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Dielectric material preparation from pineapple leaf fiber based on two-level factorial analysis and its morphological structure

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ABSTRACT

Natural fiber has earned great attention for its discovery as a green material in dielectric composites. Their excellent dielectric properties have granted them the great capability to be used in high dielectric composites. Hence, this study attempts to determine the most influential factor contributing to the permittivity of pineapple leaf fibers and to examine the morphological structure of the developed fibers. The two-level factorial analysis was applied to determine the significant, influential factors and the best conditions contributing to the permittivity value of fiber. The factors include the pineapple leaf-to-soda ratio (1:5 and 1:10), soda concentration (5–10 wt%), temperature (60–100 ℃), and pulping time (45–75 min). The fiber was extracted from the pineapple leaf through the soda pulping method, and the content was analyzed by the Kurschner-Hanack method. Based on the analysis, the pineapple leaf-to-soda ratio was observed as the most significant factor contributing to the permittivity value of fiber, with an 8.86% contribution. The best conditions were suggested at a 1:10 pineapple leaf-to-soda ratio, 5 wt% soda concentration, 100 ℃ temperature, and 45 min of pulping time, contributing to the 1.85 permittivity value of pineapple leaf fiber. The scanning electron microscope images of the material under test indicate that the morphological structures play a crucial part in determining the permittivity value of fiber. Therefore, with suitable processing factors, pineapple leaf fiber can be a great dielectric material used in many engineering applications.

Introduction

The use of natural fibers as raw materials has been of major interest in the material engineering industry. Currently, much research is conducted on pineapple leaves due to their significant amount of fiber rich in cellulosic materials [1]. Pineapple leaf is a sustainable raw material with continuous supply and is easily available in nature with biodegradable and renewable properties. Pineapple leaves are currently being discarded after post-harvesting and being wasted on major pineapple plantations. Making full use of these wastes could reduce the environmental pollution related to the disposal process and could be a potent substitution for synthetic fiber material. The high cellulose composition of approximately 81% in pineapple leaf [2] has drawn a heap of interest for its discovery as a green material in dielectric materials. Dielectric materials are conventionally developed from silica, mica, plastics, ceramics, and glass, which are non-biodegradable and, not to mention, are mostly expensive. The growing environmental concerns across the globe have elicited an awareness of the need to design eco-friendly materials.

The interest in cellulosic fibers has expanded through the decade from textile to paper production into reinforcement agents and is currently of much interest as dielectric materials. The excellent dielectric properties exhibited by natural fibers could potentially be used in high-dielectric composites. A higher dielectric constant and low loss properties are preferred if the material is developed for signal propagation. Meanwhile, high-loss properties are suitable if the material is used for signal or microwave absorbers, also known as radio frequency (RF) absorbers. The dielectric material can be used in all frequency ranges of applications. For example, the electrical properties of

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dielectric material are the main parameters for capacitor development in determining the capability of storing energy, represented by the dielectric constant or permittivity (ε). It is also used in the insulator layer of a printed circuit board at both low and high frequencies.

Recently, many researchers have been interested in developing a technique for material preparation from natural fibers that is applicable to being used as a dielectric material [3–5]. The developed dielectric materials have various electrical properties that suit their applications. The development of fiber materials using agricultural waste includes pineapple leaf [6], rice husk [7], corn husk [8], oil-palm empty fruit bunch [9,10], and banana leaf [11]. The development of pineapple leaf fiber-reinforced epoxy composites by the hand lay-up method [6] has shown an increase in dielectric constant value with increasing fiber concentration. The developed materials could be used as insulating materials, such as capacitors. The dielectric constant value of the rice husk epoxy composite shows that the developed material could be used as an alternative material in microwave applications [7]. The collected rice husk was grounded and mixed with epoxy resin before being molded in a rectangular shape and tested for dielectric properties. The printed circuit board (PCB) was successfully made from banana leaves and wheat gluten, replacing the non-biodegradable plastic materials [11]. The dielectric constant value of the developed PCB obtained is in the range of dielectric materials conventionally used for PCBs and other electronic components. The upsurge in consumption of these agricultural wastes in material development may be related to their renewable properties and continuous supply with recyclability, which can eventually reduce electronic waste.

A morphological study has also become one of the important areas to be explored in the formulation of dielectric materials. Morphology is the study of individual material within a particular material, which indicates its possible performance in several situations. The morphological study includes the study of particle size and structures, surfaces, crystallinity, and polarity of one material to understand how they behave since they determine the chemical, mechanical, electrical, and physical properties of one material. Morphological structures can be identified based on their physical and mechanical properties and elemental compositions. The performance of the dielectric properties formulated from the fiber materials is closely related to the morphological structures [12]. The techniques, parameters, or variables utilized during the preparation of fiber material might change the morphological structures and dielectric properties. Studying the morphological structure of natural fiber in the formulation of dielectric materials has also become an interesting topic since, traditionally, natural fibers are mainly used in textiles and paper-making industries and as chemical filters. Due to their similar properties to engineered fibers, natural fibers can be used as fiber reinforcement to replace polymers and bio-composites. The biodegradability features and non-carcinogenic properties of natural fibers are also beneficial in developing dielectric materials to replace non-biodegradable materials, reducing electronic waste.

Although dielectric materials made from natural fibers are known for their outstanding mechanical properties, only a few reports have explored their dielectric properties and the effect of the fibers on such properties. In addition, although the development of fiber materials using agricultural waste has been the focus of attention recently, the development is still in the early stages. The contributing factors to the performance of dielectric properties during fiber material preparation have not been well identified yet. Thus, this paper investigates the main factors contributing to the electrical properties of pineapple leaf fiber. It is necessary to determine the main factor influencing the dielectric properties during the fiber extraction process to tailor the material performance effectively. The morphological structures and elemental composition of materials are examined to correlate with their dielectric properties. A two-level factorial analysis is used to determine the effects of factors in the fiber extraction process for fiber preparation. Four factors are considered in this work, which are the pineapple leaf-to-soda ratio, soda concentration, temperature, and pulping time. The pineapple leaf fiber is obtained from the agricultural waste of the pineapple leaf.

