

Dielectric and chemical characteristics of nano-cellulose banana fiber epoxy composites for high voltage applications in power systems

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Graphical abstract

GRAPHICAL ABSTRACT

SUSTAINABLE CONVERSION OF BANANA WASTE INTO ELECTRICAL INSULATION MATERIALS FOR HIGH VOLTAGE APPLICATIONS



Abstract

The investigation examined the electrical properties of epoxy composites fortified with fibres derived from banana leaves and pseudostems. This investigation focused on crucial parameters such as dissipation factor, loss factor, and dielectric constant. The influence of various factors, including fibre loading, frequency, and chemical treatment, on the dielectric properties of the composites was investigated. The dielectric properties of composites loaded with banana leaf fibres were found to be superior to those of pure epoxy composites. This was attributed to the polarisation effect, which was enabled by the efficient interlocking between the fibres and the matrix. Subsequently, as the frequencies increased, both the orientation and interfacial polarisation exhibited a reduction, resulting in a decline in dielectric constants. The fibre loading was increased by the incorporation of hydrophilic banana leaf fibres; consequently, the dielectric

constants rose until a critical fibre volume of 17.2% of the total volume was reached. Furthermore, it was observed that the dissipation factor of banana fibre composites decreased with increasing fibre loading, suggesting enhanced interfacial adhesion between the fibres and the matrix. A range of chemical treatments were utilised to improve the adhesion between banana fibres and the matrix. These treatments included alkali, acetyl, benzyl, permanganate, and peroxide solutions. As a result, the fibres exhibited increased hydrophobicity, and the dielectric constant values of the composites were enhanced. In addition, as the weight percentage of banana leaf fibres increased, the dielectric constant values increased in comparison to pseudostem fibres as a consequence of improved fibre nanoparticle bonding. The aforementioned results were obtained over the frequency spectrum of 1–5 MHz.

Keywords: Electrical Insulation composites, Dielectric Properties, Loss factor, Natural fibres, Surface morphology

1. Introduction

Electrical and electronic insulation applications, including bearings, separators, isolators, and insulators, rely heavily on polymer. These polymer materials are utilised to protect or shield the interaction between two conductive components [Yabo et al. 2024; Jiahao Shen et al. 2024] due to their high resistivity. Outstanding electrical and mechanical robustness characterises the pure polymer. In insulation applications, numerous natural cellulose-based fibre materials have begun to supplant polymer materials in recent times. Natural fibres are abundant and possess advantageous electrical and mechanical properties; however, their propensity to absorb moisture makes their use in outdoor applications problematic. In electrical insulation applications, numerous natural fibres are typically utilised, including sisal, flex, coir, cotton, and banana. Natural fibres are incapable of functioning autonomously on account of their inadequate mechanical strength and moisture absorption characteristics; the

interfacial bonding between nanoparticles and natural fibres does not extend uniformly throughout the composites. To address these challenges associated with natural fibre, chemical treatments including alkali, acetyl, benzyl, permanganate, and peroxide are employed [Khalid *et al.* 2021]. Chemical treatments aid in the reduction of the moisture absorption ratio and promote strong adhesive-fiber interfacial bonds. A solution of 4% NaOH is appropriate for increasing the hydrophobicity and tensile strength of fibres [Mohammed *et al.* 2015]. In addition to possessing favourable electrical and mechanical properties, banana fibres are abundant and environmentally benign. Pseudostem and leaf of the banana are composed of cellulose, lignin, hemicelluloses, and fibre. The anatomical components of banana leaves are illustrated in **Figure 1(a)**, while those of the pseudostem are depicted in **Figure 1(b)**. The fibre of bananas possesses lignocellulosic properties. Nanocellulose, which is present in cellulose filaments, has a diameter and length of less than 100 nanometers. The fibres of banana pseudostems and banana leaves have respective sizes of 23.7 nm and 80-250 nm [Khalid *et al.* 2021; Jayamani *et al.* 2014]. The physicochemical parameters of plant fibres obtained from the leaves and epidermis of the plants are detailed in **Table 1**. The banana leaf fibres are composed of the following: 32.56 percent hemicellulose, 25.8 percent lignin, 25.25 percent protein, and 16 percent lignin. The composition of banana stem fibre is as follows: cellulose comprises 48%, hemicellulose 36%, lignin 19%, wax 0.5%, and ash 18.4%. The incorporation of sodium hydroxide generated a significant enhancement in the accelerator's efficiency. In comparison to other fibres, nanocellulose banana fibres adhere more securely to epoxy resin and retain greater mechanical strength [Jiahao Shen *et al.* 2022]. The dielectric properties of composite materials, including dielectric constant, dissipation factor, and loss factor, are critical when they are utilised in electrical insulation applications [Jiahao Shen *et al.* 2022]. The dielectric constant of composites increases as temperature and fibre loading increase, while it decreases as the frequency increases [Khalid *et al.* 2021]. In a laboratory setting, the dielectric properties of an epoxy resin reinforced with banana and glass fibre were examined and found to be affected by temperature and frequency. 10 Banana fibre additives are utilised in electrical insulation applications due to their electrical properties. The progressive increase in relative permittivity and subsequent decrease in loss factor have been observed as a result of the interfacial and orientation polarisation of banana fibre along the fibre path. Nano-fiber composite materials are utilised in cutting-edge electrical insulation applications in power systems due to their superior electrical and mechanical properties [Karimah *et al.* 2021; Rajamanikandan *et al.* 2021; Nimanpure *et al.* 2017]. A multitude of chemical treatment methodologies are employed in order to augment the mechanical and electrical characteristics of banana fibre. An FESEM (Field Emission Scanning Electron Microscope) is employed to examine alterations on the surface of banana fibre composites. The purpose of this

investigation is to determine the dielectric constant, dissipation factor, and dielectric loss of epoxy composites comprised of chemically modified nano-cellulose banana fibres for use in high-voltage power systems. Epoxy resin (ER), banana fronds, and banana pseudo-stem fibres comprise the majority of the materials used in this investigation. An analysis has been conducted on the dielectric properties of composite materials, focusing specifically on the influences of adhesive materials, fibre loading, fibre ratio, and various fibre treatments.

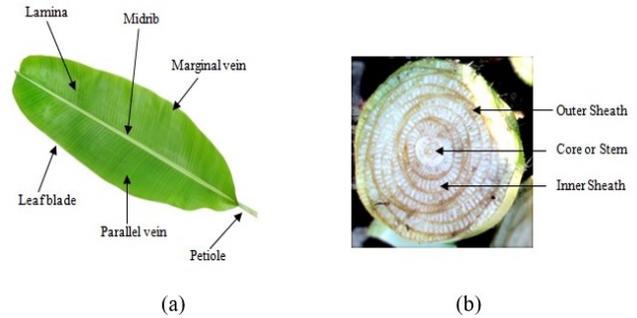


Figure 1(a). Internal Parts of Banana Leaf. **(b)** Internal Parts of Pseudo stem.

Table 1. Properties of Banana Leaves and Pseudo stem

Property	Banana Leaves	Banana Pseudo stem
Diameter (μm)	0.18-0.23	0.2.8-0.38
Density (g/cm^3)	1.48	1.58
Elastic Modulus (GPa)	2.67	6.84
Tensile strength (MPa)	48.6	48.6
Elongation (%)	2.5-7.9	7-9
Moisture absorption after 24 h (%)	9.85-12.4	11-14.6
Electrical resistivity in 100 volts (ohm $\text{cm} \times 10^5$)	4.8-7.2	7.2-14.8

2. Materials

Epoxy resin (ER) procured from M/S Bohriali Pvt Ltd, Maharashtra, India, with both the epoxy resin (Bondtite part A) and the hardener (Bondtite part B). The banana leaf and sheath fibers are purchased from the Thottiam Banana Farmer Producer Company, Trichy, Tamil Nadu, India.

