Analysis of Corn Cob as Biosilica: Frequency-Dependent Electrical and Dielectric Properties for Sustainable Functional Material Applications

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Abstract

Corn cob as biosilica is an abundant agricultural waste that remains underutilized despite its potential as a sustainable biomass-based functional material using the sol-gel method. This study investigated the DC conductivity and dielectric properties of corn cob using electrochemical impedance spectroscopy (EIS). The electrical response was analyzed through frequency-dependent conductivity, dielectric constant, dielectric loss, loss tangent, and Nyquist plots. The results showed that the DC conductivity increased with increasing frequency, ranging from 2.8×10^{-5} to 1.8×10^{-4} S/cm, indicating enhanced charge transport at higher frequencies. In contrast, the dielectric constant decreased from 3.0×10^{3} at low frequency toward a negligible value at higher frequencies, indicating reduced interfacial polarisation. The dielectric loss also decreased from approximately 6.8×10^{3}, suggesting lower energy dissipation as the frequency increased. The loss tangent decreased from y 2.2 to 2.0, then increased and decreased again at higher frequencies, indicating frequency-dependent dielectric relaxation. The Nyquist response exhibited both resistive and capacitive characteristics, confirming charge transport and polarisation processes within the corn cob structure. Overall, the DC conductivity and dielectric responses demonstrate the potential of corn cob as a biosilica material for dielectric components, polymer-composite fillers, sensing applications, and precursors for carbon-based functional materials.

Keywords: Corn cob as biosilica; DC Conductivity; Constant and Loss Dielectric; Loss Tangent; Nyquist Plot;

I. INTRODUCTION

The growing generation of agricultural waste has encouraged the development of sustainable strategies to convert biomass residues into value-added functional materials. Corn cob is an abundant agricultural residue that remains underutilized and can become an environmental burden when it is discarded or burned. Chemically, corn cob is a lignocellulosic biomass consisting mainly of cellulose, hemicellulose, and lignin, together with inorganic components containing silicon. Recent studies have confirmed the lignocellulosic nature of corn cob and demonstrated that its chemical composition provides a suitable basis for further conversion into value-added materials (Wu et al., 2021; Xu et al., 2021). In addition, the presence of silica-containing inorganic fractions makes corn cob a promising renewable precursor for silica-based materials (Al Hijri et al., 2022; Prempeh et al., 2021). (Goswami & Mathur, 2022) demonstrated that agricultural wastes, including corn cob, can serve as raw materials for producing silica nanoparticles, confirming corn cob's potential as a sustainable silica source. Therefore, converting corn cob into biosilica can provide an alternative route for agricultural-waste valorization while reducing dependence on conventional mineral-based silica resources.

Previous studies have demonstrated the feasibility of extracting silica from corn cob through thermal treatment, chemical pretreatment, and sol-gel processes. Several studies on

agricultural residues, including corncob, have shown that chemical pretreatment followed by combustion could produce silica-rich ash. In their study, acid pretreatment significantly reduced metallic impurities and enhanced the silica fraction, while corncob-derived ash contained approximately 85 wt.% SiO_2 and exhibited a predominantly amorphous structure. This finding confirms that corn cob can serve as a viable precursor for biogenic silica production. The extraction of silica from corn cob waste using a sol-gel method was confirmed by FTIR, XRF, and XRD analyses (Al Hijri et al., 2022). The extracted silica was subsequently used to fabricate silica thin films for anti-reflective coating applications, demonstrating the potential of corn-cob-derived silica as a functional material. In another study, successfully synthesized mesoporous SBA-16 from corn cob ash and reported well-ordered porous structures with high adsorption performance (Dhaneswara et al., 2022). Their findings demonstrate that corn cob ash can be transformed into structured silica materials with controllable pore characteristics and functional properties. A broader study also reported corn cob as an agricultural feedstock that can produce amorphous biobased silica through sol-gel processing (Tessema et al., 2023). Silica nanoparticles derived from solid wastes and identified agricultural residues such as corn cob, rice husk, and sugarcane bagasse are promising alternative silica sources (Malpani & Goyal, 2023). These studies establish that corn cob is a viable precursor for producing silica with useful structural and surface characteristics. However, most previous investigations have focused mainly on silica extraction, chemical composition, morphology, crystallinity, surface characteristics, and optical or adsorption-related applications rather than the frequency-dependent electrical and dielectric behavior of the resulting biosilica.

The conversion of agricultural waste into silica-based functional materials has also been demonstrated using other biomass sources. Silica-derived materials produced from agro-industrial residues showed that the characteristics of biosilica were strongly associated with the original biomass structure and processing conditions (Morales-Paredes et al., 2023). Their results demonstrated that agricultural residues can generate silica materials with different crystallinity, surface area, and structural characteristics depending on the precursor and treatment route. These findings matter because the structural characteristics of biomass-derived silica can influence its subsequent functional properties. Furthermore, recent studies on rice-husk-derived silica have demonstrated that different synthesis routes, including calcination and sol-gel processes, can significantly influence the particle size, morphology, chemical composition, and structural characteristics of the resulting silica nanoparticles (Yuan et al., 2024). These observations indicate that processing history and structural properties should be considered when evaluating the functional behavior of biosilica.

