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Investigation of Mechanical and Physical Characteristics of Coconut Petiole Fiber/Epoxy Bio-composites

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ABSTRACT

Natural fibers are increasingly being adopted as eco-friendly reinforcements in polymer composites due to their low cost, biodegradability, renewability, and widespread availability. In comparison with other lignocellulosic fibers, coconut petiole fiber available in tropical regions possesses superior mechanical properties and is one of the most widely used natural fiber for making composites. 5%, 10% and 15 wt.% fiber loadings using hand lay-up method. In order to facilitate fiber-matrix interfacial adhesion, the fibers were chemically treated using 5% sodium hydroxide (NaOH) treatment, which removed surface impurities such as lignin and pectin and enhanced both roughness of surface and crystallinity of the fibers. Mechanical properties such as tensile, flexural and impact were measured from the fabricated composites in addition to surface hardness and water absorption behaviors to assess their mechanical performance and moisture resistance respectively. The composite containing 10 wt.% fiber was found to have best performance in this case, with impact strength of 11520.24 J/m², flexural strength of 9.57 MPa, tensile strength of 11.09 MPa and Young's modulus of 1330.1 MPa respectively. It was found that the Rockwell hardness of combined system (88.5-78 HRL) decreases with increased fiber loading, since the fibers are comparatively softer than that of or being softer than epoxy matrix. The water absorption was low for all the compositions, from 1.53% to 2.02%, and it shows that then fibers were well adhered to matrix and resistant to moisture penetration. The outcomes indicate that alkali modified coconut petiole fiber can be used as a green and effective reinforcement in engineering applications involving epoxy composites.

Keywords: Bio-composites, Coconut Petiole, Adhesion, Alkali Treatment, Reinforcement

1. Introduction

With growing concerns over global warming, environmental degradation, and pollution, there is an increasing demand for sustainable solutions. Researchers are now turning their attention toward the development of eco-friendly and biodegradable materials that can serve as alternatives to non-renewable resources, which continue to harm the environment [1]. Scientists have extensively studied many natural fibers, including jute, bamboo, pineapple, coconut, sisal, hemp, kenaf, rice, and wheat, to determine which ones may be used as reinforcing particles [2].

Pectin, cellulose, hemicellulose, lignin, and waxes make up the fibers in plants. The composition ratio, which determines the fibers' mechanical properties, is affected by the climate, soil, and specific parts of the plants [3]. They are well-known for being one of the most popular and plentiful natural reinforcements used to make composites. These fibers assist build composites that are light, renewable, and biodegradable when blended with biopolymers or synthetic polymers. This means they are a good choice for manufacturing things that are good for the environment [4]. There are certain problems with natural fibers, though. For example, their size can alter, they might be porous, and their strength can change. Their performance relies on where they come from and how they are handled. Inconsistent testing procedures make them less reliable and difficult to employ in composites [5].

Scientists have looked into how to fix these problems by changing the surface of fibers, mixing them with other materials, and adding nanoparticles to make them stronger. Chemical treatments make it easier for fibers to stick to the matrix, hybridization combines the best parts of different fibers, and nanoparticles make everything work even better. The interface has a lot of surface area, which makes things stick together better. This makes them stronger, better at holding heat, and more useful. This means that natural fiber composites last longer and work better when things get tough [6].

Hand lay-up is one of the easiest techniques and also one of the most popular techniques of natural fiber composite. In this, dry fiber mats or fabrics are put in an open mold and liquid resin is poured over the fabrics to saturate and hold the fabrics together. Air bubbles that become trapped especially get removed by rollers that make certain that the resin is distributed evenly as more layers are added. When the layers have been arranged correctly, then the composite can be cured at room temperature. Still, with the help of controlled heat, it can be even stronger and more productive in general. This process is ideal in small batches, prototypes and large or complicated components [7].

One of the most common methods of enhancing the performance of natural fiber-reinforced composites is the alkali treatment that typically utilizes sodium hydroxide (NaOH). This removes the surface dirt such as waxes, hemicellulose, oils and lignin as well as roughening the surface of the fibers. This causes more cellulose to be visible, therefore, allowing the fibers to adhere to the matrix, and bind to it easier [8]. It makes natural fibers rougher and more crystalline, which makes them work better mechanically.