3. Methods

3.1. The surface modification of the fibers

Surface modifications are necessary in order to eliminate lignin from the banana fibre in order to enhance interfacial binding and hydrophobicity between the fibre and matrix. By employing these methodologies, nano-cellulose is synthesised from natural fibres. A variety of chemical substances are employed for the purpose of surface treatment on banana leaves and pseudo-stem fibres. **Table 2** illustrates the combining formulations of the resin matrix for samples S1 through S6, encompassing

different loadings of fibres. As shown in **Table 3**, the mixing formulations A-100 to A-0 (varying fibre ratios) are presented.

Table 2. Mixing formulations S1 to S6 (Various fiber loadings)

Type of Fiber (phr)a	Mixing Ratio					
	S1	S2	S3	S4	S5	S6
Banana Leaf fiber (10 nm)	0	10	20	30	40	50
Banana Pseudostem fiber (10 nm)	0	10	20	30	40	50

Table 3. Mixing formulations A-100 to A-0 (Various fiber ratios)

Fiber Condition		Concentration of fibers (%)					
		A-100	A-85	A-55	A-25	A-0	
Untreated	Banana Leaf	100	75	50	25	0	
	Banana Pseudostem fiber	0	25	50	75	100	

Table 4. Mixing formulations L to N (Chemically treated fibers)

Surface Modification	Combination of fibers	Concentration of fibers (%)					
		L	M	R	U	V	N
Untreated fibers	Banana leaf and						50
	pseudo stem						50
Alkaline	Banana leaf and	50					
	pseudo stem	50					
Acetylated	Banana leaf and		50				
	pseudo stem		50				
Benzoylation	Banana leaf and			50			
	pseudo stem			50			
Peroxide	Banana leaf and				50		
	pseudo stem				50		
Permanganate	Banana leaf and					50	
	pseudo stem					50	
Bonding agent (phr)	Bondtite part A						1
	Bondtite part B						0.5

3.2. Chemical Modification of fibers

Several chemical treatments were carried out individually on banana leaves and banana pseudostems.

3.3. Chemical modification by alkaline

The pseudostem and leaves of each banana were immersed separately in a 4% NaOH solution for forty-five minutes while being constantly stirred. After carefully washing away any leftover NaOH that had stuck to the fibres with water, the fibres were given another wash with alkaline water, which contains a little quantity of acetic acid. The fibres are then allowed to dry at room temperature. The term "nano-cellulose fibres" refers to these treated fibres.

3.4. Chemical modification by acetylating

The fibres treated with NaOH were steeped in glacial acetic acid for 45 minutes, discarded, and then immersed in acetic anhydride containing two drops of very concentrated sulfuric acid for six minutes. The fibres were

then dried at room temperature after being cleaned with water.

3.5. Chemical modification by benzoylation

After being agitated with 50 ml of benzoyl chloride for 20 minutes, the mercerized fibres were filtered, thoroughly rinsed with water, and dried. To get rid of the leftover benzoyl chloride, the fibres are rinsed with water, let to dry naturally, and then steeped in methanol for 45 minutes.

3.6. Peroxide treatment

Following treatment with a 4% NaOH solution, the fibres are submerged in dimethyl ketene for 20 minutes. In four hours at room temperature, the fibres become dehydrated.

3.7. Chemical modification by permanganate

For four minutes, 4% of the NaOH-treated fibres are submerged in a 2% KMnO₄ solution in acetone. The fibres are then allowed to dry at room temperature.

The experimental phase involved the use of many chemical modification techniques to improve the characteristics of composites reinforced with banana leaf and pseudostem fibres. To enhance the surface roughness of the fibres and promote improved interaction with the resin matrix, an alkali treatment was performed using 5% NaOH. As a consequence of this treatment, the surface area was expanded and impurities were decreased, leading to improved mechanical strength and adhesion characteristics of the composite materials.

The fibres were subjected to acetylation using acetic acid and acetic anhydride in order to decrease water absorption and maximise their hydrophobicity. Furthermore, this treatment enhanced the volume resistivity of the composite, therefore improving its suitability for electrical insulation operations by reducing conductivity caused by moisture.

A permanganate treatment, which included 0.5% KMnO_4 , was used to enhance the bonding between the fibre and matrix. The presence of permanganate ions augmented the surface reactivity of the fibres, thereby facilitating higher adhesion between the fibre and the matrix. Consequently, this contributed to heightened mechanical stability and improved electrical characteristics.

Peroxide treatment using 1% DCP was implemented to enhance the mechanical and dielectric characteristics of the composite material. By enabling cross-linking between the fibre and matrix, this method improved the overall durability and electrical insulating capability of the material.

The ideal ratio of fibre incorporation was found to be between 15-20% by weight. A 50:50 combination of banana leaf and pseudostem fibres achieved the most favourable equilibrium in terms of volume resistivity, permittivity, and mechanical rigidity. This combination maximised the benefits of both fibre types to produce a composite with exceptional performance properties. Furthermore, the addition of 5% bonding agents, such as resorcinol, was shown to significantly improve the electrical insulation and mechanical properties of the composites. The bonding agents effectively enhanced the adhesion between the fibre and matrix, leading to improved material characteristics that are well-suited for high-voltage electrical insulation applications.

3.8. Incorporation of bonding-material components

For the project, a two-part dry bonding compound was selected that consisted of epoxy resin (Bondtite part A) and hardener (Bondtite part B), all of which were of Indian Standard grade 3 and crystal clear. As seen in **Table 2**, both of the dried adhesive's components were entirely transparent.¹²

3.9. Sample Preparation of Fiber

The pseudostem and banana leaf fibres, both with and without chemical treatment, are used to create the samples. 26–30 nm fibres are reinforced with an epoxy resin matrix including varying weight percentages of banana fibres. Banana pseudostem and liquid leaves are

separated from the nanocellulose fibre using an acidic hydrolysis and 2,2,6,6-tetramethylpiperidine-1-oxyl radical (TEMPO)-mediated technique. The fine banana fibres (26 nm x 30 nm) are crushed using a mixer grinder. Banana fibres (50 percent banana leaf and 50 percent pseudostem fibres) are combined with water in a 1:0.4 ratio to create the pulp, which is then boiled at 130°C for 40 minutes following chemical treatment with a 5% sodium hydroxide solution. The chemically treated pulp is completely removed from the lignin component by soaking it in distilled water for a long time. A chemically treated banana fibre pulp is dried at 150 °C for four hours in a hot air oven. The dried banana leaf pulp is distributed uniformly across the cotton fabric sheet. Seven sheets are manufactured in the same manner. Epoxy resin has been applied to the dried hybrid banana fibre sheet, hardening it on both sides in a 1:5 ratio. The seven resin-coated sheets are combined to form a single board. A hydraulic pressing machine applies two tonnes of hydraulic pressure to up to seven layers of resin sheets placed on top of one another. Banana fibre was used to create the composite board after six hours. The preparation and production of the untreated banana leaf fibre press boards are identical to those of the treated boards; the NaOH treatment has not been applied. Mix A is a sample of a pure epoxy resin composite board that is free of pseudostem and banana leaf fibres. Blends V, W, X, Y, and Z are composites with fibre loadings of 10, 20, 30, 40, and 50 phr. They contain banana leaf and banana pseudostem fibres in a 50:50 ratio. The fibre ratios of pseudostem and banana leaf composites are investigated using varying fibre weight percentages (wt%). In contrast, composites containing 80% banana leaf (20% pseudostem), 50% banana leaf (50% pseudostem), 20% banana leaf (80% pseudostem), and 0% banana leaf (100% pseudostem) have been designated as D80, D50, D20, and D0, respectively. Pure banana leaf fibres (100% banana leaf, 0% pseudostem) have been designated as D100. Mixes, denoting the J, O, P, Q, and S, are composites made of fibres that have experienced various chemical processes, such as alkali, benzoylation, acetylation, peroxide, and permanganate. The composite, denoted as Mix T, consists of the dry adhesive agents resorcinol and hexa. The formulas for the various blends are listed in **Table 4**. **Table 5** shows the basic composition of many matrices.