Electrical characterization is important because the dielectric and conductive responses of silica-based materials provide information about charge transport, polarisation, interfacial effects, and relaxation mechanisms. Electrochemical impedance spectroscopy (EIS) is particularly useful for evaluating these properties because it enables analysis of a material's frequency-dependent response through its real and imaginary impedance components. highlighted the broad applicability of EIS for investigating electrochemical and interfacial processes, including interpreting impedance spectra through appropriate physical models (Brett, 2022). EIS has also been applied to silica-containing materials to investigate charge-transfer and electron-transport behavior, demonstrating that impedance responses can be related to the structural and interfacial characteristics of silica-based systems (Haekal & Risanti, 2023). Therefore, EIS provides a suitable approach for investigating the electrical response of biomass-derived biosilica over a broad frequency range.

The electrical and dielectric properties of biomass-derived silicate materials have recently received increasing attention. Researchers have evaluated the physical, dielectric, and electrical properties of biogenic calcium silicate glasses produced from biomass (Karmakar et al., 2026). Their results demonstrated measurable frequency-dependent AC conductivity

and dielectric permittivity, with the electrical response being associated with structural features and charge-carrier hopping mechanisms. Biogenic silicate glass-ceramics derived from biomass exhibited frequency- and temperature-dependent dielectric behavior, while the reduction in impedance at higher frequencies was associated with charge-carrier transport (Malpani & Goyal, 2023). These studies show that biomass-derived silicate materials are not only structurally interesting but can also exhibit measurable electrical and dielectric responses useful for functional-material applications. However, these studies primarily investigated biogenic silicate glasses or glass-ceramics produced through high-temperature processing rather than non-carbonized biosilica obtained directly from corn cob through a sol-gel route. The frequency dependence of electrical conductivity in disordered, amorphous, and heterogeneous materials can be described using the universal power-law behavior commonly associated with Jonscher's model. Recent studies have continued to apply this approach to describe AC conductivity and dielectric relaxation in functional materials (AlFannakh & Ibrahim, 2022). Investigations of dielectric materials have demonstrated that the frequency-dependent conductivity can provide information about charge-carrier transport, hopping mechanisms, and dielectric relaxation processes (Karmakar et al., 2026; Malpani & Goyal, 2023).

Recent research has also demonstrated the broader potential of corn cob as a precursor for functional electrochemical materials (Xie et al., 2023). The resulting corn-cob-derived carbon exhibited favorable electrochemical performance, demonstrating that agricultural residues can be transformed into functional materials for energy-related applications. In addition, the potential of corn cob combined with silica aerogel for developing bio-based functional insulation materials highlights corn cob's compatibility with silica-based functional systems (Goswami & Mathur, 2022). However, this approach involves carbonization and chemical activation, resulting in a carbon-based material whose electrical properties and charge-transport mechanisms differ fundamentally from silica obtained through sol-gel processing. Consequently, the electrical response of non-carbonized corn cob as biosilica remains relatively unexplored.

This study therefore addresses the limited investigation of the frequency-dependent electrical conductivity and dielectric properties of corn cob as a biosilica using EIS, particularly in relation to its chemical structure. This work's novelty lies in correlating the functional groups identified by FTIR with the frequency-dependent electrical and dielectric responses of the resulting biosilica. The electrical characteristics are evaluated through AC and DC conductivity, dielectric constant, dielectric loss, loss tangent, and Nyquist response over a broad frequency range. This approach provides a more comprehensive understanding of the electrical behavior of biomass-derived silica beyond conventional structural characterization. The study aims to analyze the electrical and dielectric responses of corn cob as a biosilica over a broad frequency range and evaluate its potential as a sustainable functional material for dielectric, sensing, composite, and other electronic or energy-related applications.

II. METHOD

The research used a sequential extraction and purification process to obtain biosilica from corn cob waste, followed by electrical characterization using electrochemical impedance spectroscopy (EIS). The overall procedure included preliminary washing, acid treatment, alkaline extraction, silica precipitation, drying, and electrical characterization. The experimental design was developed to remove soluble impurities and organic or mineral components from the raw material before converting the remaining silica-containing fraction into a functional biosilica powder. The process began by preparing corn cob ash as the primary raw material (Figure 1). The ash was mixed with distilled water (aquades) and magnetically stirred at 750 rpm and 100 °C. This initial washing process was intended to

remove water-soluble impurities and residual substances from the ash. After stirring, the suspension was filtered to obtain the solid fraction. The filtered material was subsequently dried in an oven at 100 °C for 1 h to remove residual moisture and obtain a dried intermediate material. Using washing and drying as an initial pretreatment step is consistent with previous studies showing that purifying corn-cob-derived ash is important before silica extraction. Corn cob ash contains a substantial silica fraction together with other mineral components; therefore, pretreatment can improve the effectiveness of subsequent extraction processes (Prempeh et al., 2021; Wu et al., 2021; Xu et al., 2021).