Materials and methods

Sample preparation

Sample collection and preparation

Pineapple leaf (PL), classified as agricultural waste, was used as the raw material in this study. The leaf was harvested from a pineapple plantation at Pekan, Pahang, Malaysia. The harvested pineapple leaf was thoroughly cleaned to remove dirt and then oven-dried at 100 °C before being cut into pieces about 2 cm long. The soda pulping method was applied for fiber extraction from the pineapple leaf. Sodium hydroxide (NaOH) was used in the extraction of soda pulping.

Experimental setup for factorial analysis

The two-level factorial analysis (TLFA) was applied to determine the significant factors and the best conditions contributing to the permittivity value of extracted pineapple leaf fiber. The TLFA is a good approach to evaluate the most significant factors and simultaneously identifying the interactive factors [13,14]. The factors include the pineapple leaf to soda (PL:S) ratio (1:5 and 1:10), soda concentration (5–10 wt%), temperature (60–100 ℃), and pulping time (45–75 min). The extraction of pineapple leaves through the soda pulping method produced raw fiber, which was tested for permittivity. The permittivity value obtained from the raw pineapple leaf fiber becomes the main indicator for the performance of the dielectric material produced. The fiber extraction was conducted according to the design table (Table 1) constructed by the Design-Expert software, where all factors were randomized with 16 experimental runs. The experimental outputs were analyzed accordingly by the mentioned software through analysis of variance (ANOVA) with a 95% confidence level [15,16]. The ANOVA functions to determine the coefficient of the model and to verify the significance of the factors chosen. It is also to determine the suitability of the chosen range [17].

Soda pulping experiment and fiber content analysis

A soda pulping experiment was conducted by preparing the precise pineapple leaf and soda ratio. To prepare 1:5 of PL:S, 100 g of PL was mixed with 500 ml of soda. Meanwhile, 1:10 PL:S was prepared by mixing 100 g of PL with 1000 ml of soda. The selected cooking temperatures of 60 and 100 ℃ were adjusted by heating the hotplate and maintained by checking with a thermometer manually. The range of cooking temperature was selected based on the preliminary study and

Table 1
A two-level factorial design table for pineapple leaf extraction.

Std	Factors				Response
	A: PL:S (g/ml)	B: Soda concentration (%)	C: Temperature (℃)	D: Pulping time (min)	Permittivity (ε)
1	1:5	5	60	45	1.64
2	1:10	5	60	45	1.53
3	1:5	10	60	45	1.50
4	1:10	10	60	45	1.69
5	1:5	5	100	45	1.62
6	1:10	5	100	45	1.85
7	1:5	10	100	45	1.74
8	1:10	10	100	45	1.69
9	1:5	5	60	75	1.67
10	1:10	5	60	75	1.78
11	1:5	10	60	75	1.53
12	1:10	10	60	75	1.62
13	1:5	5	100	75	1.55
14	1:10	5	100	75	1.44
15	1:5	10	100	75	1.58
16	1:10	10	100	75	1.73

from the previous research, which is in the range of 84–100 ℃ [18] and 90–130 ℃ [19].

The pulping time was set at 45–75 min according to the prior one-factor-at-a-time (OFAT) experiment [20]. The PL and soda mixture were heated on the hot plate according to pulping times (Table 1). The mixture was stirred during the cooking process. The cooled cooked mixture was filtered and blended until it turned into pulp. The pineapple leaf pulp was thoroughly washed with water until a clear residue was obtained before being squeezed. The squeezed pineapple leaf pulp was oven-dried at 60 °C to obtain the dried pulp. A fiber content analysis was then conducted on the dried pineapple leaf pulp.

The fiber content in the pineapple leaf fiber was determined by the Kurschner-Hanack method [21], where acetic acid and nitric acid were used as reagents. 15 ml of 80% acetic acid and 1.5 ml of concentrated nitric acid were added to a beaker containing 1 g of air-dried pineapple leaf pulp and heated to 100 °C for 20 min. The mixture was then filtered, thoroughly washed, and oven-dried at 105 °C for 24 h. The weight of the pineapple leaf pulp was recorded to determine the fiber content (%) in the pineapple leaf [22].

Best condition validation experiment

A validation experiment was performed according to the best conditions obtained from the Design-Expert software to validate the suggested best condition. The experiment was conducted to compare the suggested predicted data with the experimental data to determine the error between experimental and predicted values, calculated according to Eq. (1).

$$Error(\%) = \frac{Predicted \quad value - Experimental \quad value}{Predicted \quad value} \times 100 \tag{1}$$

Characterization technique of pineapple leaf fibers

Permittivity test

Permittivity was measured based on the waveguide technique in the microwave region as proposed by Karim *et al.* [23] and Karim *et al.* [24]. The measurement was conducted in the G-band, covering a frequency range of 3.95–5.85 GHz. The material under test (MUT) was initially machined as the dimension of the G-band waveguide was limited to 47.55 × 22.15 mm. The height of the sample was set to be the same height as the waveguide (22.15 mm), while the width can be any size to ease the sample machining process as long as it does not exceed the width of the waveguide (47.55 mm). The MUT could be placed in an arbitrary position in the waveguide, preferably at the center of the waveguide, as the electric field is strong at the center, which will lead to high-accuracy detection of scattering wave changes. The waveguide was connected to an E5071C Agilent Network Analyzer to measure the magnitude and phase of transmission coefficients, as illustrated in Fig. 1. The high-sensitive reflection coefficient is not used in this measurement technique as it is easily affected by the surrounding noise during the measurement.