Table 5. Basic composition of different matrix

Adhesive Mixing Ratio	Weight (phr) ^a
Epoxy Resin	100
Hardener	50

4. Study of dielectric properties

In order to evaluate the dielectric characteristics of hybrid banana fibre nanocellulose composites, 8 mm diameter by 3 mm thick cylindrical specimens were made. These specimens were created by compression moulding in a hydraulic press at 160°C and 120 psi (827.37 kPa) of pressure. The specimens were painted on both sides with conductive silver paint and had copper wires attached to both surfaces to act as electrodes. An HP 4192 A

Impedance Analyzer from Hewlett-Packard Germany was used for the testing, allowing for the direct measurement of dissipation, capacitance, and resistance parameters. The studies were carried out in accordance with ASTM standard D-150-74 and were done at frequencies between 10 kHz and 14 MHz. The dielectric constant of an insulating material is defined as the ratio of the charge stored when the insulating material is placed between two metallic plates and the charge stored when air (or a vacuum) replaces the insulating material. The dielectric constant, E' , was computed from capacitance using the following formula. The relative permittivity, represented by E' , could be extracted thanks to the capacitance, and the value of the capacitance could be found using the equation

$$E' = Ct/EOA \quad (1)$$

The equation displays the following values: capacitance (C), thickness (t), air permittivity (E_0), and cross-sectional area (A). An insulating material loses electrical energy when exposed to a voltage. A dissipation factor is a measure of the amount of energy dissipated. The following equation relates the dissipation variables ($\tan \delta$) and the loss factor (dielectric loss, E''):

$$\tan \delta = E''/E' \quad (2)$$

The effective conductivity is determined by electric polarization and is shown by due to the small amount of conductivity due to free charge (a good dielectric).

$$\sigma = \omega E_0 E'' = \omega E_0 \tan \delta E' \quad (3)$$

To denote the angular frequency, write it as $2\pi f$. Material's insulating resistance is determined by its volume resistivity (ρ).

$$\rho = 1/\sigma \quad (4)$$

5. Field Emission Scanning Electron Microscope

Field emission electron microscopy (FESEM) was used to identify the surface of banana leaf fibre composites that were dispersed across the surface. A FESEM analyzer called the NOVA NANOFESE Mn430, made in the US by M/S FEI, was utilised to test the specimen. There was a 1–5 kV working voltage range.

6. Results and discussion

6.1. Relative permittivity and Reaction of fiber matrix

The effects of fibre loading and the dielectric constant (E') values of epoxy resin-reinforced banana leaf/pseudostem nanocomposite fibre reinforcement with functional frequency are shown in **Figure 3**. It makes it very evident that, at all frequencies, the dielectric constant rises as fibre loading does. The samples with pure epoxy (Mix A-0 phr) show the lowest E' values. The absence of permanent dipoles is the reason for this, as the matrix only consists of carbon and hydrogen atoms. Generally speaking, the temperature and frequency of E' determine the polymer's

polarity. The refractive index, or E' , is equal to the square of n , as per the equation below.

$$E' (\text{non-polar or unionized insulators}) = n^2 \quad (5)$$

Equation (5) yields $E' = 2.48$ for ER, a non-polar molecule with an apparent refractive index of 1.438 [Mohammed et al. 2015], whereas the measured value is 3.32 (**Figure 3**). The high value found can be explained by the interfacial polarisation that arises from the presence of mixing ingredients as dirt. The dielectric constant (E') of a composite is determined by its interfacial, orientation, unaffected, and electromagnetic polarisations together. Interfacial polarisation in a nanocomposite is caused by a difference in the conductivity or polarisation between the fillers and matrix [Elloumi et al. 2021]. An electromagnetic field is used to produce the orientation polarisation of the nano-composites made of polymers with polar groups seated in them. The orientation and interfacial polarisation of a composite are influenced by the filler concentration. **Figure 2** shows that when fibre loading increases from 0 to 50 phr, the dielectric constant increases, notably at lower frequencies. The observed rise in orientation and interfacial polarisation with increased fibre loading can be explained by the presence of polar cellulose groups in natural fibres. It happens that for a given fibre loading, the E' shows greater values at lower frequencies. To make things clearer, consider the object's orientation. Polarisation diminishes with increasing frequency. Molecules can only be fully oriented at lower frequencies, therefore orientation polarisation takes longer to reach the ideal static field value than electronic and atomic polarisation. As a result, the E' lowers with increasing frequency because the orientation polarisation is behind.

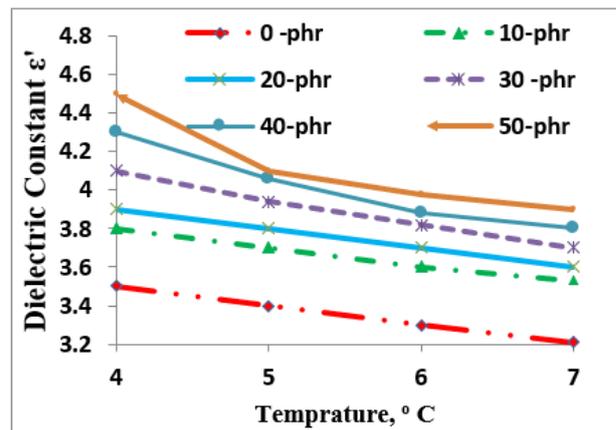


Figure 2. Relative permittivity as a function of frequency with fiber loading

6.2. Reaction of fiber ratio

The variance of E' values as a functional frequency is shown in **Figure 2** for different weight percentages of pseudostem and banana leaf fibres at a fixed total fibre input (30 phr). At constant loading, the nono-composites with just pseudostem fibres (D0% banana leaf) have the smallest E' value. Additionally, it is noted that when banana leaf fibre content increases, so do the E' values. The highest E' value is found in the nanofiber composite

made entirely of banana leaf fibres (D100-100 percent banana leaf fibre). Since pseudostem and banana leaves are both lignocellulosic materials, they both absorb moisture. On the other hand, banana leaf fibre has a higher moisture-absorbing ability than pseudostem (Table 1). As a result, dirt with high moisture content at the interface causes enhanced dielectric constant values in a composite material with a high proportion of banana leaf fibre. Figure 3 shows how the ER matrix's dielectric characteristics are improved when banana leaf fibres are added to pseudostem fibres.