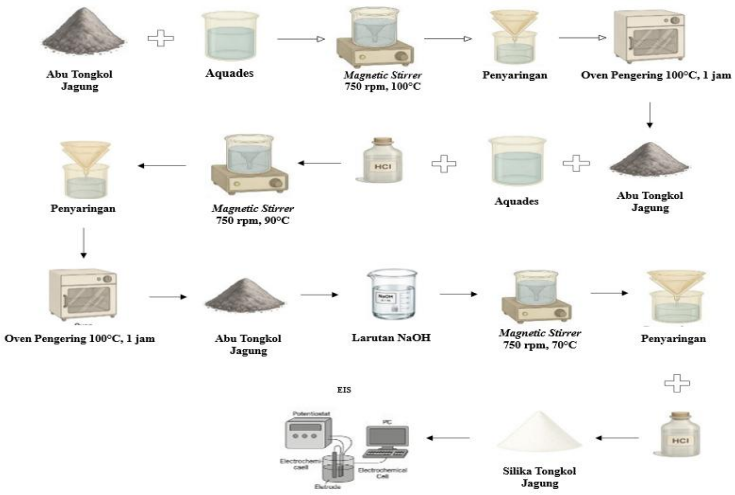


Figure 1 Research Design

The dried intermediate material was then acid-treated with hydrochloric acid (HCl) and distilled water. The mixture was stirred at 750 rpm and 90 °C. Acid treatment was used as a leaching process to reduce metallic and other inorganic impurities that may remain in the corn cob ash. After the treatment, the suspension was filtered to separate the solid fraction from the liquid phase containing dissolved impurities. The resulting solid was again dried at 100 °C for 1 h. Acid leaching is an established approach for improving the silica content of agricultural ash because acidic treatment can dissolve several metal oxides while leaving the silica-rich fraction relatively resistant under controlled conditions (Al Hijri et al., 2022; Wu et al., 2021). Following acid pretreatment, the dried material was subjected to alkaline extraction using sodium hydroxide (NaOH). The mixture was magnetically stirred at 750 rpm and 70 °C. During this stage, the silica-containing components in the treated ash reacted with NaOH and were converted into soluble silicate species. The alkaline extraction therefore separates silica from the remaining insoluble fraction and produces a silicate-containing solution. This principle is consistent with the sol–gel extraction route previously reported for corn-cob-derived silica, in which silica is dissolved under alkaline conditions before being recovered through acidification (Brett, 2022; Tessema et al., 2023). After alkaline extraction, the mixture was filtered to remove insoluble residues. The resulting filtrate, containing soluble silicate species, was subsequently treated with HCl. Acidification converts soluble silicate into silicic acid species, followed by condensation reactions that form Si–O–Si bonds and eventually produce a silica gel. The resulting silica-containing material was then separated and dried to obtain the final corn-cob-derived biosilica powder in Figure 2.



Figure 2 Corn Cob as Biosilica

FTIR analysis of silica obtained from corn cob ash has previously confirmed the formation of siloxane and silanol groups through this alkaline extraction–acid precipitation route (Brett, 2022; Tessema et al., 2023). The synthesized biosilica was then electrically characterized using electrochemical impedance spectroscopy. The biosilica sample was placed between the electrodes of the EIS measurement system, and its impedance response was recorded over the investigated frequency range. The impedance data were used to evaluate the material's frequency-dependent electrical and dielectric properties, including electrical conductivity, dielectric constant, dielectric loss, loss tangent, and Nyquist response. EIS was selected because it separates and analyses resistive, capacitive, polarisation, and relaxation contributions in functional materials. The resulting electrical properties were then correlated with the chemical characteristics identified by FTIR to evaluate the relationship between the silica structure and its frequency-dependent electrical response. The research design combines chemical extraction and electrical characterization to transform corn cob waste into a value-added biosilica material. The sequential washing, acid leaching, alkaline extraction, acid precipitation, and drying processes were designed to obtain a silica-rich powder suitable for subsequent characterization. The final EIS analysis provides an additional perspective beyond conventional structural characterization and allows evaluation of corn-cob-derived biosilica as a sustainable functional material based on its electrical and dielectric behavior.

III. RESULTS AND DISCUSSIONS

A. RESULT

The FTIR spectrum of the sample shows several characteristic absorption bands across the mid-infrared region, indicating multiple vibrational environments in the initial material, as shown in Figure 3.

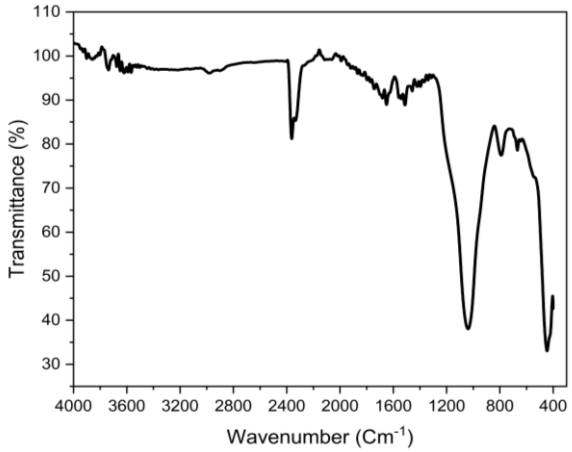
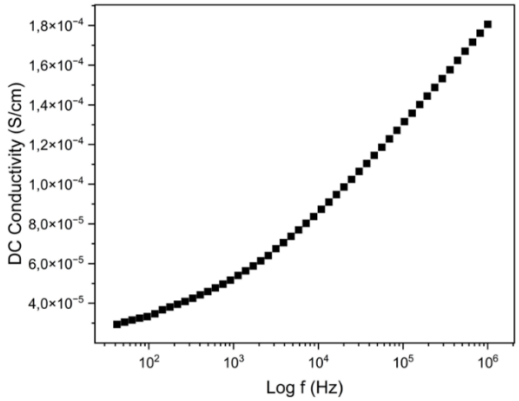


