development of more mullite and glassy phases, which improved insulation stability. These findings show that integrating CSA into ceramics intended for high-voltage applications effectively enhances their insulation performance [26].

3.4.2 Dry Power-Frequency Flashover Voltage

The dry power-frequency flashover test was performed using a 50 Hz AC power source under standard laboratory conditions. The RC specimen had a flashover voltage of 8.65 kV/mm, whereas the CSC specimen reached a higher value of 9.87 kV/mm [1]. The enhanced dielectric withstand capability is linked to the compact microstructure formed following CSA incorporation. Reducing surface pores and structural flaws helped lessen localized electric field concentration, thus postponing the onset of surface discharge. Moreover, the interlocking mullite crystals and the well-formed glassy phase improved dielectric stability and electrical breakdown resistance. The observed improvement shows that the CSA-reinforced ceramic insulator has better flashover performance and is appropriate for medium-voltage electrical insulation applications [27-28].

3.4.3 Mechanical performance

The mechanical strength of the ceramic insulators rose from 2.48 MPa in the RC specimen to 3.05 MPa in the CSC specimen. This improvement is strongly tied to the decrease in porosity and the greater densification attained during sintering. The development of interlocking mullite crystals enhanced the ceramic matrix by improving bonding between grains, enabling a more even distribution of applied load across the material. By contrast, the RC specimen had more interconnected pores, which served as stress concentration points, facilitating crack initiation and growth. As a result, the CSC sample showed greater resistance to fracture and improved structural strength, indicating that adding CSA substantially enhances the mechanical reliability of ceramic electrical insulators.

4. Conclusion

Ceramic electrical insulators containing 5 wt.% coconut shell ash (CSA) were successfully fabricated and evaluated. The addition of CSA promoted liquid-phase sintering, resulting in reduced porosity, lower water absorption, higher bulk density, and improved mechanical strength compared with the reference ceramic. XRD analysis confirmed enhanced mullite formation and a reduction in residual quartz, while SEM observations revealed a dense microstructure with improved grain bonding and interlocking mullite crystals. These microstructural modifications directly contributed to the enhanced insulation resistance **(**22.3 GΩ**)** and dry flashover voltage **(**9.87 kV/mm**)** of the CSA-reinforced ceramic insulator. Furthermore, the utilization of coconut shell ash as a partial quartz replacement offers a sustainable and cost-effective approach for producing high-performance ceramic insulators while reducing agricultural waste and conserving natural resources. Therefore, CSA is a promising alternative silica source for the development of environmentally friendly ceramic electrical insulation materials suitable for practical engineering applications.

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Graphical Abstract