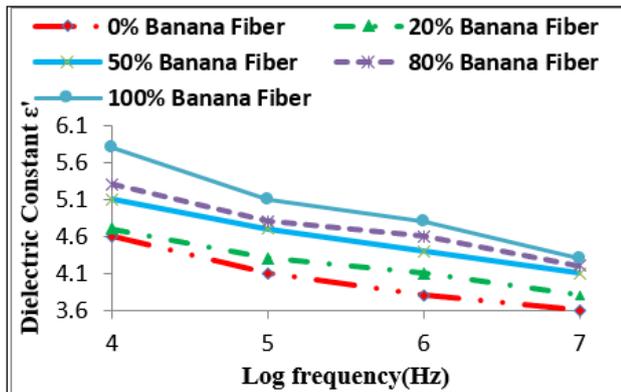


Figure 3. Dielectric constant with fiber matrix

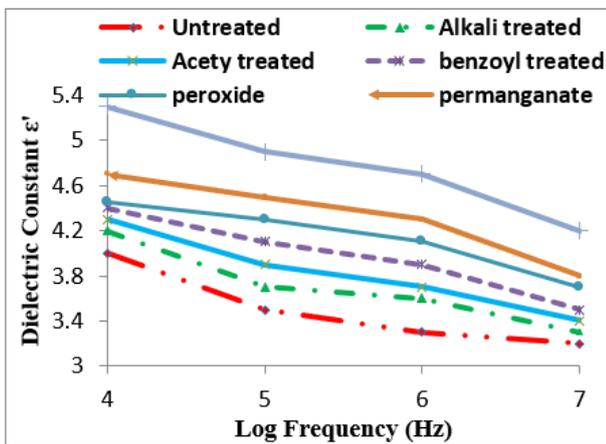


Figure 4. Dielectric constant with different chemical treatment of fibers

6.3. The interaction between the bonding agent and chemical treatment

Figure 5 shows how different chemical treatments and fibre changes affect the dielectric constant values of composites made of banana leaves and pseudostem-ER. Because the treated fibres are more hydrophobic than the untreated ones, the treated banana fibre composites have lower dielectric constant values across the board. This is explained by the fact that the orientation polarisation of the treated fibres is reduced. Moreover, the composites' ability to absorb moisture is reduced since there is less chance of polar hydroxyl groups in lignocellulosic fibres interacting with water molecules. Furthermore, fibre alteration results in a reduction in the fibres' ability to absorb moisture.

Banana fibre that has been alkali-treated exhibits the greatest reduction in dielectric constant compared to other treatments. The increased reactivity of the fibres

can be ascribed to the disruption of hydrogen bonds occurring within the hydroxyl ($-OH$) groups of cellulose. The alkali treatment of the fibres, as depicted in Scheme 1, increases their reactivity. Additionally, the treatment facilitates the bonding between banana fibre and the ER matrix through the degradation and absorption of lipids and lignin, which serves as the adhesive constituent. This causes composites to become more robust. An outcome of the treatment-induced decrease in the hydrophilic properties of the fibres is a reduction in orientation polarisation. Thus, in comparison to untreated fibres, alkali-treated fibre materials demonstrate a substantial decrease in dielectric constant values.

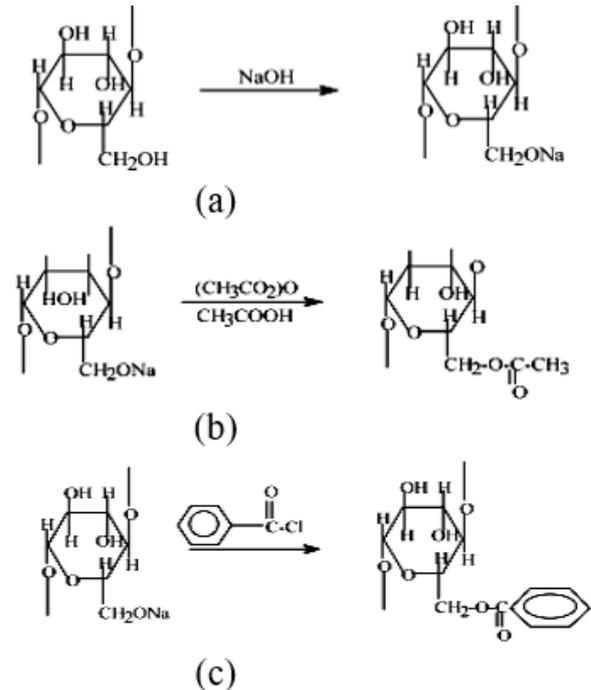
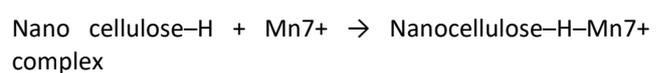


Figure 5. (a) Type 1. Impact of alkylation of pseudo stem and banana leaf fibers, (b) Type 2. Impact of acetylation of pseudo stem and banana leaf fibers, (c) Type 3. Cellulosic content of pseudo stem and banana leaf fiber may undergo a benzoylation reaction with a theoretical reaction mechanism.

The introduction of a carbonyl group through acetylation increases the vulnerability of hydrogen atoms on the acetyl carbon atom to bonding with active sites on ER, thereby promoting enhanced adhesion. Scheme 2 depicts the alterations in structure that occur as a result of acetylation. In the same way that benzoylation increases the reactivity of hydrogen atoms attached to the benzoyl carbon atom, it facilitates covalent bonding with the $-OH$ groups present on cellulosic fibres. Scheme 3 illustrates how this results in an increase in fibre hydrophobicity and a decrease in orientation polarisation. Furthermore, the application of permanganate treatment induces an additional decrease in dielectric constant values. The permanganate ion (Mn^{7+}) promotes ER attachment to the pseudostem and leaf fibres of bananas. This advancement is facilitated by a chemical reaction that is hypothesised to involve cellulose groups and manganese ion.



Nanocellulose–H–Mn7+ complex → Nano cellulose + H++ Mn7+

Nano cellulose + ER → Nano cellulose–ER

The polymerization of the composite is catalyzed by the highly reactive permanganate ions (Mn7+), which play a pivotal role in fortifying the bond between the fiber and matrix. However, among all fiber treatments, peroxide (DCP) treatments exhibit the most significant reduction in dielectric constant. This can be attributed to the cross-linking process induced by peroxide and nano-cellulose interaction. During composite preparation, the infusion of peroxide at elevated temperatures can initiate cross-linking processes, thereby enhancing adhesion at the interface between the ER binder and nano-cellulose fibers. The following representation illustrates the peroxide-initiated, free-radical interaction between the ER binder and nano-cellulose fibers:

ER binder + peroxide → Initiation Free radicals ER binder + peroxide Initiation Free radicals

Free radicals + nano-cellulose fibers → Propagation Cross-linking Free radicals + nano-cellulose fibers Propagation Cross-linking

Cross-linked ER binder + fiber matrix → Termination Enhanced adhesion Cross-linked ER binder + fiber matrix Termination Enhanced adhesion

R–O–O–R → 2RO*

RO* + ER–H → ROH + ER*

RO* + Nano cellulose–H → Nano cellulose* + ROH

In nano-cellulose, the -OH and -CH atoms along with the methylol (-CH₂OH) group are where hydrogen is extracted. When manufacturing composite materials, a few different reactions could occur.

(1) The combination of ER micro radical increases the molecular weight and bonding between the matrix of ER.

ER + ER → ER–ER (2)

(2) Adding ER radicals to nano cellulose fibres by a process called incorporation

ER + Nano cellulose → ER–Nano cellulose

After being treated with peroxide, fibre loses some of its hydrophilic nature, which lowers its dielectric constant ratios.