Figure 3. FTIR spectra for the corn cob as biosilica

Figure 3 presents the Fourier transform infrared (FTIR) spectrum of the corn cob sample, providing information on the functional groups and chemical constituents present in the lignocellulosic structure. Corn cob is a lignocellulosic biomass mainly composed of cellulose, hemicellulose, and lignin, although their relative contents may vary by anatomical part of the cob and biomass origin. Therefore, the FTIR spectrum can be used as an initial fingerprint to identify the major chemical bonds associated with these components. Previous studies have demonstrated that FTIR analysis is particularly useful for monitoring the structural characteristics and chemical changes of corn cob before and after physical or chemical treatment (Stachowiak-Wencek et al., 2019; Gandam et al., 2022).

The frequency-dependent electrical conductivity of the corn-cob-derived silica increases continuously over the investigated frequency range. The absence of a frequency-independent plateau suggests that the measured conductivity is strongly influenced by dispersive charge transport rather than governed exclusively by long-range DC conduction (Figure 4). The gradual increase at low and intermediate frequencies can be associated with localized charge carriers and interfacial polarisation, whereas the more pronounced increase above approximately 10^4 Hz indicates enhanced carrier hopping and/or short-range charge displacement under the alternating electric field. Such behavior is commonly described by the frequency-dependent conductivity of disordered or heterogeneous materials, in which charge carriers are constrained by localized states and interparticle interfaces.



Gambar 4. DC Conductivity for the corn cob as biosilica

The gradual increase at low and intermediate frequencies can be associated with localized charge carriers and interfacial polarisation, whereas the more pronounced increase above approximately 10^4 Hz indicates enhanced carrier hopping and/or short-range charge displacement under the alternating electric field. This behavior is commonly described by the frequency-dependent conductivity of disordered or heterogeneous materials, where charge carriers are constrained by localized states and interparticle interfaces.

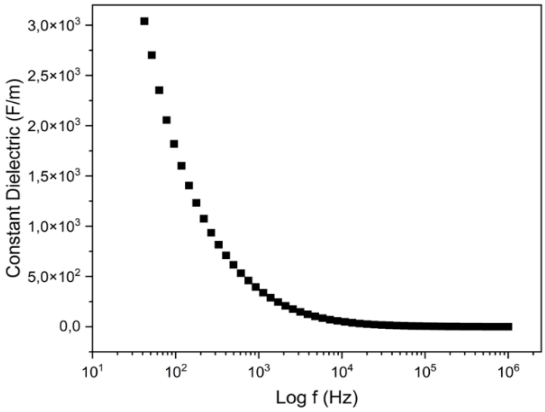


Figure 5. The dielectric constant of the corn cob as biosilica

Figure 5 shows that the dielectric constant exhibits pronounced frequency dispersion, decreasing sharply from approximately 3.0 x 103 at low frequency to a very small value at high frequency. At low frequencies, charge carriers have time to migrate and accumulate at interfaces, grain boundaries, particle–particle contacts, or electrode/sample interfaces, increasing the apparent permittivity. As frequency increases, the applied electric field reverses more rapidly, progressively restricting the displacement of slower charge carriers. Consequently, interfacial polarisation becomes less effective, and the dielectric response decreases substantially.

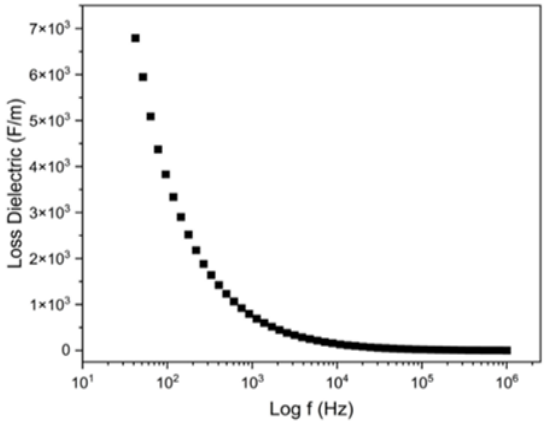


Figure 6 The dielectric loss of the corn cob as biosilica

The dielectric loss decreases markedly with increasing frequency, from a high value at low frequency to nearly zero at the highest frequency, as shown in Figure 6. The large low-frequency dielectric loss indicates substantial energy dissipation associated with charge migration, interfacial charge accumulation, and polarisation relaxation. As the frequency increases, the contribution of slowly responding charge carriers to the polarisation process becomes progressively suppressed, resulting in a substantial reduction in dielectric loss. The concurrent decrease in both dielectric constant and dielectric loss therefore indicates that the dominant low-frequency response originates from space-charge and interfacial polarisation rather than from purely intrinsic dipolar polarisation.