The dielectric constant of the MUT is estimated from the measured transmission coefficient using an inverse technique [25]. The transmission coefficient was calculated using an electromagnetic theory formulation by guessing the initial value of the dielectric constant. The guessing of the dielectric constant was repeated until the measured and calculated transmission coefficient values were in good agreement. The last guess value of the dielectric constant is considered the dielectric constant of the MUT.

Morphological analysis of pineapple fiber by scanning electron microscopy

The surface morphology of pineapple leaf fiber obtained from the pulping process of PL was studied using scanning electron microscopy (SEM; Hitachi/TM3030 PLUS, Japan) from the top view. The surface morphology examination was performed by selecting six MUT samples from 16 experimental runs. The MUT sample was chosen based on the permittivity values with the lowest, average, and highest permittivity values. The examination based on the selected samples is crucial to making a significant correlation afterward. The samples were then coated with 3 nm gold using a vacuum sputter coater (Quorum Technologies Q300TD) to provide a conductive surface on the samples that could inhibit charging, prevent charring, and enhance the secondary electron (SE) signal required for an excellent image of the SEM morphological study of pineapple leaf fibers. 15 kV was used as the accelerating voltage.

Energy-dispersive X-ray spectroscopy analysis of pineapple leaf fibers

Energy-dispersive X-ray spectroscopy (EDX SEM; Hitachi/TM3030 PLUS, Japan) was used as the analytic technique for identifying the elements of composition present in the pineapple leaf fibers. Backscattered secondary electrons (BSE) in SEM were used to reveal variations in the elemental composition of localized areas of pineapple leaf fiber samples. The EDX analyses were incorporated into the features of the SEM.

Results and discussion

Two-level factorial analysis

Numerical model for dielectric material development

The output of the experiments is illustrated in Table 1, with the permittivity value ranging from 1.44 to 1.85. The permittivity value varied with the different experimental conditions. The highest permittivity value (1.85) was obtained at the experimental setup of 1:10 PL:S, 5 wt% soda concentrations, at a temperature of 100 ℃, and 45 min of pulping time. Meanwhile, the lowest permittivity value was obtained at a PL:S ratio of 1:10, a soda concentration of 5 wt%, a temperature of 100 °C, and a pulping time of 75 min. Interestingly, the only difference between the lowest and highest permittivity values was observed at the different pulping times. Longer pulping times reduce the permittivity value, and vice versa.

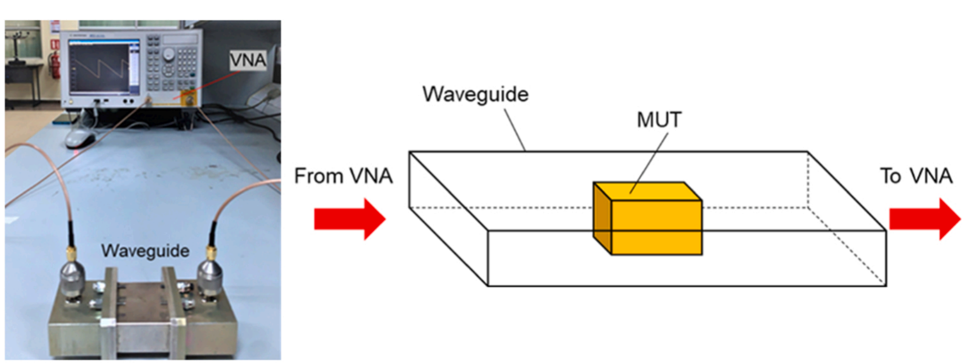

Fig. 1. Setup for permittivity measurement.

The analysis of variance was used to analyze the permittivity value based on a 95% confidence level and is summarized in Table 2. The p-value of the model was 0.0011, which was lower than 0.05, indicating the significance of the model. The R^2 value of 0.9979 shows high statistical significance for the model. This value implied that the model was accepted and could represent the process since the satisfactory R^2 value for a biological process should at least be 0.8 [26]. Based on the p-value for each factor, PL:S, temperature, and pulping time were significant towards the permittivity value exhibited by the p-value of less than 0.05.

Eq. (2) identifies the interaction between all factors on permittivity value. The equation displays a model that correlates the interaction between input and output variables, with A, B, C, and D representing PL:S, soda concentration, temperature, and pulping time, respectively.

$$\begin{aligned} Permittivity = {} & 1.63 + 0.032A - 4.47^{-4}B + 0.015C - 0.023D + 0.015AB \\ & + 0.035BC - 0.054CD - 0.02ABC + 0.013ABD - 0.016ACD \\ & + 0.041BCD + 0.055ABCD \end{aligned} \tag{2}$$

Effect of process factor on permittivity value

The percent contribution of independent and interaction factors is presented in Table 3. It was observed that the PL:S were the most influential factors contributing to the permittivity value, with an 8.86% contribution, followed by pulping time and temperature, with 4.49% and 1.93% contributions, respectively. The low percentage contribution by soda concentration demonstrated that the factor had the least impact on the permittivity value. Meanwhile, the interaction between temperature and pulping time (CD) represented the highest contribution to the permittivity value, with 24.62%. Apart from that, the interaction between soda concentration and temperature (BC) contributed as much as 10.63% towards the permittivity value, suggesting the importance of the interacting factors, as portrayed by the Pareto chart in Fig. 2.