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After this treatment, fibers like abaca, kenaf, and jute have much higher tensile strength, flexural strength, and Young's modulus [9]. The mechanical performance of composites reinforced with coconut coir fiber and manufactured with isophthalic resin has been evaluated for potential automotive applications. The results revealed improved strength and hardness, confirming their suitability as lightweight, sustainable alternatives for automotive components [10].

Scientists and researchers are doing a lot of studies to find ways to make natural fibers less limited. There have been many studies on jute, kenaf, hemp, bamboo, sugarcane, and rice husk, but coconut petiole fiber has not gotten as much attention. The coconut petiole fiber has a lot of potential as a reinforcing material because it is used a lot in tropical countries like Brazil, Sri Lanka, Indonesia, the Philippines, and India. More than 90 countries grow coconuts, and they all make 61.4 million tons of them annually [11].

This study examines the potential of coconut petiole fiber as a reinforcement in epoxy resin to develop durable, biodegradable biocomposites, evaluating their key mechanical properties for sustainable applications. For example, we check how hard they are, how well they resist impact, how strong they are when pulled, and how well they bend. We also check to see how well they soak up water. The results show that coconut petiole fiber is good for the environment and has good mechanical properties. The study supports the use of coconut petiole fiber as a sustainable substitute for synthetic fibers in the automotive, construction, and engineering industries, where the need for environmentally friendly materials is growing.

2. Materials

2.1 Coconut Petiole Fiber

Figure 1 shows coconut petiole fiber as a reinforcement material because of its unique shape and mechanical properties. The fiber comes from the petiole, which is the stalk which connects the coconut leaf to the main stem of the palm. These fibers are made up of bundles that have a lot of cellulose and not a lot of lignin. These two things work together making them very strong, stiff, and structurally sound.

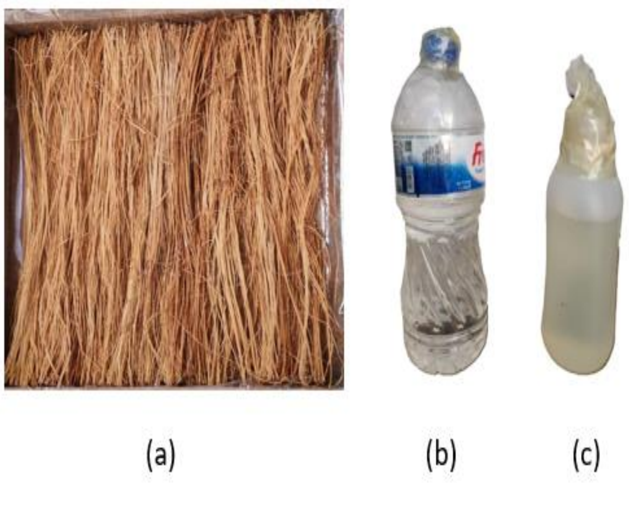

Fig 1: (a) Coconut Petiole Fiber (b) Epoxy Resin (c) Hardener.

Epoxy resin (figure 1) used as the matrix material because it has better mechanical and chemical properties [12]. Epoxy resin is a strong thermosetting material that stays stable at high temperatures, shrinks very little while curing, and sticks well to most surfaces. It also resists corrosion and many chemicals. In a composite, it helps transfer the applied load to the reinforcing fibers while keeping the structure firm. When a hardener is mixed in, it reacts with the resin and forms a cross-linked network [13]. This reaction makes the composite stronger, stiffer, and more durable, which makes it work better overall.

2.2 Sodium Hydroxide (NaOH)

To help the coconut petiole fibers bond better with the epoxy, they were treated with a sodium hydroxide (NaOH) solution. A specific length of time was spent at a controlled temperature of the fibers in this solution. It causes removal of impurities such as waxes, oils, lignin and hemicellulose, roughing the fiber surface, and enhancing adhesion of the fibers to the epoxy.