Treatment with chemical peroxide can lessen the hydrophobicity of fibres, which lowers their relative permittivity. When a bonding agent is present in a composite, the relative permittivity decreases. Tetra and phenol are the components used in the dry bonding method of this composite system. A hexa-resorcinol reaction occurs at 160°C during the curing phase, attaching banana leaf and pseudostem fibres to the epoxy resin matrix to form a composite material. By decreasing spaces between fibres and the resin matrix, this resin improves interfacial adhesion and prevents moisture from penetrating the composite. Relative permittivity values are reduced in part because of modified interfaces.

Researchers have learned how surface shape contributes to better adhesion between chemically treated and bonding material-added composite materials. **Figure 6** shows photos taken with a field emission scanning electron microscope (FESEM) demonstrating the treated and untreated fibre composites' tensile failure surfaces under tensile loading. seen holes on cleaned fibre surfaces are seen on the tensile failure surface of unbounded composites in **Figure 6a**, suggesting inadequate wetting of the resin matrix and fibre. Strong adhesion between the fibre and matrix is shown by fragments sticking to the fibre surface after alkali treatment, as seen in **Figure 6(b)**. The bonding agent-coated composite's tensile failure surface is shown in **Figure 6(c)**. By helping rubber particles adhere firmly to fibre surfaces, bonding agents lessen the chance that fibres will break since the fiber-rubber matrix linkages are stronger.

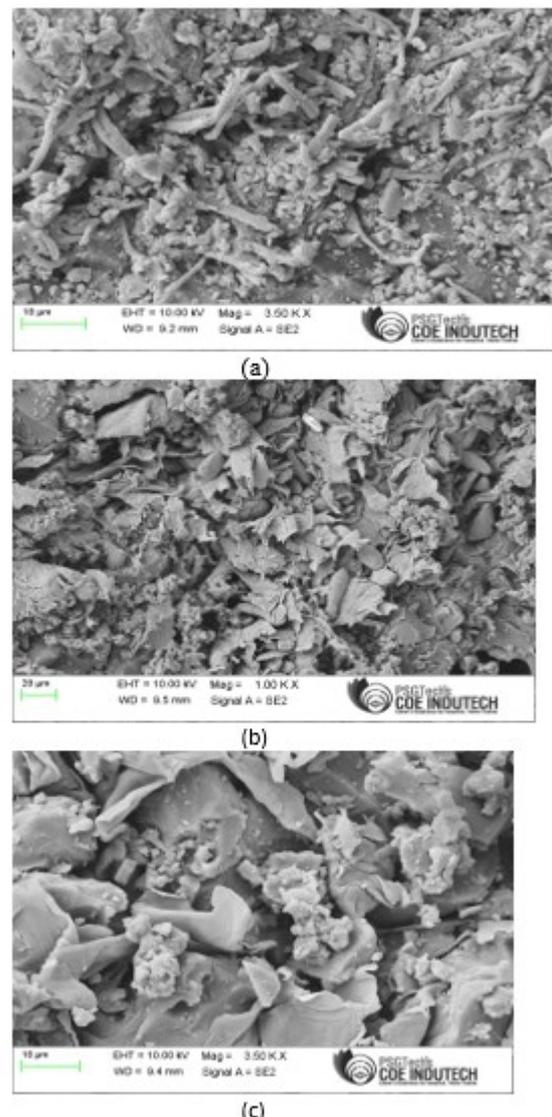


Figure 6. (a) Tensile failure of the untreated fibers composite. (b) Tensile failure of alkali treated fibers composite. (c) FESEM image of tensile failure of bonding agent added composites.

7. Volume resistivity and Effect of fibre to fibre ratio

Measuring volume resistivity is important because an insulator's capacity to tolerate the leakage of electric current is critical. The volume resistivity of nano-

composite insulators with different fibre loadings is shown in **Figure 5**. Volume resistivity has been found to decrease as frequencies and the weight percentage of banana fibre rise. The existence of short banana leaf and pseudostem fibres with polar groups, which aid in the polarisation process, is responsible for this decrease. Furthermore, banana leaf and pseudostem fibres' lignocellulosic nature makes them susceptible to moisture absorption, which increases polarisation and, as a result, decreases volume resistivity with a higher filler content.

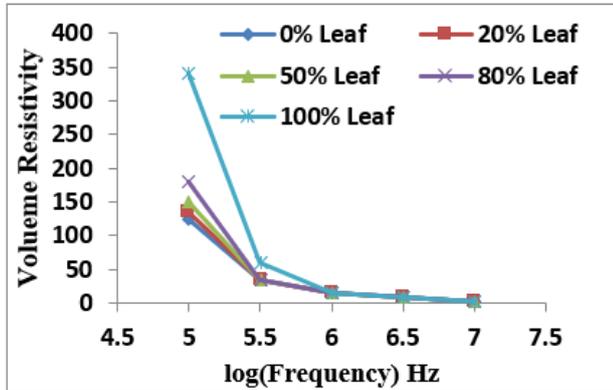


Figure 7. Variation volume resistivity and fiber loading

7.1. Reaction of fiber ratio

The specific resistance variation for various weight percentages of pseudo-stem and banana leaf fibres, while maintaining a constant total fibre loading, is shown in **Figure 8**. These findings demonstrate how particular resistance varies throughout time. Notably, the composite system with the highest volume resistivity across all frequencies is made entirely of pseudo-stem fibres, specifically 100% banana leaves. This may be partially explained by the fact that pseudo-stem fibres have a higher electrical resistance than banana leaf fibres. Furthermore, the volume resistivity of composite systems rises in direct proportion to the weight percentage of pseudo-stem fibre. On the other hand, of all the composite systems that were evaluated, the one made entirely of banana leaf (L100) showed the lowest volume resistivity. This is explained by the fact that, as shown in **Table 1**, banana leaves have a higher percentage of nano-cellulose fibres than pseudo-stem fibres and a better capacity to absorb water.

7.2. Effect of fiber ratio

Figure 8 illustrates the variation in volume resistivity with frequency for different weight percentages of banana leaf and pseudo-stem fibers while maintaining constant total fiber loading. In this scenario, the total amount of fiber loading in the product remains unchanged. The composite system exclusively composed of pseudo-stem fibers, without any banana leaf, exhibits the highest volume resistivity across all frequencies. This phenomenon can be attributed, at least in part, to the higher electrical resistance of pseudo-stem fibers compared to banana leaf fibers.

Increasing the weight proportion of pseudostem fibres integrated into composite systems can enhance their

volume resistivity. The banana leaf has a higher proportion of nano-cellulose and a stronger ability to absorb water than the pseudostem because it contains more of it. This is due to the increased concentration of nano-cellulose in banana leaves. As a result, the composite material composed entirely of banana leaf fibre had the lowest volume resistivity (100% banana leaf-L100) of all the systems examined.

