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INNOVATION IN ACTION: TURNING IDEAS INTO REALITY

Chapter 47

Dielectric Characterization of Flexible Pineapple Leaf Fiber (PALF) Reinforced Polydimethylsiloxane (PDMS) Composite as a Potential Antenna Substrate for Wearable Antenna Application

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ABSTRACT

The rapid advancement of wearable technology has increased the demand for flexible, lightweight, and high-performance antenna substrates. This study investigates the dielectric properties of Pineapple Leaf Fiber (PALF) reinforced Polydimethylsiloxane (PDMS) composites as a potential substrate for wearable antennas. The fabrication method used was Manual Polymer Mixing Method. The composites, with fiber loadings from 10wt.% to 90wt.%, underwent alkaline treatment using Sodium Hydroxide (NaOH) to enhance fiber-matrix compatibility. Dielectric properties were analyzed using a Vector Network Analyzer (VNA) to measure dielectric constant, loss tangent, and permittivity. Results indicate that increasing fiber loading improves the dielectric constant, while alkaline treatment reduces the loss tangent, enhancing performance. The treated composites demonstrated superior mechanical stability and flexibility, crucial for wearable applications. Additionally, CST Studio-designed antenna prototypes showed improved radiation patterns, return loss, and efficiency, confirming PALF-PDMS as a suitable dielectric substrate. These findings highlight the potential of sustainable natural fibers for advanced, eco-friendly electronic applications.

Key Words: Biofibre-reinforced composites, Pineapple Leaf Fibre (PALF), Polydimethylsiloxane (PDMS), Dielectric characterization, Fibre Loading, Alkaline treatment

1. INTRODUCTION

Natural fibres have gained attention as reinforcement materials due to their excellent mechanical properties, biodegradability, and eco-friendly nature. In contrast, conventional materials such as FR4, Rogers RT/duroid 5880, and polyimide, though widely used, present several drawbacks including rigidity, environmental concerns, high cost, and lack of biodegradability (ENGHETA, 2005; HUANG ET AL., 2013). One significant limitation is their fixed dielectric constant, which cannot be easily modified, a challenge that natural fibres can potentially overcome. Biofibre-reinforced polymer composites offer a promising alternative thanks to their mechanical strength, flexibility, and sustainable profile. Moreover, the dielectric properties of biofibres, particularly their typically low dielectric constant and loss, can be tuned by adjusting the material's weight percentage. Although previous studies have highlighted the promise of bio-based materials in electronic applications, comprehensive research on their dielectric characterization as substrate materials remains limited (LEE, 2017; MISHRA & RAJPUT, 2020).

2. LITERATURE REVIEW

A study (Zulkifli et al., 2017) demonstrated that altering filler content results in varied tangent loss and dielectric constant values. Moreover, different agricultural waste materials—such as rice straw, rice husk, sugarcane bagasse, and banana leaves—when combined with Epoxy 331, exhibit distinct dielectric behaviours. A higher dielectric constant is desirable for substrate applications, while a higher loss tangent is beneficial for microwave absorber use. Further research (Jayamani et al., 2014; Kulandaisamy & Govindasamy, 2020) revealed that increasing the fibre weight percentage in hybrid composites tends to raise the dielectric constant, dissipation factor, and loss factor. Interestingly, the type of polymer matrix shows minimal influence on the dielectric performance of these composites. Additionally, composites made with fibres that underwent alkaline treatment generally exhibited a lower dielectric constant, attributed to enhanced fibre hydrophobicity.

3. MATERIALS AND METHODS

3.1. Materials

Pineapple Leaf Fibre (PALF), a natural fibre, was selected for further study due to its distinctive properties and strong potential for the targeted application. Polydimethylsiloxane (PDMS) was chosen as the polymer matrix because of its recognized flexibility, optical clarity, and biocompatibility (Gbotemi et al., 2018). Additionally, alkaline treatment using Sodium Hydroxide (NaOH) has proven to be an effective method for enhancing fibre–matrix compatibility, improving the fibre's structural qualities, and contributing to the development of high-performance composite materials (Bekele et al., 2023; Kaima et al., 2023).

(a) (b)

Figure 1: PALF (a)Pure (b) Treated

3.2. Fibre Treatment

The pineapple leaf fibre undergoes an alkaline treatment to improve the compatibility of the fibres with the polymer matrix. The surface treatments using Sodium Hydroxide (NaOH) were then applied to the fibres. Pineapple leaf fibres were soaked in 1.5M concentration of NaOH solution for 3 hours at room temperature. Then the fibres were washed several times with distilled water until neutral pH was achieved and finally the oven dried at 80 ^{o}C for 48 hours as depicted in Figure 1(b).