2. Methodology

3.1 Sample Fabrication

Hand Lay-up method was used to fabricate the samples. We added coconut petiole fibers to the epoxy resin at three different levels: 5%, 10%, and 15% by weight. The fibers were sun-dried, weighed, and arranged evenly in the mold before adding the resin. Then the samples were fabricated and kept in the room temperature under pressure for 24 hours. Afterward, the cured sheets were conditioned and cut into ASTM-standard specimens for mechanical testing.

3.2 Mechanical Properties Testing

3.2.1 Tensile Test

The tensile strength test is used to find out important mechanical properties of a material, such as its yield strength, ultimate strength, ductility, and tensile strength. This test pulls the sample in one direction, which makes it stretch or get longer until it breaks. This process helps us find out how much weight the composite sample can hold and how much force it takes to break it. In the experiment Universal Testing Machine was used to determine the properties. Sample were subjected to increasing stress at a constant rate until it ultimately fails. Throughout the test, the elongation of the gauge section was recorded for calculation. The following equation is used to find the strain (ε):

$$\varepsilon = \frac{L - L_0}{L_0} \quad (1)$$

L= final length after stretching

L_0= original gauge length

To calculate the stress (σ) developed in the specimen, the applied force and the cross-sectional area are measured. The stress is computed as follows:

$$\sigma = \frac{F}{A} \quad (2)$$

F = applied tensile force (kN)

A = cross sectional area (m^2)

3.2.2 Impact Test

The impact test is commonly used to find out how tough a material is, how strong it is against impacts, and how sensitive it is to flaws or notches. It tells you how much energy a material can take before it fails. Among the available methods, the Charpy and Izod tests are most common. In this study, the Charpy impact test was employed. The Charpy test, or the Charpy V-notch test, measures the amount of energy a specimen absorbs when it fails. A pendulum strikes a notched sample, and the difference between its initial and final heights corresponds to the energy absorbed up to fracture. This absorbed energy, expressed in joules. A notable distinction between the Charpy and Izod tests is the orientation of the specimen: the Charpy test positions the sample horizontally, while the Izod test holds it vertically. The impact strength of the specimen can be calculated using the following formula:

$$\text{Impact Strength} = \frac{mg(h_o - h_1)}{A} \tag{3}$$

m= mass of pendulum (kg)
g = acceleration due to gravity (m/s^2)
h_o = initial height of the pendulum (m)
h_1 = final height after impact (m)
A= cross-sectional area of the specimen (m^2)

Fig 2: (a) Coconut Petiole (b) Specimens before test.

3.2.3 Hardness Test

The Rockwell hardness tester is employed to determine the hardness of a wide range of materials, including carbides, thin steel, aluminum alloys, copper alloys, hard cast irons, steels, plastics, nylon, polystyrene, plexiglass, and various rigid sheet and plate materials. The machine uses various types and sizes of indenters depending on the material being tested. As shown in Figure 3, the Rockwell hardness tester gives a direct hardness reading, making the measurement process simple and efficient.

3.2.4 Flexural Strength Test

The flexural test, also known as the bending test, examines how materials behaved under bending forces. It is often carried out on metals, polymers, and composites. During the test, each sample was bent until it either broke or deformed permanently. Measurements of bending stress, strain, and modulus of elasticity were used to determine important properties like flexural strength and stiffness. The results from these tests allowed predictions of material behavior in real-world use. This helps industries like aerospace, automotive, and construction design and improve structures and parts.

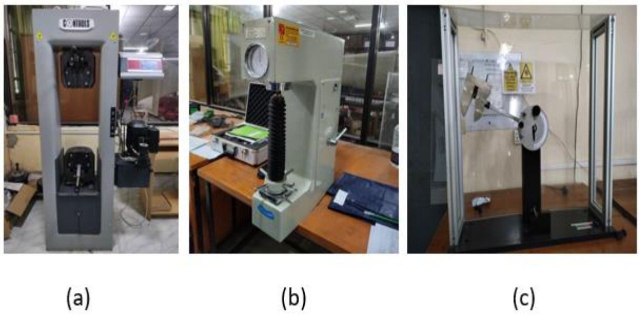

Fig 3: (a) Universal Testing Machine (b) Rockwell Hardness Testing Machine (c) Impact Testing Machine.