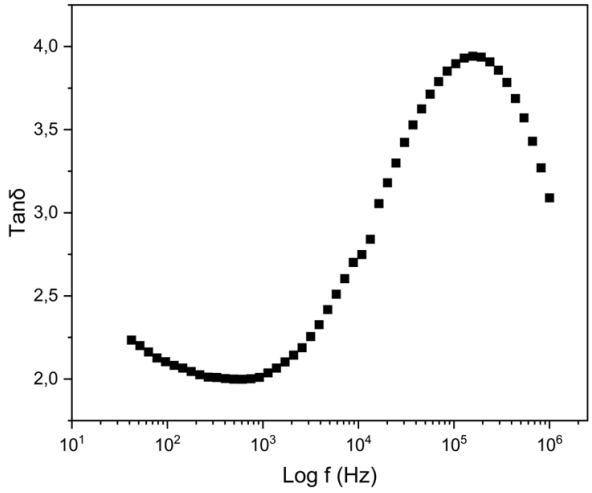


Figure 7 The loss tangent of the corn cob as biosilica

Figure 7 shows that the loss tangent (tan δ) displays a non-monotonic frequency dependence. The loss tangent decreases initially in the low-frequency region. The emergence of a broad maximum suggests a characteristic dielectric relaxation process associated with charge-carrier redistribution or hopping within heterogeneous regions of the material. The subsequent decrease at the highest frequencies indicates that the charge carriers cannot fully follow the rapidly

alternating electric field. The relatively high magnitude of tan δ shows that energy dissipation through conduction and relaxation processes contributes substantially to the sample's dielectric response.

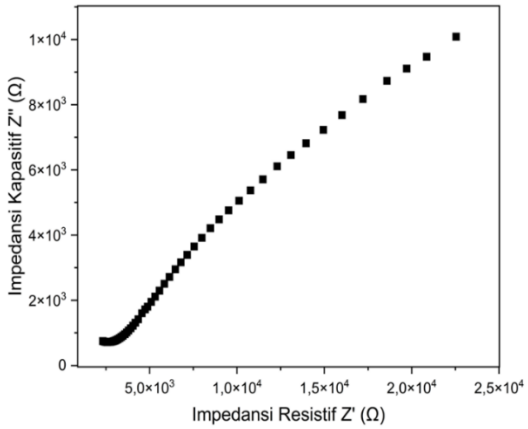


Figure 8 The Nyquist plot of the corn cob as biosilica

Figure 8 depicts that the Nyquist representation exhibits a strongly non-ideal impedance response characterized by a small curved feature at low Z', followed by an approximately linear increase of Z'' with Z'. The absence of a well-resolved semicircular arc suggests that a single ideal parallel RC relaxation cannot describe the material's electrical response. Instead, the impedance behavior is consistent with a distributed relaxation process involving heterogeneous charge transport, interfacial polarisation, and non-ideal capacitive behavior. The inclined low-frequency impedance component may reflect electrode polarisation and diffusion-related charge accumulation, whereas the higher-frequency region reflects the intrinsic response of the silica-containing particulate network.

B. DISCUSSION

This research successfully synthesized corn cob powder as bio-silica. FTIR characterization shows changes in functional groups, indicating interactions between O and Si groups that strengthen molecular interactions and increase the potential for ion-conductive pathways (Figure 3). The spectrum shows a weak and broad absorption band in the region of approximately 3400–3500 cm^{-1}. This band is primarily attributed to O–H stretching vibrations associated with hydroxyl groups in cellulose, hemicellulose, and lignin. The broad shape of this absorption is related to hydrogen bonding between hydroxyl groups and may also be influenced by physically adsorbed moisture on the biomass surface. Similar absorption in the 3400–3500 cm^{-1} region has been reported for raw corn cob and other lignocellulosic materials. In particular, hydroxyl groups are closely related to the polysaccharide structure of cellulose and hemicellulose, which contain abundant hydrogen-bonded –OH groups (Stachowiak-Wencek et al., 2019; Baker and Oguntoye, 2023). A weak absorption around 2350 cm^{-1} is also observed in the spectrum. This band should be interpreted cautiously because absorption near this wavenumber is commonly associated with atmospheric CO_2 rather than being a characteristic functional group of the corn cob itself. Atmospheric CO_2 can interact with the infrared beam during measurement and produce a band around this region. Therefore, this absorption should not be considered direct evidence of a specific chemical component in the sample. This is important in FTIR analysis because environmental contributions and residual compounds may produce additional spectral features not necessarily related to the intrinsic chemical structure of biomass (Zhuang et al., 2020). The region around 2,900 cm^{-1} is generally associated with C–

H stretching vibrations of aliphatic groups present in cellulose, hemicellulose, and lignin. Although this absorption may appear relatively weak compared with the dominant bands in the fingerprint region, it provides additional evidence for organic lignocellulosic structures in corn cob. Previous FTIR studies of corn cob have reported C–H stretching bands around 2890–2925 cm^{-1}, which are attributed to aliphatic moieties in cellulose and lignin (Stachowiak-Wencek et al., 2019).