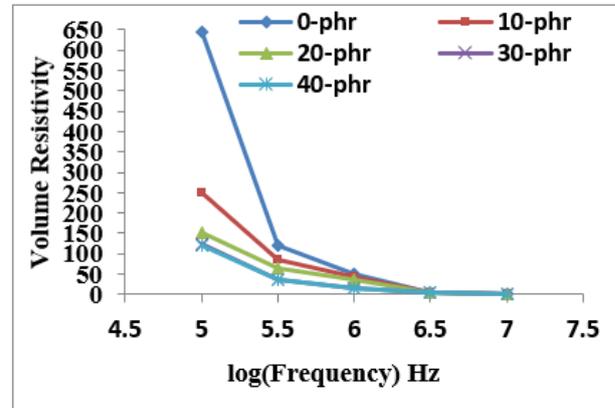


Figure 8. Variation in functional frequency and volume resistivity influenced by the fiber ratio

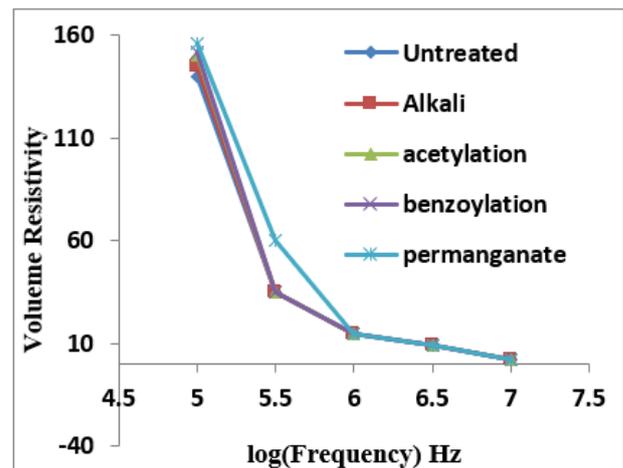


Figure 9. Volume resistivity varies as a result of chemical treatment and bonding agents.

7.3. Reaction of the bonding agent and the treatment of the fibre

The frequency-dependent volume resistivity of all composites, which have either had bonding agent added to them or their chemical composition changed, is shown in **Figure 9**. The volume resistivity of untreated composites is found to be substantially less than that of treated ones. The electric resistance of composites reduces exponentially with an increase in relative permittivity. The fibres' ability to absorb moisture is reduced when surface alterations are made to them because they change the degree of dispersion and lower relative permittivity. When specimens are chemically treated, they absorb more water than untreated specimens do, which increases their resistance. By improving fiber-to-matrix interfacial adhesion and decreasing vacancies, the insertion of a bonding agent

increases volume resistivity. By including a bonding agent, the volume resistivity is improved and maintained.

7.4. Electric current conductivity

The connection between electrical conductivity and fibre loading at two different frequencies—9 to 13 MHz—is shown in **Figure 10**. It demonstrates how adding thickness to fibres can raise their frequency-dependent conductivity. Aggregates compress more tightly against one another as fibre loading rises, decreasing their ability to withstand internal friction. As a result, total resistance falls as the loading level increases. Internal contact resistance and aggregate or agglomeration resistance combine to form the total resistance. Furthermore, the quantity of fibre supplied directly correlates with the number of polar groups. This phenomenon has a role in the change in conductivity that is seen at different fibre loading levels.

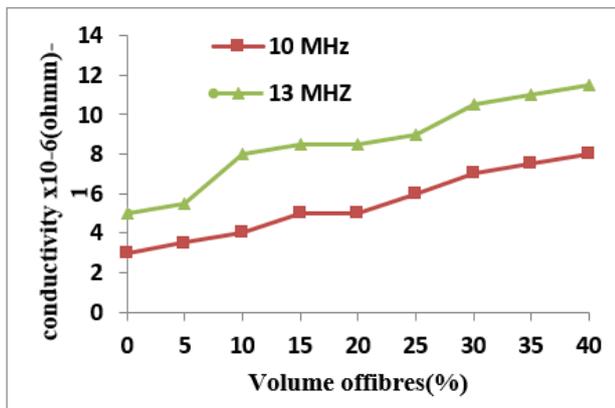


Figure 10. Composite conductive properties as an operation of fiber loading

The net resistance is the total of the resistances at both high and low frequencies when the contact resistance is much less than the combined resistance. This is the case when there is a notable decrease in the overall resistance of the system. Fibres help composite materials cross the "percolation threshold," which is the point at which they go from being insulating to conducting. Electrical conductivity starts to rise at a fibre volume loading of 15.6%, and as the volume percentage of fibres crosses this threshold, the slope starts to shift quickly. The conductivity in the percolation zone is significantly impacted by the dispersion process. A sudden shift in conductance is expected when the volume percentage of conductive particles exceeds this threshold. When a conductive phase is incorporated into an insulating phase, percolation takes place and a conductive network is created inside the insulating material. Because fiber-reinforced composites are made up of multiple individual fibres, they are an excellent example of an insulating material that needs low-resistance routes. Both flexible and rigid components contribute equally to current flow in an insulating material. Matrix with very poor conductivity and low fibre concentration is shown in **Figure 11**.

When separated from high-resistance fibers, isolated or agglomerated fibers lose their ability to transfer energy. There is a relationship between the crucial value c and the

value of the percolation peak given by Pc in Zallen's model.

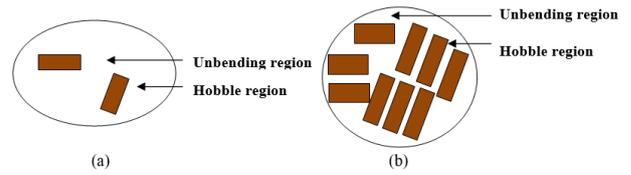


Figure 11. (a) At lower fiber loading, the percolation idea is illustrated graphically by showing the hobbling and unbending zones. (b) The hobble and unbending zones exhibit the percolation idea at increased fiber loading.

$$\varphi c = fPc \tag{6}$$

wherein f is the filler ratio with a range that is between 0 and 1.

When the volume proportion of fibers reaches 15.6%, there is an evident and sudden change in the slope. The hybrid composites have now attained the percolation barrier that they have been pursuing.

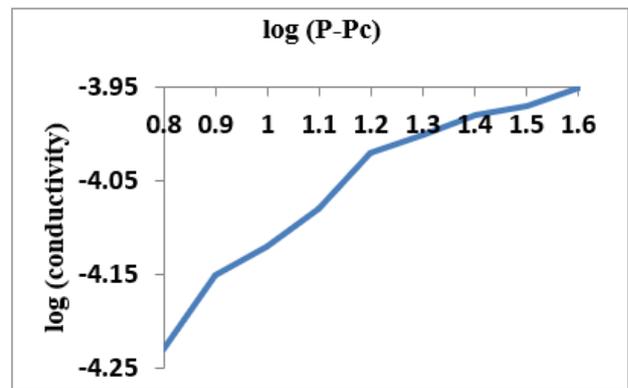


Figure 12. With a log Vs log (P - Pc) graph, you can show how the scaling law model of percolation works.

F = 0.7925 in the Zallen equation depicts that the conductive phase is made up of random, tightly packed rods that are all facing the same direction. To get the effective coordination number Z, use the following formula:

$$Pc = 2f/Z \tag{7}$$

Z was determined to have a value of 10.27

$$\sigma = \sigma_0 (P - Pc)^\beta \tag{8}$$

The following are the crucial exponents in terms of percolation: C, the conductivity of the composites; and P, the density of the conducting stage, which is the critical exponent. **Figure 12** illustrates this value, 0.34, as the slope of the log-Vs-log (Pc) graph. The maximum number of phases that can be obtained by the percolation concept is three.