3.2.5 Water Absorption Test

The water absorption test is an important test for composite materials because these materials often soak up water. It is very important to understand this property, especially when composites are going to be used outside or in environments where they might get wet. For this test, specimens were first weighed in their dry state to obtain the initial mass. They were then fully immersed in deionized water for 24 hours. The specimens were removed after being immersed, the water surface wiped and surface weight determined once again to determine the final weight of the specimens. The ratio of water absorption was determined by the formula below:

$$\text{Water Absorption (\%)} = \frac{w_2 - w_1}{w_1} \times 100 \tag{4}$$

W_2= weight of the specimen after water immersion (g)
W_1= initial (dry) weight of the specimen (g)

Fig 4: Water Absorption Test.

4. Results and Discussion

Graphs were created from the experimental data to understand how the material responded under different conditions. They highlighted how changing the fiber content affected properties like hardness, tensile strength, and impact resistance. By comparing the different mixtures, it was possible to identify the fiber proportion that delivered the best mechanical performance before any decrease occurred.

4.1 Tensile Test

In Figure 5, it shows the impact of fiber addition on the composite's strength. As more fibers are added, the tensile strength rises, peaking at 11.09 MPa at 10% fiber and then slightly declining at 15%. Additionally, the Young's modulus increases, rising from 977.55 MPa for 5% fiber to 1330.10 MPa at 10% and 1351.50 MPa at 15%. This demonstrates how adding more fiber makes the composites stiffer. The largest shift is between 5% and 10%.

Adding fibers increases both tensile strength and Young's modulus because they help transfer stress more effectively from the matrix to the fibers. The best interaction between the fibers and the matrix occurs at 10% fiber content. The slight drop beyond this point may result from fiber clustering or a reduction in the continuity of the matrix.

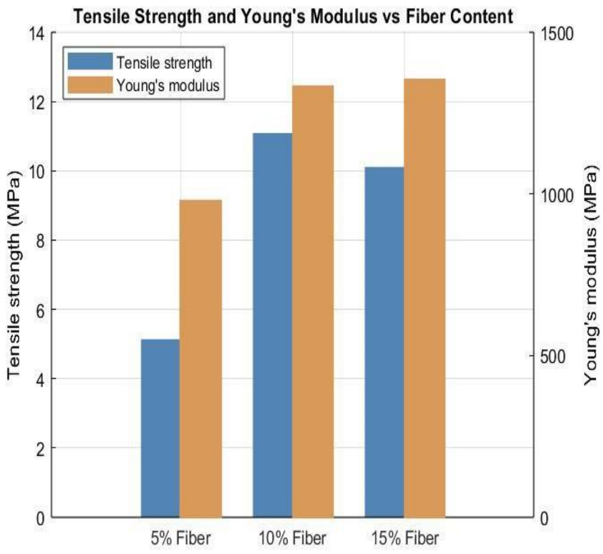

Fig 5: Tensile Strength & Modulus of Elasticity of 5%, 10% and 15% fiber percentage.

4.2 Impact Test

Figure 6 presents how strong composites are with 5%, 10%, and 15% fiber. The impact strength rises from 7,934.83 J/m² at 5% fiber to 11,520.24 J/m² at 10%, then slightly decreases to 10,911.12 J/m² at 15%. The composite absorbs the most energy at 10% fiber content. The rise in impact strength with added fiber is attributed to better energy absorption and more effective stress transfer between the matrix and fibers [14]. The peak at 10% shows optimal fiber-matrix bonding, while the slight decrease at 15% is likely due to fiber clumping or poor wetting, which lowers toughness. These findings emphasize the importance of maintaining the right fiber content to balance toughness and structural integrity, since too much fiber can disrupt stress distribution and reduce overall performance.

4.3 Hardness Test

Figure 7 shows the Rockwell scale L hardness of coconut petiole fiber-epoxy composites with 5%, 10%, and 15% fiber when they are under a 60 kg-f load. As the fiber content goes up, the hardness goes down [15]. At 5% fiber, it is 88.5; at 10% and 15%, it is 83.5 and 78, respectively. Coconut petiole fibers are softer than the epoxy matrix, which is the primary cause of this trend. The composite becomes less resistant to indentation as the fiber content increases because a larger portion of it is composed of these softer fibers.