In the region between approximately 1600 and 1650 cm^{-1}, the absorption can be associated with O–H bending vibrations of absorbed water. However, this region may also contain contributions from other structural vibrations, particularly aromatic skeletal vibrations associated with lignin. Therefore, assign this band by considering the overall spectral pattern rather than relying on a single peak. In lignocellulosic biomass, absorption near 1618 cm^{-1} has been reported to involve aromatic skeletal vibrations, C=O-related contributions, and adsorbed O–H, while a band around 1508 cm^{-1} is commonly associated with C=C–C aromatic skeletal vibrations of lignin (Zhuang et al., 2020). The absorption region around 1450–1500 cm^{-1} can also be attributed to C–H deformation vibrations and aromatic skeletal vibrations in lignin. In particular, lignin-related aromatic structures may contribute to absorption around 1500–1510 cm^{-1}. The presence and intensity of these bands can provide qualitative information regarding the lignin fraction of the biomass. Corn cob has a heterogeneous lignocellulosic structure, and differences between the outer portion and pith can influence the relative intensity of lignin- and carbohydrate-related FTIR bands (Gandam et al., 2022). The most pronounced absorption in the spectrum occurs in the fingerprint region around 1050–1100 cm^{-1}. This region is particularly important for identifying the polysaccharide structure of corn cob because it mainly reflects C–O and C–O–C stretching vibrations of cellulose and hemicellulose. Studies on corn cob-derived cellulose have reported characteristic absorptions near 1026–1033 cm^{-1}, which are assigned to C–O–C skeletal vibrations of the pyranose ring. Other studies have similarly identified bands around 1050 cm^{-1} as C–OH stretching and C–O deformation vibrations associated with lignocellulosic components (Baker and Oguntoye, 2023; Zhuang et al., 2020).

Additional absorptions below 900 cm^{-1} can be associated with deformation and skeletal vibrations of the carbohydrate structure. A band near 850–900 cm^{-1} is particularly relevant to cellulose because it may be related to C–O–C vibrations and structural features of the glycosidic linkage. Corn cob-derived microcrystalline cellulose has been reported to show a characteristic absorption near 850 cm^{-1}, supporting the presence of a cellulose-based structure (Baker and Oguntoye, 2023). The FTIR spectrum confirms the characteristic molecular fingerprint of corn cob and indicates hydroxyl, aliphatic C–H, carbonyl/aromatic, and C–O/C–O–C-containing structures associated with its lignocellulosic composition. The dominant absorption in the 1050–1100 cm^{-1} region, together with the O–H stretching band at approximately 3,400–3,500 cm^{-1}, supports the presence of polysaccharide-rich components, particularly cellulose and hemicellulose. Meanwhile, absorptions in the 1,500–1,650 cm^{-1} region may indicate contributions from lignin and adsorbed water. Thus, the FTIR results provide a useful baseline for evaluating the chemical structure of corn cob and for comparing structural modifications resulting from subsequent physical, chemical, thermal, or conversion treatments.

Figure 4 shows the frequency-dependent electrical conductivity of corn cob-derived biosilica measured using electrochemical impedance spectroscopy (EIS). The DC conductivity increases continuously with frequency over the investigated range, indicating that charge transport in the biosilica is strongly frequency-dependent. In the lower-frequency region, the conductivity is 2.8×10^{-5} S/cm and gradually increases to 1.8×10^{-4} S/cm at around 10^6 Hz. Thus, the conductivity increases by 6.4 times over the investigated frequency range. This behavior indicates that the applied alternating electric field facilitates the

movement of mobile charge carriers and reduces the limitation imposed by localized charge trapping and interfacial polarisation. The increase in conductivity with frequency is common in disordered, amorphous, and heterogeneous materials and can be described by Jonscher's universal power law. At low frequencies, charge carriers have sufficient time to accumulate at interfaces, grain boundaries, defects, or electrode–sample interfaces, resulting in a relatively low apparent conductivity. As the frequency increases, the electric field changes more rapidly, allowing localized charge carriers to respond more effectively and producing an increasing conductivity response.

Charge transport in corn cob as a biosilica is not governed solely by long-range free-carrier motion. Instead, localized charge movement, hopping processes, and polarisation effects may contribute to the measured electrical response. In disordered materials, the frequency-dependent component of conductivity is generally associated with localized charge carriers that respond to the alternating electric field at higher frequencies. Therefore, the increasing conductivity at high frequency may indicate enhanced carrier hopping or localized displacement within the biosilica structure. Similar frequency-dependent behavior has been reported for silicate-based materials, where electrical conduction is influenced by the structural disorder and mobility of charge carriers. The relatively low conductivity at low frequencies may also relate to electrode and interfacial polarisation. At low frequencies, charge carriers can accumulate at interfaces and become temporarily trapped, increasing the polarisation contribution and limiting effective charge transport through the sample. As frequency increases, these slow polarisation processes become less dominant, while faster localized charge transport becomes increasingly significant. This interpretation is consistent with the general behavior of impedance-based conductivity measurements in heterogeneous and non-crystalline materials.