The Pareto Chart in Fig. 2 displays the main and interaction effects of all factors on the permittivity value. The bar in orange exhibited positive effects, while the blue-colored bar indicated negative effects. The positive effect is obtained when the factor is proportional to the response value, while the negative is disproportional. The main factors of PL:S, temperature, and pulping time were observed to affect the permittivity value as represented by the bars above the t-value limit line, with PL:S being the highest above the Bonferroni limit line. Both PL:S and the temperature positively contributed to the permittivity value, as displayed by the orange bar color, as opposed to pulping time, which contributed negatively to the permittivity value. This response is explained by its blue-colored bar. The solid-to-liquid ratio (pineapple leaf-to-soda ratio) is important in cellulose fiber extraction [27]. At a low soda volume, it is difficult for the soda to infiltrate the pineapple leaf and dissolve the lignin, resulting in a small amount of cellulose fiber being extracted. According to Song *et al.* [27], the dissolving capacity of any substance increases with temperature increment. More lignin from the pineapple leaf was dissolved at a high temperature, increasing fiber extraction as well as its concentration. The increase in fiber concentration resulted in an increase in permittivity value.

Table 2
Analysis of variance (ANOVA) table for permittivity.

Source	Sum of Square	df	Mean square	F value	p-value Prob>F
Model	0.19	12	0.016	119.41	0.0011
A: PL:S	0.017	1	0.017	127.29	0.0015
B: Soda Concentration	3.197E-006	1	3.197E-006	0.025	0.8853
C: Temperature	3.608E-003	1	3.608E-003	27.77	0.0133
D: Pulping Time	8.371E-003	1	8.371E-003	64.43	0.0040
AB	3.756E-003	1	3.756E-003	28.91	0.0126
BC	0.020	1	0.020	152.70	0.0011
CD	0.046	1	0.046	353.60	0.0003
Residual	3.898E-004	3	1.299E-004		
Cor Total	0.19	15			
R^2	0.9979				
Adjusted R^2	0.9896				

Table 3
The contribution of main and interacting factors.

Term	Percent contribution (%) Permittivity (ε)
A: PL:S	8.86
B: Soda concentration	1.713E-003
C: Temperature	1.93
D: Pulping time	4.49
AB	2.01
AC	0.11
AD	0.027
BC	10.63
BD	0.077
CD	24.62

In contrast, the pulping time has negatively affected the permittivity value. The longer pulping time causes the permittivity value to decrease. This was due to the pineapple leaf fibers being dissolved in the solution when a longer pulping time was applied, reducing the fiber amount. The reduced amount of fiber extracted decreased the permittivity value with increasing pulping time. Wutisatwongkul et al. [19] found that the shorter pulping time for pineapple leaf fiber extraction resulted in better pulp production, whereas longer pulping time caused the cellulose fiber to be dissolved. Soda concentration is insignificant as the bar was way below the t-value limit line. The p-value for soda concentration in Table 2 exhibited a value of more than 0.05, which indicates the factor is insignificant. The interaction between temperature and pulping time (CD) contributed the most to the permittivity value, with negative effects.

Meanwhile, the interactions of soda concentration and temperature (BC) and PL:S and soda concentration (AB) were also significant, which is explained by the bar position beyond the t-value limit line. Both interactions contributed positively toward the permittivity value. Hence, these interactions caused more pineapple leaf fibers to be efficiently extracted, which increased the permittivity value, as the strong interactions between these factors induced the delignification of the pineapple leaf.

The effect of the three most significant independent parameters on the permittivity value was displayed in Figs. 3 to 5. Fig. 3 exhibits the effect of the pineapple leaf-to-soda ratio on the permittivity value. It was observed that the permittivity value was highest when the ratio of 1:10 was applied in the experiment. The addition of a soda fraction instead of a pineapple leaf sample in the treatment caused a significant increment in the permittivity value. The addition of soda during the cooking process accelerated the delignification process, resulting in more pineapple leaf fiber in the mixture and increasing the permittivity value. A similar observation was obtained by Gao *et al.* [28], where the increase in the solid-to-liquid ratio from 1:5–1:10 resulted in more cellulose fiber being hydrolyzed in the sample.

Fig. 4 displays the effect of temperature on the permittivity value. It was observed that the increase in temperature from 60 to 100 ℃ causes a rise in permittivity value. The maximum permittivity value was obtained at 100 ℃. This may be due to more pineapple leaf fibers being released at this temperature, which increases the permittivity value. More fibers could be extracted as the temperature rises, since high temperatures could enhance delignification [29]. Elloumi *et al.* [30] also highlighted that the increase in cellulose fiber content in a composite increases the permittivity value.

Fig. 5 demonstrates the effect of pulping time on the permittivity value. The maximum permittivity value was obtained at 45 min of

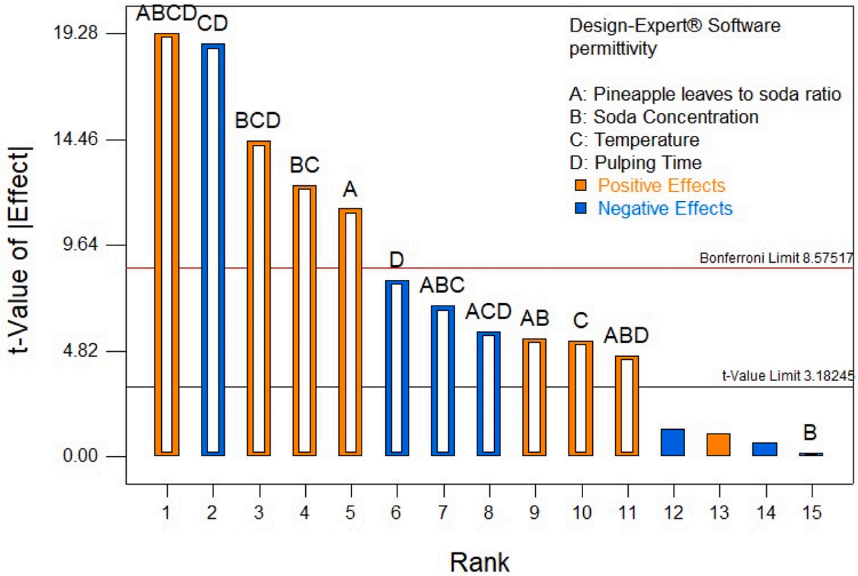

Fig. 2. Pareto chart for permittivity.