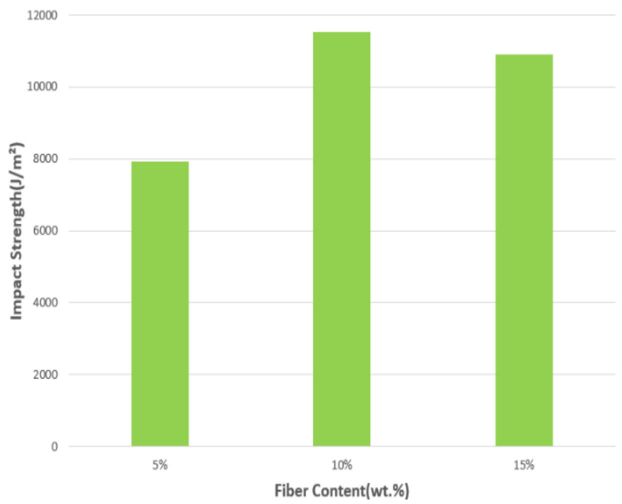

Fig 6: Impact Strength of 5%, 10% and 15% fiber percentage.

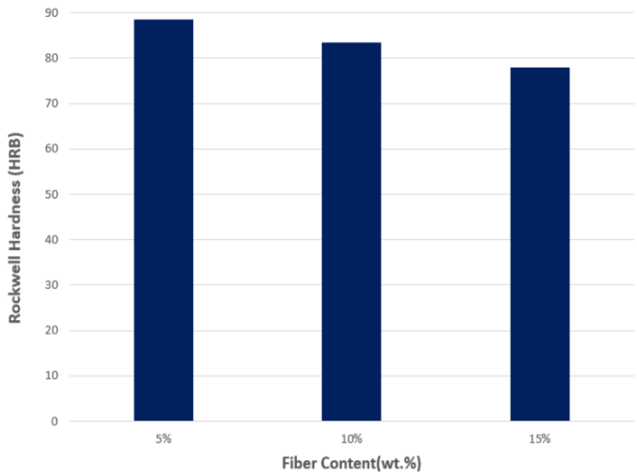

Fig 7: Rockwell Hardness of 5%, 10% and 15% fiber percentage.

Weak fiber-matrix interfacial bonding can also create micro voids or stress concentrations, further lowering hardness.

4.4 Flexural Test

Figure 8 shows the flexural strength of composites with 5%, 10%, and 15% fiber. The flexural strength increases from 7.34 MPa at 5% fiber to 9.57 MPa at 10%, then decreases to 5.21 MPa at 15%. It increases to 10% because the fibers strengthen the matrix and help it support the weight. The 15% drop is most likely the result of the fibers adhering to one another and the matrix not wetting well, which weakens the material's bending strength.

4.5 Water Absorption Test

The water absorption of composites with 5%, 10%, and 15% fiber is shown in Figure 9. Absorption goes up a little from 1.53% (5%) to 1.62% (10%) and then to 2.02% (15%). This proves that the fibers do not take much water even at increased concentration and are highly attached to the matrix. The increased level of fiber would lead to a temporary rise in water absorption since natural fibers have a hydrophilic nature [16].

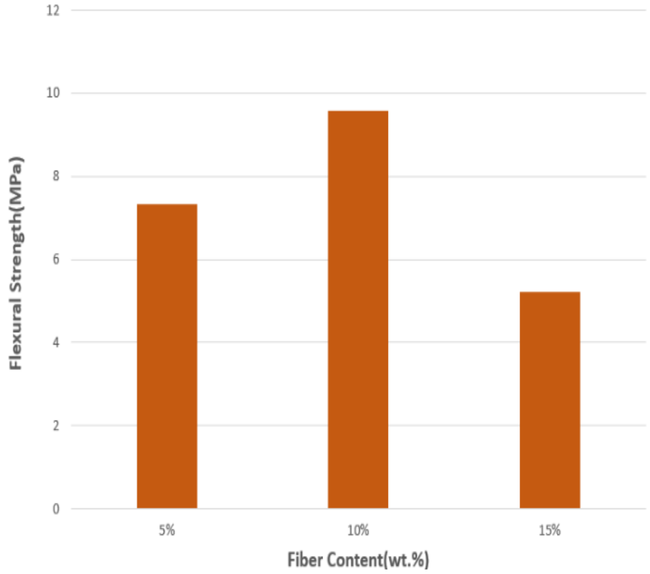

Fig 8: Flexural Strength of 5%, 10% and 15% fiber percentage.