3.3. Composite Preparation (Manual Polymer Mixing Method)

Raw pineapple leaf fibres (PALF) were processed by grinding into fine particles or cutting into 10 mm lengths for treated samples. Polydimethylsiloxane (PDMS) was mixed with its curing agent in a 10:1 ratio, after which the treated fibres were gradually added to ensure uniform dispersion. Both PALF and PDMS were accurately measured and blended in a specific ratio. The mixture was stirred continuously for five to ten minutes as PDMS was added gradually, promoting even distribution. Finally, the composite mixture was poured into a mold and compressed with weights to ensure consistent thickness.

3.4. Composite Formulation

Different fibre loadings were formulated by varying the weight percentage of PALF within the composite, specifically at 10wt%, 20wt%, 30wt%, 40wt%, 50wt%, 60wt%, 70wt%, 80wt%, and 90wt%. These loading levels were applied to both untreated (pure) and alkaline-treated fibres.

3.5. Dielectric Measurement

The dielectric constant, also known as relative permittivity (εr), plays a vital role in influencing the impedance, bandwidth, and radiation efficiency of antennas by controlling the propagation speed of electromagnetic waves through a material. For wearable antenna designs to perform effectively, precise measurement of the dielectric constant is essential (John & Thomas, 2008; Mishra & Rajput, 2020).

Table 3 Pure Fibre Dielectric Properties

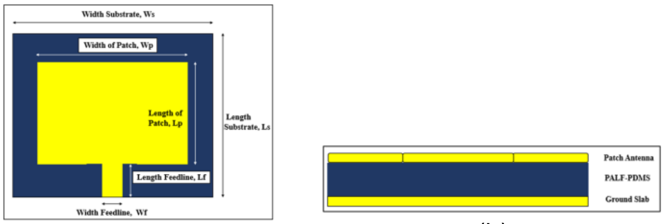
Weight Percentage / Parameter	10	20	30	40	50	60	70	80	90
Dielectric Constant, ε_r	1.65	1.67	1.89	1.92	1.94	1.95	2.18	2.6	2.63
Tangent Loss, tan δ	0.04	0.18	0.19	0.2	0.2	0.23	0.25	0.38	0.41

Table 2 Treated Fibre Dielectric Properties

Weight Percentage / Parameter	10	20	30	40	50	60	70	80	90
Dielectric Constant, ε_r	1.58	1.59	1.71	1.78	1.85	2.14	2.59	2.7	2.98
Tangent Loss, tan δ	0.14	0.16	0.18	0.25	0.25	0.31	0.34	0.43	0.44

3.6. Antenna Fabrication

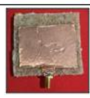
After curing, a copper sheet was applied on the top surface of each substrate to form the radiating patch and feedline, based on the design shown in Figure 2(a). An SMA connector was soldered at the edge of the feedline for RF measurements. The backside of each substrate was fully covered with copper tape to act as the ground plane, resulting in a complete microstrip antenna structure, as illustrated in Figure 2(b). A total of 18 microstrip patch antennas were fabricated using PALF (pineapple leaf fiber)-reinforced PDMS (polydimethylsiloxane) composites as the substrate material shown in Table 3.



(a) (b)

Figure 2: Microstrip Patch (a) Antenna Dimension (b) Cross Sectional

Table 3 Fabrication of Antenna

Weight Percentage	10wt.%	20wt.%	30wt.%	40wt.%	50wt.%	60wt.%	70wt.%	80wt.%	90wt.%
Pure									
Treated									

4. RESULTS AND DISCUSSION

This study confirms the potential of Pineapple Leaf Fibre (PALF) reinforced Polydimethylsiloxane (PDMS) composites as effective substrate materials for dielectric applications. The dielectric constant of both pure and treated composites increases with rising fibre loading, with a notable enhancement observed in treated PALF beyond 60 wt.% as shown in Table 1 and Table 2. This improvement is attributed to the stronger interfacial bonding between fibre and matrix following alkaline (NaOH) treatment.

4.1 Effect of Fibre Loading:

The dielectric constant increases proportionally with fibre loading. While pure PALF composites exhibit higher dielectric constants at lower fibre percentages, treated PALF surpasses the pure variant above 60 wt.%. This is due to enhanced interfacial polarization and the higher cellulose content in treated fibres.

4.2 Effect of Alkali Treatment:

Alkaline treatment removes non-cellulosic components, improving fibre-matrix compatibility and reducing hydrophobicity. This results in better fibre orientation and bonding, especially at higher fibre loadings, which contributes to the increase in dielectric constant beyond 70 wt.%.

5. CONCLUSION AND RECOMMEDATIONS

This study demonstrated that PALF-reinforced PDMS composites possess favorable dielectric properties, mechanical flexibility, and sustainability, making them suitable as wearable antenna substrates. The material showed a stable dielectric constant and low loss tangent, along with enhanced flexibility and structural integrity, supporting efficient and eco-friendly communication. For future work, research should long-term stability under environmental and mechanical stress and investigate large-scale fabrication methods to enable practical use in next-generation wearable technologies.

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