

Investigation on the Electrical Breakdown Voltage Performance of LLDPE-Natural Fiber Composite Under Normal and Saltwater Immersion Conditions

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ABSTRACT

The development of environmentally friendly insulating materials has attracted significant attention due to increasing environmental concerns associated with conventional petroleum-based polymers. This study investigates the dielectric performance of Linear Low-Density Polyethylene (LLDPE)–Natural Rubber (NR) composites reinforced with Empty Fruit Bunch (EFB), Oil Palm Frond (OPF), and Pineapple Leaf Fibre (PALF) under normal and saltwater immersion conditions. Twelve composite samples were fabricated using a fixed LLDPE–NR ratio of 80:20 with fibre loadings of 2.5%, 5%, 7.5%, and 10%. Samples were immersed in a 3.5% NaCl solution for 120 days to simulate coastal environmental conditions. Moisture absorption and AC breakdown voltage tests were conducted according to IEC 60243-1 standards. Results showed that EFB composites exhibited the lowest moisture absorption, while PALF composites recorded the highest water uptake. Under normal conditions, the highest breakdown voltage of 38.57 kV was achieved by the 5% EFB composite. After saltwater immersion, the 5% OPF composite demonstrated the best dielectric performance with a breakdown voltage of 34.53 kV. The findings indicate that fibre type and fibre loading significantly influence dielectric properties and environmental durability. The 5% OPF composite is identified as the most suitable candidate for insulation applications in humid and coastal environments.

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1. INTRODUCTION

Electrical insulation materials are essential components in power and high-voltage systems, as they prevent unintended current flow, electrical discharge, and dielectric failure while ensuring the safety and reliability of electrical equipment [1], [2]. Conventional polymeric insulators such as polyethylene (PE), linear low-density polyethylene (LLDPE), and cross-linked polyethylene (XLPE) are widely used due to their high dielectric strength, low dielectric loss, and good chemical stability [3], [4], [5]. However, these materials are derived from non-renewable petroleum resources and are non-biodegradable, which raises environmental sustainability concerns [3], [4].

In response to these issues, research on sustainable and eco-friendly insulating materials has increased significantly. Natural fibre-reinforced polymer composites have emerged as promising alternatives due to their renewability,

biodegradability, low density, and low cost [6], [7]. Agricultural by-products such as pineapple leaf fibre (PALF), empty fruit bunch (EFB), and oil palm frond (OPF) are abundantly available in Malaysia and have been widely investigated as reinforcing fillers in polymer composites [6], [8]. When incorporated into polymer matrices such as LLDPE and natural rubber (NR), these fibres can enhance mechanical strength and modify dielectric behaviour, making them suitable for insulation applications [9], [10], [11].

LLDPE–NR-based composites have shown promising performance in high-voltage insulation systems due to their improved dielectric stability, flexibility, and resistance to electrical stress [9], [10], [12]. Studies have reported that polymer blending and filler incorporation can improve charge trapping characteristics and reduce electrical degradation under stress conditions [11], [12]. However, the dielectric

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performance of such composites remains highly dependent on environmental conditions.

Environmental factors such as moisture and salt contamination significantly influence the electrical performance of insulating materials. Water absorption can increase permittivity and conductivity, leading to reduced dielectric strength and accelerated ageing [9], [13], [14]. Saltwater environments introduce ionic species such as Na^+ and Cl^- , which enhance charge transport and leakage current, thereby further reducing insulation performance [15]. In coastal and marine applications, such conditions may severely compromise the reliability of polymer-based insulation systems [16], [17].

Although previous studies have investigated moisture effects on LLDPE–NR composites and natural fibre-reinforced polymers [8], [9], [14], limited research has focused on their breakdown voltage performance under saltwater immersion conditions. Existing studies are mostly restricted to dry or humid environments, without fully representing aggressive ionic contamination conditions [18]. Furthermore, comparative studies involving different natural fibres such as PALF, EFB, and OPF under identical electrical testing conditions remain limited.

Therefore, this study investigates the breakdown voltage performance of LLDPE–NR composites reinforced with PALF, EFB, and OPF under both normal and saltwater immersion conditions. The breakdown strength evaluation is conducted in accordance with IEC 60243-1 standards [2], while the saltwater medium is prepared following ASTM D1141-98 specifications [19]. The study aims to evaluate the influence of saltwater exposure on dielectric performance and identify the most stable and salt-resistant natural fibre composite. The findings are expected to contribute to the development of sustainable, eco-friendly insulation materials suitable for low- and medium-voltage applications in humid and coastal environments.