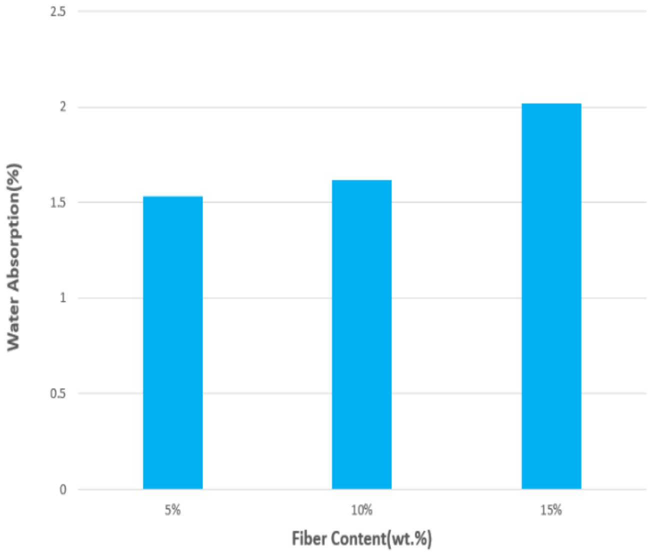

Fig 9: Water Absorption of 5%, 10% and 15% fiber percentage.

4.6 Summary of Result

Table 1: Summary of the findings from the experiment.

Fiber Content (wt.%)	**5%**	**10%**	**15%**
Tensile Strength (MPa)	5.14	11.09	10.11
Hardness (HRL)	88.50	83.50	78
Impact Strength (J/m²)	7934.83	11520.24	10911.12
Flexural Strength (MPa)	7.34	9.57	5.21
Elastic Modulus (MPa)	977.55	1330.10	1351.50
Water Absorption (%)	1.53	1.62	2.02

5. Conclusion

The coconut petiole fiber-epoxy composites developed in this study showed tensile strengths of 5.14-11.08 MPa and Young's modulus values between 977.55 and 1351.5 MPa, which are notably lower than those reported for coconut fiber composites in polyester or PLA matrices (e.g., tensile strength of 46 MPa at 1.5% fiber in polyester, and modulus values above 5000 MPa for pure fibers). Flexural strength was also limited (5.21-9.57 MPa), compared with literature values where treated coconut leaf stalk/polyester composites achieved 78.83-149 MPa depending on fiber content.

Conversely, the impact strength of the epoxy composites (7934.83-11,520.24 J/m²) was similar to or greater than that of coconut petiole fiber-PLA composites (≈8200 J/m²), which showed a high toughness and high energy absorption. The hardness (78-88.5 HRL) was greater than the one typically observed to be in the same natural fiber composite, but the water absorption (1.53-2.02%) was low, indicating that the fibers and the matrix are compatible.

The materials are ideal in green applications that require them to be strong, waterproof, and wear-free. They are eco-friendly because they are made of natural coconut petiole fibers only, and they only partially decompose. They are tough, have low water absorbency, and are extremely durable to destruction; thus, they are suitable for long-lasting, sustainable, eco-friendly domestic products, maritime accessories, and similar products. It is hoped that further improvements will be possible by fiber surface modification and optimized processing so that they will be useful in applications that value toughness and durability, though they have limitations to tensile and flexural properties that indicate that some problems with fiber-matrix adhesion and dispersion will arise.

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7. Nomenclature

Symbol	Meaning	Unit
ε	Strain	-
σ	Stress	MPa
F	Applied Force	kN
E	Youngs Modulus	MPa
HRL	Rockwell Hardness Scale L	-
L	Final length	M
L_0	Original gauge length	M
A	Cross-sectional area	mm^2/m^2