8. Dissipation factor

The amount of power lost in different components in relation to the total power passing through them is measured by the dissipation factor. These functions are equal to tangent functions when the loss angles line up with the storage angles. When doing electromechanical

testing, the relationship between storage (ϵ') and dielectric loss (ϵ'') is determined using the formula $\tan \delta = \epsilon''/\epsilon'$. These functions resemble tangent functions because their loss angles are parallel to the storage angles. The material responds similarly to mechanical and electrical stimuli because of the ER matrix's flexibility. For example, data on voltage-current and stress-strain obtained during dynamic testing might be out of phase. The dissipation factor ($\tan \delta$) of an insulator is an important quantity to calculate because it indicates the amount of electrical energy from an alternating current that is transformed into heat inside the insulator.

8.1. Effect of a larger percentage of fiber loading

As a function of frequency logarithm, **Figure 13** shows the effect of the dissipation factor ($\tan \delta$) for different fibre loadings and operating conditions. The dissipation factor was found to increase with frequency, fibre concentration, and total fibre used in the experiment. This pattern holds true throughout the shift, demonstrating a very high degree of flexibility. The dissipation factor has two peaks, one at 5 MHz and the other at 10 MHz.

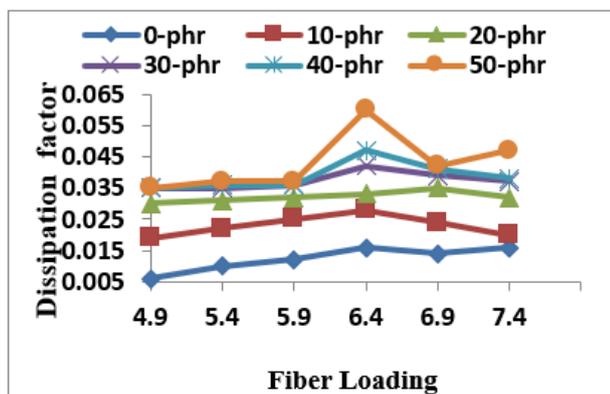


Figure 13. Dissipation factor and fiber loading

Irrespective of the system's state of being filled or empty, the peak locations remain consistent. Although the mechanism accountable for flexibility remains unaffected by the integration of fibres, their existence amplifies flexibility across all frequencies. Both ionic conductance and dipole polarisation have a significant impact on the loss factor (ϵ'') value. The structure contains numerous zones of dielectric loss, many of which manifest multiple losses. Polarity and mobility of carriers within the system exhibit an impact on the dissipation factor's quantitative value. The form of flexibility can be inferred from its polarity, while its duration can be determined by the time required to resolve the value of $\tan \delta$ at a particular frequency while in that period of flexibility. Moreover, the intrinsic efficacy of dissipation consistently escalates in correlation with the fibre content. This potency is amplified as the number of fibres increases while it decreases in ER.

This phenomenon is consistent at all frequencies. In addition, this is due to the fact that the polymer ER crystallizes under stress, giving it greater strength than other polymers. The delay in electronic and atomic polarization observed in ER is comparable to that noticed in ER, and it is this delay that gives ER its adaptability. It

has been discovered that an increase in the bonding frequency correlates with a rise in the dissipation factor of the amorphous region's flexibility. It is assumed that the flexibility of the polar group dipoles is responsible for the increase in $\tan \delta$ that occurs after the incorporation of fibers into the ER matrix, which occurs after the incorporation of fibers into the ER matrix. This increase in $\tan \delta$ occurs after the introduction of fibers into the ER matrix. Increased loss or dissipation is caused by the presence of lignocelluloses fibers, such as those present in banana leaves and Pseudostem, which have the potential to absorb water.

8.2. Effect of dissipation factor due to chemical Treatment

The dissipation factor of composites composed of chemically treated banana fibres is visually represented in **Figure 14**. This figure effectively conveys the degree of flexibility as well as the dissipation factor. Changes to the fibres' chemical composition have no effect on the relaxation system. Conversely, with increased utilisation, the degree of flexibility of the system grows. Dipolar flexibility is the cause of latency, an aspect that is not considered in its untreated state.

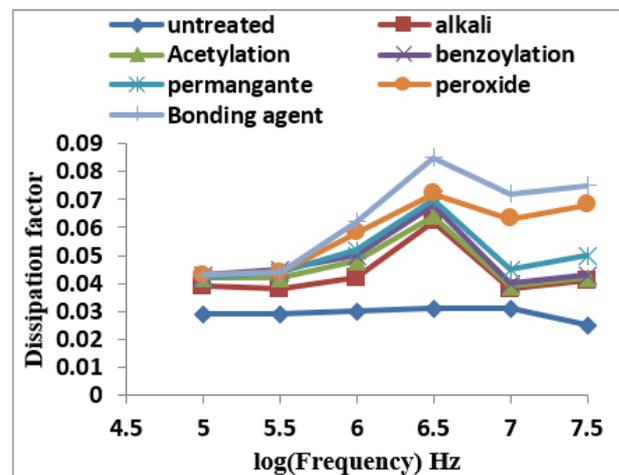


Figure 14. Dissipation factor vs. frequency, chemical treatments and bonding agent

A delay in response, referred to as latency, is caused by the orientation of the electric field when it is applied to dipoles. The incorporation of a bonding agent worsens the loss factor of the system. This attribute makes the system highly suitable for antistatic purposes, as it maintains charges even subsequent to the removal of the bonding agent. In addition, electrical resistance is increased by the bonding agent's presence, which renders the system highly suitable for antistatic applications. In regions undergoing substantial electrical discharge, the rate at which an electric charge decays is determined by the permittivity and volume resistivity of the material. Due to their low resistance and rapid charge dissipation, metals exhibit exceptional conductivity. Materials that possess the ability to retain charges and have chain flexibility and reparability are viable options for prolonged use. The accumulation of static charge presents the packaging industry with a significant challenge. In place of conventional matrices, anti-static constituents such as granules and fibres may be integrated. The incorporation

of lignocellulosic fibres into composite materials has the potential to augment their dielectric characteristics, consequently leading to a decrease in surface charges. The results of this research indicate that the integration of banana leaf and pseudostem fibres into hybrid fiber-reinforced ER composites may present a viable approach for the fabrication of economically viable antistatic materials.

9. Conclusion

This research focused on the impact of frequency and chemical modifications on banana leaf and pseudostem fiber-reinforced epoxy resin composites, specifically analyzing their dielectric loss factor, volume resistivity, relative permittivity, and adhesive properties. The findings revealed that interfacial polarization increased the relative permittivity at low frequencies, especially as the fiber content increased. Chemically treated composites showed varying levels of relative permittivity, and the introduction of a bonding agent improved fiber-to-matrix adhesion, reducing permittivity. Increased fiber content lowered resistivity, while chemical treatment raised it. Conductivity improved with the incorporation of conductive fibers and particles, with an optimal fiber loading factor of 9.32%. At 5 MHz, nanocomposites exhibited greater dielectric adaptability due to a combination of chemical treatments, resin matrices, and fiber loadings, resulting in enhanced dissipation factors. The bonding agent further increased electrical resistance and charge retention. In conclusion, banana fiber-reinforced composites with chemically modified epoxy resin show significant potential for power system electrical insulation applications. The present work has successfully shown that epoxy resin composites reinforced with banana leaf and pseudostem fibres exhibit exceptional dielectric characteristics under certain prescribed conditions and changes. The ideal fibre loading ratio was determined to be between 20% and 20% by weight. The most optimal combination of high dielectric strength and volume resistivity was achieved by a 50:50 blend of banana leaf and pseudostem fibres. Applied chemical treatment with 5% NaOH, the fibres exhibited enhanced interfacial adhesion, resulting in reduced dielectric losses and higher volume resistivity. Treatment with 1% DCP peroxide significantly improved dielectric characteristics by promoting cross-linking. The implementation of a 5% bonding agent, such as resorcinol, greatly increased the electrical resistance and enhanced the overall dielectric performance by decreasing permittivity and increasing resistivity. The composite exhibited increased relative permittivity at low frequencies as a result of interfacial polarisation. Nevertheless, the dielectric performance of the material remained consistent throughout a frequency range spanning from 5 MHz to 10 MHz. The use of natural fibres in the composite enhanced its environmental sustainability while maintaining excellent electrical insulation characteristics, therefore rendering the material appropriate for environmentally friendly high-voltage applications. Through the optimisation of these

properties, the composite materials that have been produced show considerable promise for application in power system electrical insulation and other dielectric applications.