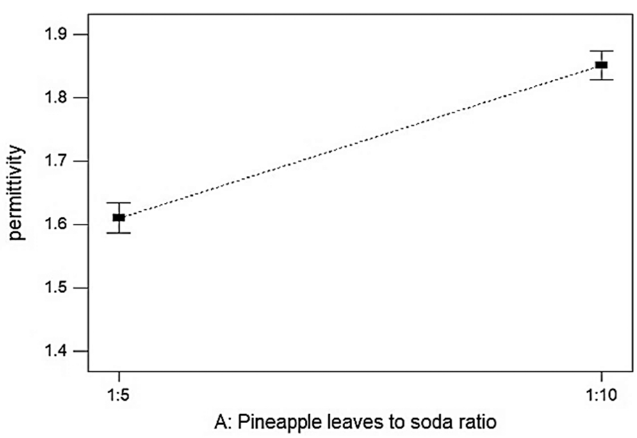

Fig. 3. The effect of pineapple leaves to soda ratio on permittivity value.

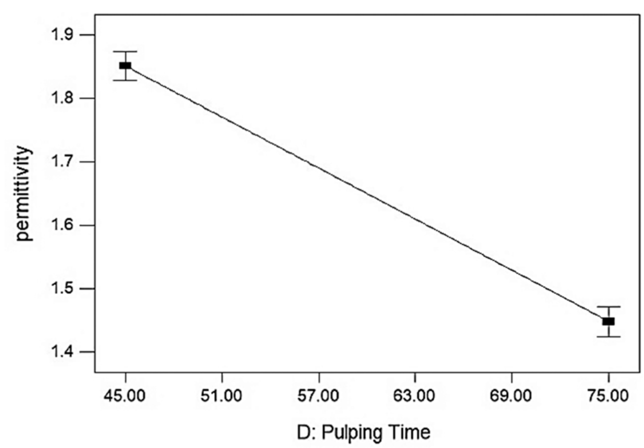

Fig. 5. The effect of pulping times on permittivity value.

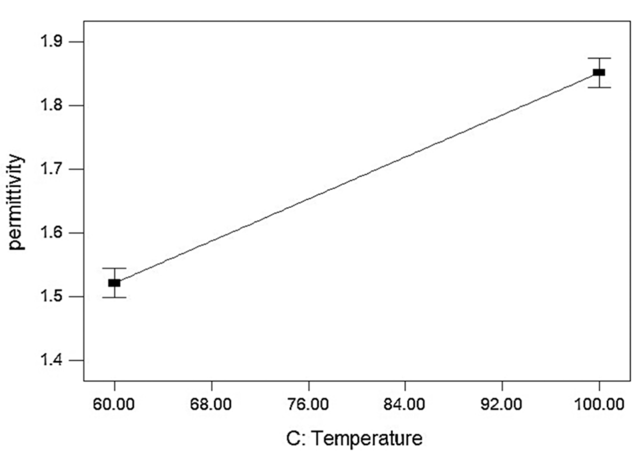

Fig. 4. The effect of temperature on permittivity value.

pulping time. The permittivity value decreased when the pulping time was increased from 45 to 75 min. As Liu *et al.* [31] mentioned, the cellulose fiber yield reached a plateau over 60 min of reaction time, where any variance beyond that time was insignificant. Lim *et al.* [32] investigated the effect of reaction time on cellulose fiber content from 40 to 120 min. From the investigation, the reaction time of 100 min was the maximum time for cellulose fiber extraction, and it decreased marginally after 100 min. A longer reaction period may have reduced the cellulose fiber yield and increased energy consumption. This might be due to the cellulose fiber being easily degraded with a longer pulping time at the last pulping stage. Most of the lignin was separated at these last stages, exposing cellulose fiber macromolecules in the solution and eventually reducing productivity [27].

The two interacting parameters that contributed the most to the permittivity value were portrayed in Figs. 6 and 7. The nonparallel line between both factors in each figure represents that the interaction existed and was significant toward the permittivity value. The interaction effect between factors B (soda concentration) and C (temperature) is presented in Fig. 6. Soda concentration affected the permittivity value at the different temperature settings differently. At 60 ℃, the increase in soda concentration has caused an increase in the permittivity value. Meanwhile, at 100 ℃, the increase in soda concentration resulted in a decreased permittivity value. At higher temperatures, soda acts efficiently in pineapple leaf fiber extraction; hence, only a small amount of soda is required. The large amount of pineapple leaf fiber extracted at this temperature has contributed to the high permittivity value. Meanwhile, more soda is needed to delignify the pineapple leaf fiber in the

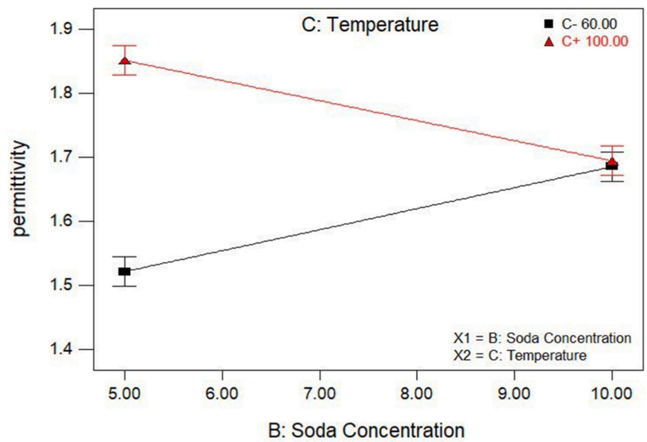

Fig. 6. The effect of soda concentration and temperature on permittivity value.