2. METHODOLOGY

2.1 Research Flowchart

As shown in Fig. 1, the study begins with the selection of raw materials, namely LLDPE, Natural Rubber (NR), and natural fibres (PALF, EFB, and OPF). The materials are mechanically mixed and moulded into standardized disc specimens using a hot-press machine. The prepared samples are then divided into two groups: one stored under normal conditions and the other immersed in a 3.5% NaCl saltwater solution to simulate a coastal environment. Moisture absorption is monitored throughout the immersion period. Subsequently, all samples undergo AC breakdown voltage testing in accordance with IEC 60243. Finally, the results are analysed and compared to evaluate the effect of saltwater exposure on the dielectric performance of the composite materials.

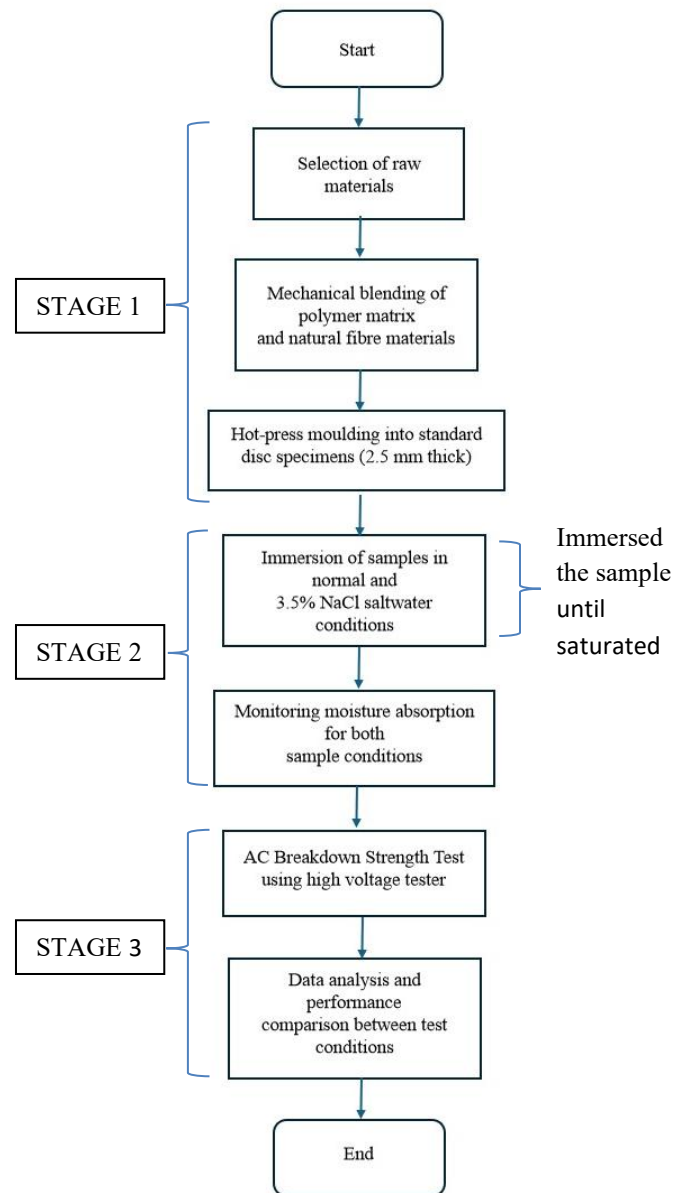


Fig. 1. Flowchart for Methodology Process

2.2 Sample Development

This section describes the preparation of composite samples consisting of three materials: low linear density polyethylene (LLDPE), natural rubber (NR), and natural fibres (NF). The composites were prepared by blending LLDPE and NR with natural fibres, namely pineapple leaf fibre (PALF), empty fruit bunch (EFB), and oil palm frond (OPF). These three types of natural fibres were selected to compare their effectiveness as reinforcement fillers in the polymer matrix. Each fibre type was incorporated separately into the LLDPE–NR blend, while the ratio of LLDPE–NR was fixed at 80:20 for all samples. Consequently, a total of twelve composite samples were produced with varying natural fibre loadings. Table 1 presents the composition of each material.

Table 1. Composition of LLDPE, Nr and NF.