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References

- Airinei, A., Asandulesa, M., Stelescu, M. D., Tudorachi, N., Fifere, N., Bele, A., & Musteata, V. (2021). Dielectric, Thermal and Water Absorption Properties of Some EPDM/Flax Fiber Composites. *Polymers*, **13** (15), 2555.
- Bouaamlat, H., Hadi, N., Belghiti, N., Sadki, H., Naciri Bennani, M., Abdi, F., Abarkan, M. (2020). Dielectric Properties, AC Conductivity, and Electric Modulus Analysis of Bulk Ethylcarbazole-Terphenyl. *Advances in Materials Science and Engineering*, **2020**, 1–8.
- Elloumi, I., Koubaa, A., Kharrat, W., Bradai, C., & Elloumi, A. (2021). Dielectric Properties of Wood-Polymer Composites: Effects of Frequency, Fiber Nature, Proportion, and Chemical Composition. *Journal of Composites Science*, **5** (6), 141.
- Haseena, A. P., Unnikrishnan, G., & Kalaprasad, G. (2007). Dielectric properties of short sisal/coir hybrid fibre reinforced natural rubber composites. *Composite Interfaces*, **14** (7-9), 763–786.
- Jayamani, E., Hamdan, S, Rahman, M. R., & Bakri, M. K. B. (2014). Comparative Study of Dielectric Properties of Hybrid Natural Fiber Composites. *Procedia Engineering*, **97**, 536–544.
- Jiahao Shen., Yuanxiao Yang., Zezhou Yang., Jun Li., Xinhui Li., Yimin Xie & Qinghua Feng. (2024). All-natural, thermally conductive, flame-retardant electrical insulating lignocellulose-mica composite film fabricated via in-situ mineralization. **220**, 119173.
- Jiahao Shen., Zezhou Yang., Jingyi Lian., Jun Li., Xinhui Li., Yimin Xie., Yunjian Wu., Qinghua Feng & Xiaoxing Zhang. (2022). An all-natural, bioinspired, biodegradable electrical insulating composite based on lignocellulose and mica tailings. **253**, 5.
- Karimah, A., Ridho, M. R., Munawar, S. S., Adi, D. S., Ismadi, Damayanti, R., Fudholi, A. (2021). A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations. *Journal of Materials Research and Technology*, **13**, 2442–2458.
- Khalid, M. Y., Al Rashid, A., Arif, Z. U., Ahmed, W., Arshad, H., & Zaidi, A. A. (2021). Natural fiber reinforced composites: Sustainable materials for emerging applications. *Results in Engineering*, **11**, 100263.
- Khan, I., Saeed, K., & Khan, I. (2017). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*.
- Li, M., Pu, Y., Thomas, V. M., Yoo, C. G., Ozcan, S., Deng, Y, Ragauskas, A. J. (2020). Recent Advancements of Plant-Based Natural Fiber-Reinforced Composites and Their Applications. *Composites Part B: Engineering*, 108254.
- Mohammed, L., Ansari, M. N. M., Pua, G., Jawaid, M., & Islam, M. S. (2015). A Review on Natural Fiber Reinforced Polymer

- Composite and Its Applications. *International Journal of Polymer Science*, **2015**, 1–15.
- Mohammed, L., Ansari, M. N. M., Pua, G., Jawaid, M., & Islam, M. S. (2015). A Review on Natural Fiber Reinforced Polymer Composite and Its Applications. *International Journal of Polymer Science*, **2015**, 1–15.
- Mylsamy, K., & Rajendran, I. (2010). Investigation on Physio-chemical and Mechanical Properties of Raw and Alkali-treated Agave americana Fiber. *Journal of Reinforced Plastics and Composites*, **29** (19), 2925–2935.
- Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, **143**, 172–196.
- Nimanpure, S., Hashmi, S. A. R., Kumar, R., Nigrawal, A., Bhargaw, H. N., & Naik, A. (2017). Sisal fibril epoxy composite-a high strength electrical insulating material. *Polymer Composites*.
- Quiles-Carrillo, L., Montanes, N., Pineiro, F., Jorda-Vilaplana, A., & Torres-Giner, S. (2018). Ductility and Toughness Improvement of Injection-Molded Compostable Pieces of Polylactide by Melt Blending with Poly(ϵ -caprolactone) and Thermoplastic Starch. *Materials*, **11** (11), 2138.
- Rajak, D. K., Pagar, D. D., Kumar, R., & Pruncu, C. I. (2019). Recent progress of reinforcement materials: a comprehensive overview of composite materials. *Journal of Materials Research and Technology*, **8** (6), 6354–6374.
- Rajamanikandan T, Banumathi S, Karthikeyan B, Palanisamy R, Mohit Bajaj, Hossam M Zawbaa, Salah Kamel, "Investigation of dielectric and mechanical properties of Lignocellulosic Rice Husk Fibril for high and medium voltage electrical insulation applications, *Journal of Materials Research and Technology* 22, 865-878, 2023.
- Rajesh, C., Manoj, K. C., Unnikrishnan, G., & Purushothaman, E. (2011). Dielectric Properties of Short Nylon-6 Fiber-Reinforced NBR Composites. *Advances in Polymer Technology*, **32** (S1), E90–E102.
- Sankaran, S., Deshmukh, K., Ahamed, M. B., & Khadheer Pasha, S. K. (2018). Recent advances in electromagnetic interference shielding properties of metal and carbon filler reinforced flexible polymer composites: A review. *Composites Part A: Applied Science and Manufacturing*, **114**, 49–71.
- T.Rajamanikandan, S.Banumathi, R.Asokan, "Investigation of the Dielectric Characteristics of Rice husk Residue-Reinforced Epoxy Resin". *International journal of Electrochemical Science*, 2021, Volume **16**, Issue: 12, ISSN: 1452-3981.
- Thyavihalli Girijappa, Y. G., Mavinkere Rangappa, S., Parameswaranpillai, J., & Siengchin, S. (2019). Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review. *Frontiers in Materials*, **6**.
- Yabo Cao, Zezhou Yang., Xinhui Li., Yimin Xie., Qinghua Feng., Xiaoxing Zhang., & Xinlin Tuo. (2024). Multifunctional, Length-Tailored Hydroxyapatite Nanowire/Aramid Nanofiber Composites: Implications for Electrical Insulation Applications. *ACS Applied Nano Materials*, **7**, **17**.
- Yabo Cao., Jun Li., Xinhui Li ., Yimin Xie., Qinghua Feng., Xiaoxing Zhan & Xinlin Tuo. (2024). A sol-gel strategy for constructing a hydroxyapatite nanowire/aramid nanofiber electric insulating composite with excellent flame retardancy and mechanical property. *Materials Today Communications*, **39**, 108627.