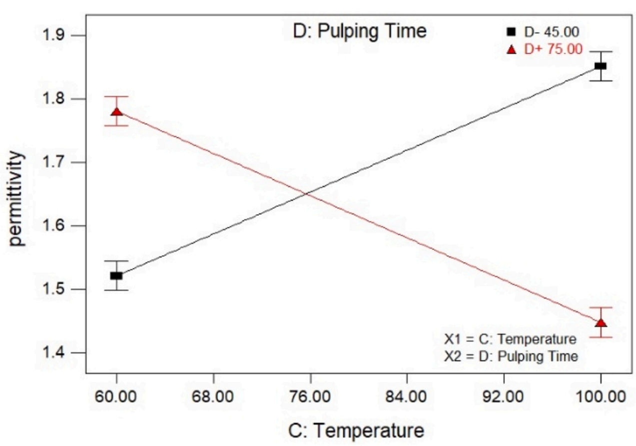

Fig. 7. The effect of temperature and pulping times on permittivity value.

solution at a lower temperature setting. The low amount of pineapple leaf fiber extracted at this temperature explains the low permittivity value. The permittivity displayed the highest value at 5 wt% soda concentration and 100 ℃ temperatures. These conditions indicate that pineapple leaf fiber was efficiently extracted at a higher temperature, as explained by the high permittivity value.

Fig. 7 demonstrates the effect of temperature and pulping time on the permittivity value. The high temperature and a lower pulping time (45 min) resulted in the maximum permittivity value. The increase in pulping time from 45 to 75 min decreased permittivity at 100 °C. The high temperature accelerated the delignification process, in which 45 min was adequate to extract maximum pineapple leaf fiber. Hence, the increase in pulping time was observed to negatively affect the permittivity value at a higher temperature because the pineapple leaf fiber was dissolved with a longer pulping time. Meanwhile, at 60 ℃, the fiber extraction exhibited a high permittivity value when a longer pulping time was applied. This suggests that more time is needed for pineapple leaf fiber extraction in a low-temperature setting. The increase in extracted pineapple leaf fiber has resulted in an increase in permittivity value.

Therefore, it can be concluded that temperature and pulping time were related to each other, where at a low temperature, a longer pulping time was required for the delignification process to occur. Similarly, at a higher temperature, a low pulping time was adequate for the process to take place. A higher permittivity value has resulted from increased pineapple leaf fiber concentration. According to Elloumi *et al.* [30], the increase in permittivity value with the rise in fiber content was due to the hygroscopic polar groups of cellulose fiber. However, the maximum permittivity value was higher at higher temperatures and lower pulping times.

Best condition of process factors for the highest permittivity

The best conditions for the maximum permittivity value were obtained at 1:10 PL:S, 5 wt% soda concentration, 100 ℃ pulping temperature, and 45 min of pulping time, as summarized in Table 4. At this condition, the optimum permittivity value of 1.85 was obtained. With this reported permittivity value, the extracted pineapple leaf fiber can be used as an insulator for coaxial cable and communication applications.

Jayamani *et al.* [6] applied 5 wt% soda concentrations for cellulose extraction from pineapple leaf. The maximum permittivity value obtained at 3 MHz was 4.2 when composited with 20% epoxy resin. The obtained permittivity value, which was way higher than in the current study, was due to the resin application. The increase in the resin composition of the composite has increased the permittivity value. Patra and Bisoyi [33] evaluated the dielectric value of a sisal fiber-reinforced polyester composite at 2 Hz and found that the dielectric value was up to 7.2. The value was again beyond the value obtained in the current study, which was due to the use of polyester resin and cobalt naphthalene as accelerators in that study.

Up to the present, there has not been much research on the permittivity of raw pineapple leaf fiber; instead, many studies have focused on composite materials. Also, only a few studies are available on permittivity, as more studies are focused on the application of fiber in paper production. As a result, permittivity values were compared for various plant-based materials used as dielectric materials. Zulkifli *et al.* [7] evaluated the permittivity values of banana leaf, sugarcane bagasse, rice straw, and rice husk within the 1–20 GHz frequency range. The highest permittivity value was observed in banana leaves with a 4.2 when composited with 50% filler. The lowest permittivity value was exhibited by sugarcane bagasse, with a 2.8 at the same filler loading. Therefore, the permittivity value of the raw fiber extracted from pineapple leaves in this work could be considered high and, therefore, could be exploited further for use as dielectric materials.

Pineapple leaf fiber characteristics

Morphological structure

SEM images for selected experimental standards were graphically presented in Fig. 8. The diameter size, Ø, and the distance between the pineapple leaf fibers, Δ, were summarized in Table 5 and were arranged in ascending permittivity values. According to the table, the smallest pineapple leaf fiber diameter of 3.78 ± 0.89 µm and the distance between pineapple leaf fibers of 4.90 ± 0.45 µm exhibited by Fig. 8f contributed significantly to the highest permittivity value obtained in this study. The pineapple leaf fibers were observed to be tightly arranged to each other, reducing the air void or porosity of the MUT sample, thereby increasing the permittivity value of the pineapple leaf fiber. As shown in Fig. 8a, the loose fiber arrangement, i.e., 8.69 ± 1.81 µm fiber distance, contributed to the lowest permittivity value. It was also noted from the table that the increment in permittivity value was due to the reduction of fiber diameter and fiber distance.

The morphological characteristics of the developed pineapple leaf fibers influenced the permittivity value obtained in this study. As the

Table 4
The suggested-best condition for maximizing permittivity value.