The DC conductivity obtained in this study is also relevant to the potential utilization of biomass-derived silica as a functional material. Although the measured conductivity remains relatively low compared with conventional electronic conductors, its frequency-dependent response demonstrates that corn cob-derived biosilica possesses measurable electrical activity. Previous studies on biomass-derived silica and other biomass-based materials have shown that structural characteristics, amorphous phases, defects, and surface chemistry can influence their electrical and electrochemical responses. Corn cob-derived carbon materials exhibit electrical and electrochemical properties that depend strongly on their structure and porosity. Therefore, the conductivity response observed in Figure 4 provides additional evidence that corn cob can be converted into value-added functional materials. In particular, the frequency-dependent conductivity of the resulting biosilica may be relevant for dielectric materials, sensing devices, insulating or semiconducting composite fillers, and other applications where controlled electrical response is required. The conductivity profile demonstrates that corn cob-derived biosilica exhibits a pronounced frequency-dependent electrical response, with conductivity increasing from 2.8×10^{-5} to 1.8×10^{-4} S/cm, indicating enhanced charge-carrier response at higher frequencies and suggesting contributions from localized charge transport and hopping mechanisms.

Figure 5 presents the frequency dependence of the dielectric constant (ε') of corn-cob-as biosilica obtained from electrochemical impedance spectroscopy (EIS). The dielectric response decreases markedly with increasing frequency, particularly in the low- and intermediate-frequency regions, then gradually approaches a nearly constant value at high frequencies. At the lowest investigated frequencies, ε' reaches 3.0×10^3, then decreases rapidly as frequency increases and approaches a very low value at 10^6 Hz. This behavior indicates strong dielectric dispersion and shows that the polarisation mechanisms within the corn cob as biosilica depend strongly on the frequency of the applied electric field. The relatively high dielectric response observed at low frequencies can be associated with the accumulation of mobile charge carriers at interfaces and structural heterogeneities within the

sample. Corn cob biosilica produced through biomass conversion may contain structural defects, pores, residual surface hydroxyl groups, and heterogeneous regions. These features can act as charge-accumulation sites and contribute to interfacial polarisation. Interfacial polarisation can produce a large apparent dielectric response at low frequencies because the applied electric field changes sufficiently slowly to allow charge carriers to migrate and accumulate at these interfaces.

As the frequency increases, the dielectric constant decreases significantly. This decrease can be explained by the reduced ability of slower polarisation mechanisms to follow the rapidly alternating electric field. At low frequencies, several polarisation mechanisms, including interfacial, dipolar, ionic, and electrode polarisation, can contribute to the total dielectric response. However, at higher frequencies, the time available for charge redistribution becomes shorter. Consequently, mobile charge carriers cannot accumulate effectively at interfaces, and interfacial polarisation decreases. Similar frequency-dependent decreases in dielectric constant have been reported for silica-containing systems and other heterogeneous dielectric materials. The rapid decrease observed is particularly pronounced from 10^1 to 10^3 Hz. This region may represent the dominant polarisation-dispersion region of the corn cob as biosilica. Above approximately 10^4 Hz, the curve flattens progressively, indicating that slow polarisation processes become less significant. At this stage, only faster polarisation mechanisms can respond to the alternating electric field. For silica-based materials, the high-frequency dielectric response is more strongly associated with ionic and electronic polarisation, which contributes less to the overall dielectric constant than interfacial polarisation at low frequencies. The observed dielectric behavior also reflects the structural characteristics of corn-cob-derived silica. Previous research has demonstrated that silica can be successfully extracted from corn cob through alkaline extraction and acid precipitation, producing predominantly amorphous silica containing siloxane and silanol groups. These surface and structural characteristics can influence charge distribution and polarisation behavior during electrical measurements. Therefore, the frequency-dependent dielectric response observed in this study may reflect the combined effects of surface functional groups, structural defects, porosity, and heterogeneous interfaces within the biosilica.

Figure 6 shows the frequency dependence of the dielectric loss (ε") of corn-cob-derived biosilica. The dielectric loss decreases continuously with increasing frequency, from approximately 6.8×10^3 F/m at low frequencies to a value approaching zero at around 10^6 Hz. The pronounced decrease indicates that energy dissipation and polarisation processes in the biosilica are strongly frequency-dependent. At low frequencies, the high dielectric loss can be attributed to mobile charge carriers accumulating at interfaces, defects, pores, and electrode–sample boundaries. As frequency increases, charge carriers have less time to accumulate at interfaces and cannot follow the rapidly alternating electric field effectively. Consequently, interfacial polarisation decreases, and the dielectric loss is substantially reduced. The gradual stabilization of ε" at high frequency indicates that slow polarisation mechanisms become less significant. Similar dielectric responses have been reported for silica-based systems, where low-frequency dielectric enhancement is associated with interfacial charge polarisation. The observed behavior is consistent with the structural characteristics of corn-cob-derived silica. Previous studies have confirmed that silica extracted from corn cob contains siloxane (Si–O–Si) and silanol (Si–OH) groups and can be amorphous. These structural features can influence charge localization and polarisation during electrical measurements. The decrease in dielectric loss demonstrates reduced energy dissipation at higher frequencies and confirms the frequency-dependent dielectric behavior of corn-cob-derived biosilica. This response supports its potential application as a biomass-derived functional dielectric material.