No.	Sample	LL DPE (%)	NR (%)	NF (%)	Fiber Type
1.	A	78	19.5	2.5	EFB
2.	B	76	19.0	5.0	
3.	C	74	18.5	7.5	
4.	D	72	18.0	10.0	
5.	E	78	19.5	2.5	OPF
6.	F	76	19.0	5.0	
7.	G	74	18.5	7.5	
8.	H	72	18.0	10.0	
9.	I	78	19.5	2.5	PALF
10.	J	76	19.0	5.0	
11.	K	74	18.5	7.5	
12.	L	72	18.0	10.0	

2.3 Saltwater Preparation

The saltwater solution was prepared at a concentration of 3.5% sodium chloride (NaCl) using distilled water. The concentration was calculated based on the weight/volume percentage (% w/v), as expressed in (1):

$$\% \frac{w}{v} = \frac{\text{mass of solute (g)}}{\text{volume of solution (mL)}} \times 100 \quad (1)$$

Where:

- Mass of solute (g) = the weight of the substance is dissolving
- Volume of solution (mL) = the total volume of the final solution

Therefore:

$$\text{Mass of NaCl (g)} = \frac{3.5 \times 100}{100} = 3.5 \text{ g} \quad (2)$$

Hence, NaCl weighing 3.5 g was required to make 100 mL of solution. The calculated quantity of NaCl was then dissolved in a suitable quantity of distilled water and stirred well all the time until it was completely dissolved, making a homogeneous solution. The solution of saltwater thus obtained was further stored in tightly closed containers to avoid evaporation and contamination before conducting the immersion test.

2.4 Immersion Procedure

The samples were individually placed in separate containers and exposed to identical ambient temperature conditions. Two testing conditions were established. The first involved storing the samples in a dry environment under normal conditions, while the second involved complete immersion of the samples in a 3.5% NaCl saltwater solution. The immersion process was carried out over a period until saturated. Observations and measurements were taken at two-day intervals to monitor changes in the samples.

The samples with different materials of natural fibres were immersed in 3.5 NaCl for a period until it saturated. Fig. 2. shows that all the samples were immersed.

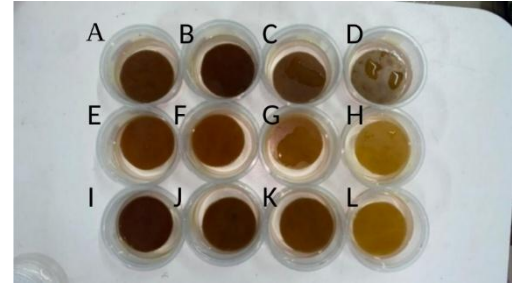


Fig. 2. Sample Immersed in 3.5% NaCl Solution in Different Containers

2.5 Moisture Absorption Measurement

Moisture absorption was measured by comparing the initial mass (M_0) and humid mass (M) (3):

$$M = \frac{M - M_0}{M_0} \times 100\% \quad (3)$$

The dry weight of each specimen is first measured using a digital weighing scale. Then, each specimen is placed in a saturated saltwater solution. At a pre-set time interval, each specimen is retrieved from the saltwater solution, and the excess water present on each specimen is removed using a tissue paper before weighting to check for water absorption. This process continued until a constant weight for each specimen was attained, manifesting a saturated state. Such a test aims to assess how natural fibres affect the hydrophilic properties of a composite material.

2.6 Sample Preparation

During normal conditions, samples designated for the normal condition were used as prepared, without any additional drying or conditioning. Each sample was carefully inspected to ensure there were no cracks, warping, or surface imperfections on each. This method determines the dielectric properties of the composites in their common as-fabricated state.

While in saltwater conditions, humid testing involved samples immersed in a 3.5% NaCl solution until the samples in moisture saturation. During the duration of immersion, mass was periodically recorded every 2 days until the mass stabilized to measure water absorption. Finally, excess surface solution was wiped off with a soft tissue paper without pressurizing the test specimens, which may affect the electrical contact. In this procedure, an investigation into the effect of absorbed moisture on the breakdown voltage performance of the composite material was carried out.

2.7 AC Breakdown Voltage Testing

The AC breakdown voltage test was conducted to evaluate the dielectric performance of the composite materials under high-voltage AC stress. The tests were conducted in two different states, in normal and saltwater immersion conditions. For saltwater immersion conditions, the sample was soaked in a 3.5% NaCl solution to investigate the influence of moisture on the dielectric properties of composite materials. Such a comparison will help assess how absorbed natural fibres affect a material with good insulation capabilities when subjected to high-voltage AC.

A composite disc measuring 5 cm in diameter and 2.5 mm in thickness was created to provide consistent samples with repeatable outcomes. The samples were all carefully evaluated to check for smooth surfaces, uniform thickness, and the absence of defects that could affect the breakdown measurements.