Factors	Value
A: Pineapple leaf to soda ratio	1:10
B: Soda concentration	5 wt%
C: Temperature	100 ℃
D: Pulping time	45 min
Permittivity	1.85

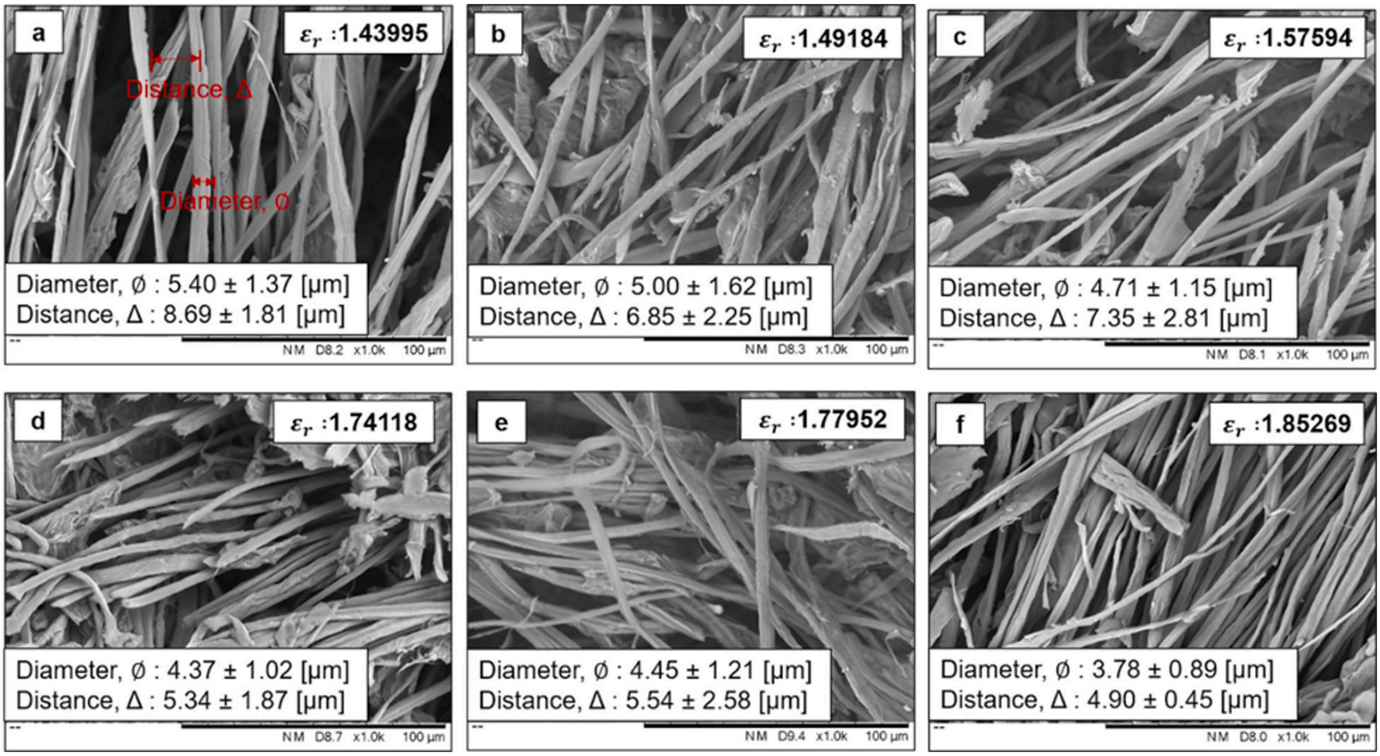

Fig. 8. SEM images of selected experimental conditions.

Table 5
Fiber diameter and distance between fibers.

Label	STD	Diameter (µm)	Distance between fiber (µm)	Permittivity (ε)
a	14	5.40 ± 1.37	8.69 ± 1.81	1.44
b	3	5.00 ± 1.62	6.07 ± 2.01	1.50
c	15	4.71 ± 1.15	7.35 ± 2.81	1.58
d	7	4.37 ± 1.02	5.34 ± 1.87	1.74
e	10	4.45 ± 1.21	5.54 ± 2.58	1.78
f	6	3.78 ± 0.89	4.90 ± 0.45	1.85

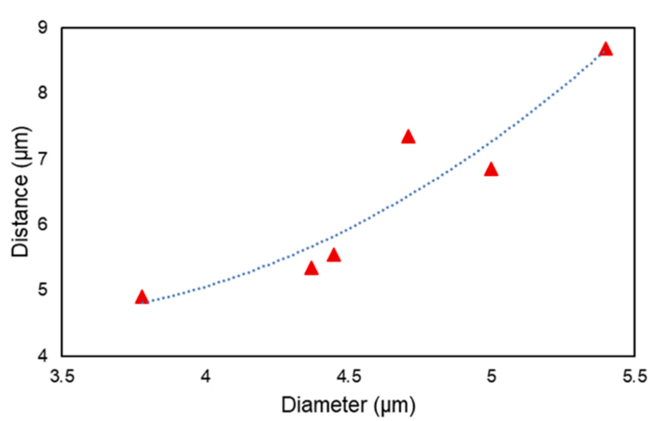

Fig. 9. Relationship between fiber diameter and distance between the fiber.

fiber diameter increases, the permittivity value decreases. The same trend was also observed for the distance between fibers. As portrayed in Fig. 9, the fiber diameter and the distance between fibers were proportionally related.

The relationship between fiber diameter and fiber distance against the permittivity value is shown in Fig. 10. The existence of an air void might explain the increase in permittivity value as the distance between fibers increases. A similar result was observed by Jabal *et al.* [4], who studied the effect of the morphological structure of coconut shell powder and coconut shell-activated carbon on their dielectric properties. The larger diameter of the void space exhibited by the coconut shell powder indicates the high porosity of the material. Meanwhile, the coconut shell-activated carbon displayed less void space, hence reducing the porosity of the surface. The large diameter of void space decreases the ability of one material to absorb and store electromagnetic energy, thus affecting its dielectric properties. The presence of void space will reduce the value of the surface area and disrupt the absorption performance of electromagnetic energy. This is due to the surface area acting as an absorption or storing medium.