Figure 7 shows the frequency dependence of the loss tangent (tan δ) of corn-cob-derived biosilica. The loss tangent initially decreases from approximately 2.2 at low frequency to a minimum value of about 2.0 near 10^3 Hz. This initial decrease indicates reduced dielectric energy dissipation as slow polarisation processes become less dominant. As frequency increases further, tan δ rises markedly and reaches a maximum of about 3.9 at around 10^5 Hz. This pronounced maximum can be associated with a dielectric relaxation process, where the characteristic response of mobile charge carriers and dipolar or interfacial polarisation becomes most significant. The relaxation behavior relates to the heterogeneous, amorphous structure of biosilica, which can contain surface hydroxyl groups, structural defects, and interfaces that influence charge distribution. Corn cob biosilica has been reported to be predominantly amorphous, with silanol (Si–OH) and siloxane (Si–O–Si) groups. At frequencies above approximately 10^5 Hz, tan δ gradually decreases to about 3.1 at 10^6 Hz, indicating reduced dielectric loss when the applied field changes too rapidly for slower polarisation mechanisms to respond effectively. The non-monotonic tan δ response confirms frequency-dependent dielectric relaxation and energy dissipation in the corn-cob-derived biosilica.

Figure 8 presents the Nyquist plot of corn-cob-derived biosilica obtained from electrochemical impedance spectroscopy (EIS). The plot is characterized by an initially low capacitive impedance response followed by a continuous increase in both the real impedance (Z') and capacitive impedance (Z''). The curve starts at approximately 3.0×10^3 Ω on the real impedance axis and gradually extends toward about 2.3×10^4 Ω, while Z'' increases to 1.0×10^4 Ω. This behavior indicates that the biosilica's electrical response is governed by a combination of resistive and capacitive contributions. Unlike a conventional electrochemical system exhibiting a well-defined semicircle, the present spectrum does not show a complete semicircular arc. Instead, the curve exhibits a gradual transition from a relatively small capacitive response in the initial region to an approximately linear increase at higher impedance values. Such behavior can indicate non-ideal capacitive characteristics and heterogeneous charge transport within the sample. In EIS analysis, a semicircular region generally indicates a parallel resistive-capacitive process, whereas an inclined linear region can relate to diffusion, polarisation, or distributed relaxation processes.

The absence of a well-defined semicircle may reflect the heterogeneous, porous structure of corn-cob-derived biosilica. Silica obtained from corn cob has been reported to exhibit an amorphous structure containing siloxane (Si–O–Si) and silanol (Si–OH) groups. These structural features can generate localized charge sites and heterogeneous interfaces that influence the impedance response. The increasing Z'' component further indicates a significant capacitive contribution, suggesting that charge accumulation and polarisation occur within the biosilica during the alternating-current measurement. The inclined region at higher impedance values may also indicate a distributed transport process rather than an ideal resistor or capacitor. However, this region should not be assigned directly to Warburg diffusion without additional frequency-resolved analysis because a true Warburg response is generally identified by an approximately 45° linear region and should be confirmed through equivalent-circuit fitting. The Nyquist response demonstrates that corn-cob-derived biosilica exhibits mixed resistive and capacitive behavior with significant polarisation and non-ideal charge-transport characteristics. These properties are consistent with a heterogeneous biomass-derived silica structure and support its potential as a functional dielectric or sensing material.

EIS results show that the bio-silica powders produce the best impedance profile, characterized by a more defined semicircular curve shape, indicating more efficient ionic relaxation. Although resistance remains high, it has been shown to improve stability, chemistry, internal structure, and ionic conductivity. Thus, corn cob as bio-silica has great potential as a safe, efficient solid electrolyte for lithium-ion battery applications.

IV. Conclusion

This study successfully synthesized silica from corn cob biomass through a sol–gel-based process, demonstrating the potential of agricultural waste as a sustainable source of functional silica material. FTIR characterization confirmed characteristic functional groups associated with the silica structure, particularly Si–O–Si and Si–OH groups, along with hydroxyl-related vibrations. These spectral features indicate the formation of a silica-based structure and provide evidence of chemical transformation of the original corn cob biomass during synthesis. Electrical characterization using electrochemical impedance spectroscopy (EIS) further showed that corn cob biosilica exhibits a frequency-dependent electrical response. The dielectric constant and dielectric loss decreased markedly with increasing frequency, which can be attributed to the decreasing contribution of interfacial and electrode polarisation at higher frequencies. The Nyquist plot exhibited combined resistive and capacitive characteristics without a clearly defined semicircular arc, suggesting non-ideal capacitive behavior, heterogeneous charge distribution, and polarisation effects within the biosilica structure. Although the relatively high impedance indicates that the material is not yet suitable as a standalone highly conductive solid electrolyte, its measurable electrical response and frequency-dependent dielectric properties demonstrate significant potential for functional applications. Corn cob as biosilica is an environmentally friendly, value-added biomass material with potential for use in dielectric materials, sensing systems, polymer composites, and as a silica-based component in electrochemical and energy-related applications. Further optimization of synthesis conditions, particle size, purity, and structural properties is required to improve electrical performance and assess suitability for solid-electrolyte applications.

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