2.8 Test Setup and Procedure

The AC breakdown test was carried out using a high-voltage AC power supply and a pair of spherical electrodes as in Fig. 3., the composite sample was placed at the center, with both electrodes carefully aligned to ensure equal contact with the surface of the composite. The experiment was conducted at room temperature (approximately 25°C), under standard pressure, and without the influence of environmental factors such as humidity, temperature variations, or airflow.

At a constant rate of 1-2 kV per second, the magnitude of the applied AC voltage increased until an electrical breakdown took place. An electrical breakdown occurred when a sudden current spike took place in the specimen, which marked the point of electrical failure of the material. The breakdown voltage (V_b) was recorded for each test.



Fig. 3. Dielectric Breakdown Testing Application

For Normal Samples:

- The sample was inspected for any visible defects.
- The sample was placed between the spherical electrodes.
- The AC voltage was gradually increased at a rate of 1–2 kV/s.
- Electrical breakdown was observed.
- The breakdown voltage (V_b) was recorded.

For Saltwater Immersion Samples:

- The sample was removed from the 3.5% NaCl solution after saturation was achieved.
- Excess surface solution was gently wiped off.
- The sample was inspected for cracks or surface imperfections.
- The sample was placed between the electrodes.
- The AC voltage was gradually increased at a rate of 1–2 kV/s.
- Electrical breakdown was observed.
- The breakdown voltage (V_b) was recorded.

Each condition was tested on multiple replicates to ensure repeatability and reliability of results.

2.9 Data Analysis

The breakdown voltage (V_b) obtained from each test was recorded and analysed. Comparisons were made between

samples under normal and saltwater immersion conditions to evaluate the influence of moisture absorption on the dielectric performance of the composites. The results were further compared according to fibre type and fibre loading percentage to determine the composite formulation with the best insulation performance.

3. RESULT AND DISCUSSION

The results include moisture absorption, physical characteristics, and AC breakdown voltage testing of LLDPE–Natural Rubber–Natural Fiber composites under normal and saltwater immersion conditions. A comparison is made between the three fibre types (PALF, EFB, OPF) to determine their influence on dielectric performance. The discussions are supported by graphs, tables, and observations, and relate the findings to previous studies.

3.1 Percentage Saltwater Absorption Results

Moisture absorption was monitored in a period. Table 2 shows the percentage of moisture absorbed by each fibre type after 120 days.

Table 2. Moisture Absorption% for 120 Days (Saturated Condition)

No.	Sample	Initial Mass (g)	Final Mass	Saltwater Absorption %	Type Nature Fibre
1.	A	5.63	5.66	0.53	EFB
2.	B	5.50	5.55	0.91	
3.	C	5.96	6.04	1.34	
4.	D	5.63	5.69	1.07	
5.	E	5.56	5.61	0.90	
6.	F	5.68	5.73	0.88	OPF
7.	G	5.36	5.43	1.31	
8.	H	5.96	6.07	1.85	
9.	I	5.61	5.68	1.25	PALF
10.	J	5.73	5.83	1.75	
11.	K	5.70	5.83	2.28	
12.	L	5.70	5.83	2.28	

The moisture absorption results showed that all composite samples absorbed saltwater during the 120-day immersion period. The percentage of moisture absorption ranged from 0.53% to 2.28%, indicating relatively low water uptake for all samples. Among the fibre types investigated, EFB composites exhibited the lowest moisture absorption, while PALF composites recorded the highest values. Sample A (2.5% EFB) showed the lowest moisture absorption of 0.53%, whereas Samples K and L (7.5% and 10% PALF) recorded the highest moisture absorption of 2.28%. It shows more clearly in Fig. 4.

The results indicate that fibre type significantly influences the moisture absorption behavior of the composites. PALF fibres are more hydrophilic and therefore absorb more moisture than EFB and OPF fibres. In contrast, EFB composites demonstrated better resistance to moisture penetration. Although all samples remain below 3% moisture absorption, increased water uptake may contribute to a reduction in dielectric performance due to the formation of conductive pathways within the composite structure.