Elemental composition of pineapple leaf fiber

An EDX analysis of the pineapple leaf fiber with the highest permittivity value was performed to identify the elemental composition of the materials in the MUT sample. The carbon composition was found to be the most abundant in the MUT sample. The percentage of carbon and its corresponding permittivity value for each sample were summarized in Table 6. As seen from the table, the highest carbon percentage of 55.08% was seen at the highest permittivity value. Meanwhile, the lowest carbon composition of 47.81% resulted in the lowest permittivity value obtained in this study.

As depicted in Fig. 11, the permittivity value increased as carbon composition increased. Therefore, the high permittivity value reported in this study might be due to the high carbon composition in the pineapple leaf fiber. The increase in permittivity as the carbon content increases may be attributed to the presence of polarizable electrons [34]. The permittivity value exhibited by the synthesized carbon indicates the ability of carbon to store energy [35]. Since carbon elements can be found abundantly in most agricultural wastes, it is forecast that these materials will be of great significance in designing many more future dielectric applications.

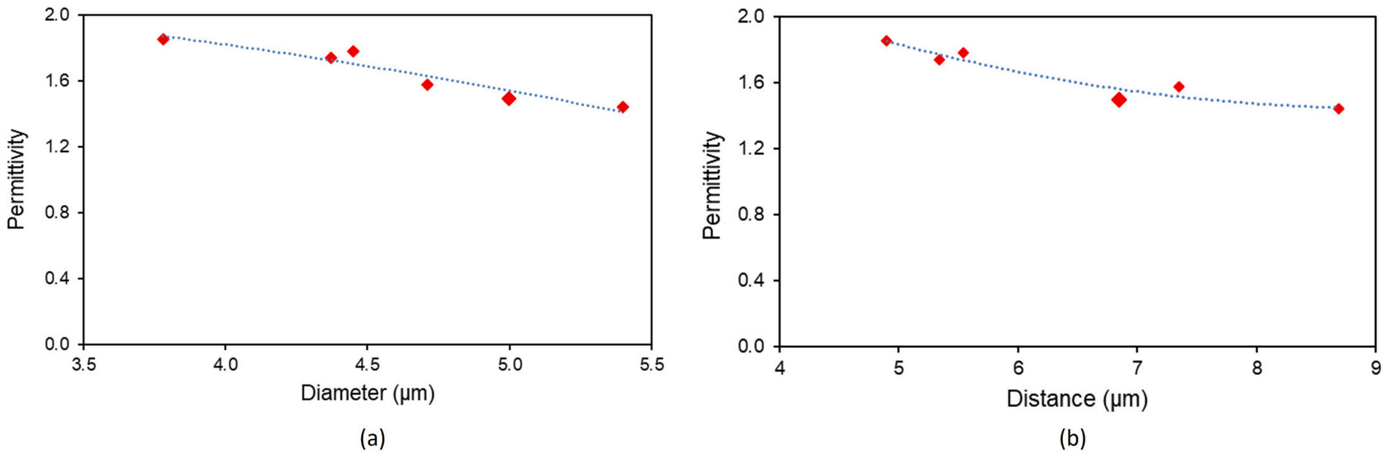

Fig. 10. The behavior of (a) diameter and (b) distance on permittivity value.

Table 6
Carbon percentage and permittivity value for the chosen experimental standard.

Label	STD	Carbon (wt%)	Permittivity (*e*)
a	14	47.81	1.44
b	3	48.68	1.50
c	15	48.07	1.58
d	7	51.15	1.74
e	10	53.22	1.78
f	6	55.08	1.85

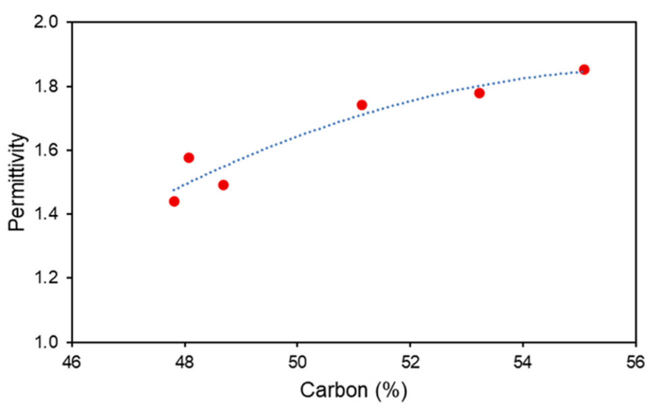

Fig. 11. Percentage of carbon obtained versus permittivity.

Conclusion

The permittivity value of fibers extracted from pineapple leaves shows that the fibers could be a potent dielectric material. The pineapple leaf-to-soda ratio is the most significant factor in the permittivity value, with an 8.86% contribution. The highest permittivity value reported in this study is 1.85 in an experimental condition of 1:10 PLS, 5 wt% soda concentration, 100 ℃ temperature, and 45 min of pulping time. The morphological observation of the obtained pineapple leaf fiber revealed that the fiber diameter and the distance between fibers influence the permittivity value. The smallest fiber diameter resulted in the highest permittivity. The large distance between fibers indicates the high porosity of the sample, causing the permittivity value to be reduced. The existence of a large air void or high porosity reduced the ability of the pineapple leaf fiber to store electromagnetic energy. The significant factors identified by the TLFA could be modified during the extraction process to produce material with the desired permittivity value. Manipulating agricultural wastes into valuable raw materials not only preserves the raw materials for future generations but also reduces electronic waste and environmental pollution related to the disposal of these wastes.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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