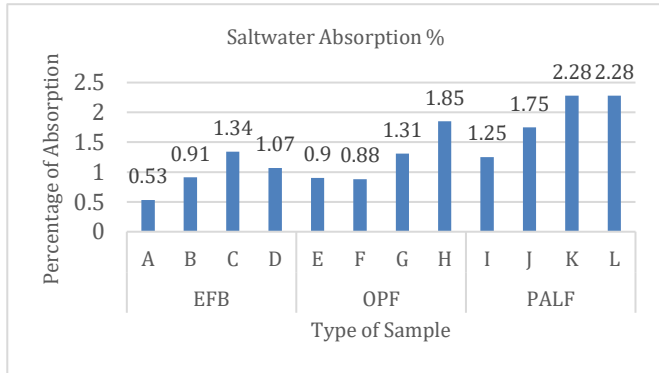


Fig. 4. The Histogram Chart of Saltwater Absorption Percentage of Sample (%)

3.2 AC Breakdown Voltage of Composites

There are a few variables that can affect the breakdown voltage of solid insulation. From the results obtained from the AC breakdown voltage testing done in the present investigation, there are various ratios of natural fiber that affect the breakdown voltage of the natural rubber (NR) and linear low-density polyethylene (LLDPE) matrix samples.

The breakdown test results revealed that varying the natural fibre content, specifically EFB (Empty Fruit Bunch Fibre), OPF (Oil Palm Frond Fibre), and PALF (Pineapple Leaf Fibre) at 2.5%, 5%, 7.5%, and 10% within a fixed LLDPE–NR matrix ratio of 80:20, significantly influenced the breakdown voltage performance of the composites.

3.3 Comparison of Voltage Breakdown Between Samples Under Normal and Saltwater Immersion Conditions

Dielectric performance of the composite can be affected by environmental exposure. By analyzing the performance trends for each natural fibre, this section will highlight how water absorption influence insulation capability and identify which combination showed the most stable performance.

Table 3. Value of Voltage Breakdown Between Samples Under Normal and Saltwater Immersion Conditions

No.	Sample Code	Type of Nature Fiber	Breakdown Voltage (kV)	
			Under Normal Condition	Saltwater Immersion Condition
1.	A	EFB	34.97	31.70
2.	B		38.57	29.45
3.	C		37.05	19.47
4.	D		28.49	19.23
5.	E	OPF	34.86	30.70
6.	F		34.62	34.53

No.	Sample Code	Type of Nature Fiber	Breakdown Voltage (kV)	
			Under Normal Condition	Saltwater Immersion Condition
7.	G	PALF	25.91	12.26
8.	H		12.75	9.15
9.	I		33.62	23.01
10.	J		17.72	11.23
11.	K		14.42	8.88
12.	L		12.14	8.08

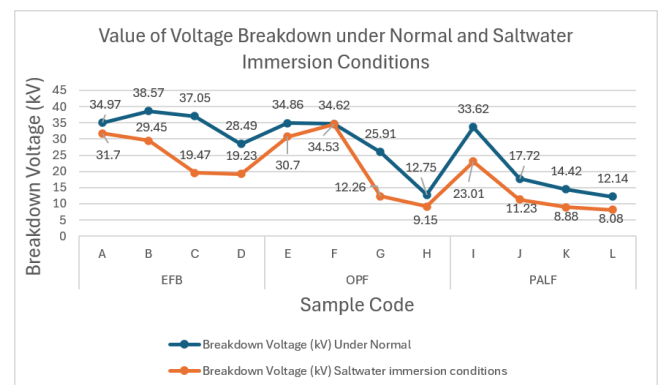


Fig. 5. Graph of Comparison Voltage Breakdown Between Samples Under Normal and Saltwater Immersion Conditions

The comparison of the AC breakdown voltage of the LLDPE–NR composites reinforced with different percentages of Empty Fruit Bunch (EFB) fibre under normal and saltwater immersion conditions is presented in Table 3 and Fig. 5. Under normal conditions, increasing the EFB content from 2.5% to 5% increased the breakdown voltage from 34.97 kV to 38.57 kV, indicating an improvement in the dielectric strength of the composite. However, further increasing the EFB content resulted in a reduction in breakdown voltage, with values of 37.05 kV at 7.5% and 28.49 kV at 10% EFB. Under saltwater immersion conditions, the breakdown voltage decreased from 31.70 kV at 2.5% EFB to 29.45 kV at 5%, 19.47 kV at 7.5%, and 19.23 kV at 10% EFB. These results indicate that saltwater immersion adversely affected the dielectric performance of the EFB composite by reducing its ability to withstand electrical stress. The 5% EFB composite recorded the highest breakdown voltage under normal conditions.

For the Oil Palm Frond (OPF) composite, the breakdown voltage remained relatively stable under normal conditions as the fibre content increased from 2.5% to 5%, with values of 34.86 kV and 34.62 kV, respectively. However, a significant reduction was observed at higher fibre loadings, where the breakdown voltage decreased to 25.91 kV at 7.5% OPF and further to 12.75 kV at 10% OPF. Under saltwater immersion conditions, the breakdown voltage increased slightly from 30.70 kV at 2.5% OPF to 34.53 kV at 5% OPF, before declining sharply to 12.26 kV at 7.5% and 9.15 kV at 10% OPF. These findings indicate that the 5% OPF composite maintained good dielectric performance under both testing conditions, while excessive fibre loading considerably reduced the breakdown strength, particularly at 7.5% and 10% OPF.

In contrast, the composite reinforced with Pineapple Leaf Fibre (PALF) exhibited a continuous decline in breakdown voltage with increasing fibre content under both testing conditions. Under normal conditions, the breakdown voltage decreased from 33.62 kV at 2.5% PALF to 17.72 kV, 14.42 kV, and 12.14 kV at 5%, 7.5%, and 10% PALF, respectively. A similar trend was observed after saltwater immersion, where the breakdown voltage decreased from 23.01 kV at 2.5% PALF to 11.23 kV, 8.88 kV, and 8.08 kV at 5%, 7.5%, and 10% PALF, respectively. Compared with the lower fibre loading, the higher PALF content resulted in substantially lower breakdown voltage under both conditions, indicating a deterioration in dielectric performance with increasing PALF content.

3.4 Discussion

The results demonstrate that both fibre type and fibre loading significantly influence the breakdown voltage performance of LLDPE–NR natural fibre composites. Under normal conditions, the breakdown voltage increased at lower fibre loadings but decreased when the fibre content became excessive. This behavior suggests that a moderate amount of fibre improves the composite structure, while excessive fibre loading introduces voids, agglomeration, and interfacial defects that facilitate electrical breakdown.

Sample B containing 5% EFB recorded the highest breakdown voltage of 38.57 kV. This result indicates that 5% EFB provided the optimum balance between reinforcement and insulation performance. However, increasing the EFB loading beyond 5% resulted in a reduction in breakdown voltage due to the increased likelihood of structural defects within the composite.

Following 120 days of saltwater immersion, most samples experienced a reduction in breakdown voltage. Moisture and salt ions absorbed into the composite increased electrical conductivity and reduced dielectric strength. This observation is consistent with the moisture absorption results, where samples with higher water uptake generally exhibited lower breakdown voltage values.

Among the immersed samples, Sample F containing 5% OPF achieved the highest breakdown voltage of 34.53 kV. The breakdown voltage decreased by only 0.09 kV compared to the normal condition value of 34.62 kV, indicating excellent resistance to saltwater degradation. In contrast, PALF composites showed the highest moisture absorption and the greatest reduction in breakdown voltage, suggesting lower resistance to moisture-related deterioration.

Overall, Sample B (5% EFB) demonstrated the best breakdown voltage performance under normal conditions, whereas Sample F (5% OPF) exhibited the most stable performance after saltwater immersion. Therefore, the 5% OPF composite is considered the most suitable material for electrical insulation applications in humid and coastal environments.

4. CONCLUSION

This study investigated the electrical performance of LLDPE–NR composites reinforced with different natural fibers. Specifically, EFB, OPF, and PALF fibers were used, and their behaviors were evaluated under normal conditions and after saltwater immersion. Composite samples were fabricated and tested for moisture absorption and AC breakdown voltage.

After 120 days of saltwater immersion, all samples absorbed moisture, which affected their dielectric performance. When it came to breakdown voltage, both the kind of fiber and the percentage used mattered a lot. For instance, under normal conditions, the EFB composite containing 5% fibre loading recorded the highest breakdown voltage of 38.57 kV. Typically, boosting the fiber content past a certain point lowered the breakdown voltage, since natural fibers tend to soak up moisture. The absorbed moisture reduced the insulation capability of the composites and consequently lowered their overall performance.

The comparison between normal and saltwater immersion showed that all samples saw a drop in breakdown voltage after being in saltwater for a long time. The extra moisture made the composites more conductive and less able to handle electrical stress. Interestingly, EFB and OPF performed better than PALF after being immersed in saltwater.

This study successfully achieved its objectives. The results show that natural fibre–reinforced LLDPE–NR composites have potential to be used as eco-friendly electrical insulation materials. In addition, this research provides valuable insights for future studies on sustainable polymer insulators and their performance in moist environments.

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