Research Article

Influence of Water Absorption on Mechanical and Morphological Behaviour of Roystonea-Regia/Banana Hybrid Polyester Composites

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Abstract

This study investigated the properties of hybrid composites made from Roystonea-Regia and banana fibers for potential applications in industries requiring lightweight, environmentally favorable, and mechanically strong materials. The analysis of density and void fraction revealed that the addition of banana fibers increased the composite's density, despite the fact that the actual density was slightly lower than the theoretical density due to confined gases during fabrication. The results of tensile tests revealed that water absorption negatively affected tensile strength, whereas alkali treatment and hybridization enhanced performance. The composition of 10 wt % Roystonea-Regia and 5 wt % banana had the highest tensile strength of 64.76MPa, which was attributable to the hydrophilicity and hydration content of the banana fiber. Further flexural and impact experiments confirmed that the influence of water absorption of composites showed a decrement in mechanical properties. The highest impact strength of 45.28 J/m and flexural strength of 75.6MPa were noted for 10 wt % Roystonea-Regia and 5 wt % banana. In addition, Scanning Electron Microscopy (SEM) analysis revealed that alkali treatment improved fiber-matrix interface bonding and roughened fiber surfaces, thereby enhancing the composites' overall performance. The study provides precious insights into the potential of Roystonea-Regia and banana hybrid composites for industrial applications as lightweight, environmentally friendly, and mechanically robust materials.

Keywords: Banana fibers, Density, Hybrid composites, Roystonea-Regia fibers, Tensile strength, Water absorption

1 Introduction

In recent years, there has been an increasing interest in the development of eco-friendly and sustainable materials, prompting researchers to investigate natural fibers as possible reinforcements for composite materials. Natural fibers derived from plants and animals offer several benefits, including accessibility, low weight, corrosion resistance, and biodegradability. They are considered eco-friendly substitutes for synthetic materials [1]–[4]. Roystonea-Regia (Royal Palm) and banana fibers have shown promise due to their unique properties among natural fibers [5]. While natural fibers have many advantages, they also have some disadvantages. Their susceptibility to water absorption, which can affect the mechanical properties of the fiber-matrix composite, is a significant disadvantage. Understanding the water absorption behavior of natural fiber materials and its effect on their mechanical properties is essential for their successful implementation in the engineering and industrial sectors. Comparing the water absorption behavior of natural fiber-based composites, such as palmyra and glass fiber composites, has revealed that natural fiber composites have reduced impact strength and higher water absorption [6]–[9].

Investigations on Roystonea-Regia fiber and epoxy composites have shown that increasing the fiber content increases tensile strength, bending resistance, and shear strength while decreasing impact strength [5]. The volume percentage of the banana fiber was shown to have a significant influence on the mechanical properties of the composites in an assessment of the mechanical behavior of banana bunch fiber-reinforced polyester composites [10]. The physicochemical properties of natural fibers, including cellulose content, lignin, hemicelluloses, density, and crystallinity index, have been analyzed using characterization techniques. Natural fibers are hydrophilic and absorb more water than synthetic fibers due to their cellulose-rich composition [11], [12].

In natural fiber composites, water absorption can cause fiber swelling and micro-crack formation, thereby influencing the composites' mechanical and dimensional properties [13] Epoxy has been widely used due to its desirable properties, making the selection of matrix material crucial. Improved tensile behavior, flexural modulus, and hardness properties have been observed in composites containing Roystonea-Regia and banana fibers. The addition of ceramic additives has increased the flexural strength of composites, while alkali treatment of Roystonea-Regia fibers has improved their tensile properties [14]–[17].

In this investigation, hybrid Roystonea-Regia/banana polyester composites were fabricated by hand. Alkaline treatment was applied to the composites to modify the fiber surface properties and eliminate impurities. Density and void fraction measurements were used to evaluate the physical characteristics of the composites. In addition, the composites were subjected to water absorption in order to assess their degradation properties. The influence of alkaline treatment on the mechanical properties of water-absorbent composites was investigated using tensile, flexural, and impact experiments. By comprehensively evaluating the mechanical behavior and water absorption properties of Roystonea-Regia/banana hybrid polyester composites, this study seeks to shed light on their suitability for various applications. The findings will contribute to the development of sustainable composite materials and encourage their use in industries seeking lightweight, eco-friendly, and mechanically robust materials.

2 Experimental Methods

2.1 *Materials*

The study utilized commercially available banana and Roystonea-Regia fibers that were obtained from Kovai Green Fibres, Coimbatore, as well as a polyester resin matrix (Density: 1.5 g/cm^3, Viscosity: 450 Cp) sourced from Naptha Resins and Chemicals, Bengaluru. Both fibers were extracted through a water-retting process. The importance of both banana fibers and Roystonea-Regia fibers in the study is emphasized. Figure 1(a) showcases the Roystonea-Regia tree, while Figure 1(b) displays the extracted fibers obtained from its leaves. Figure 2 shows the chopped banana fibers used in the study. Table 1 presents the physical and mechanical properties of Roystonea-Regia and banana fibers, respectively. The properties of polyester resin are shown in the Table 2.

(a)

(b)

Figure 1: (a) Roystonea-Regia tree and (b) Roystonea-Regia fiber.

Table 1: Physical and mechanical properties of fibers

Sl. No.	Properties	Roystonea-Regia Fiber	Banana Fiber
1	Density (g/cm^3)	0.825	1.35
2	Diameter (µm)	200–300	80–250
3	Tensile Strength (MPa)	363 ± 19	529–754
4	Young's modulus (GPa)	21 ± 0.6	8–20
5	Elongation (%)	4.01 ± 0.29	1.0–3.5
6	Alpha-cellulose (%)	58	65
7	Hemi-cellulose (%)	24	18
8	Lignin (%)	14	5

Table 2: Properties of polyester resin

Sl. No.	Properties	Polyester Resin
1	Density (g/cm^3)	1.5 ± 0.01
2	Viscosity (Cp)	450 ± 50
3	Tensile Strength (MPa)	7300
4	Tensile Modulus (GPa)	5.3

Figure 2: Chopped banana fibers.

2.2 *Fibre extraction*

2.2.1 Banana fibre extraction

Utilizing the tuxying technique to extricate the primary fibers from dried banana stalks obtained from a nearby farm, banana fiber was extracted. The stalks were transformed into segments known as tuxies. To facilitate the removal of lignin and pectin membranes from the outer surface of these tuxedos, they were immersed in water for two days [18]–[20].

The tuxies were then desiccated and crushed with pruning shears to produce fibers with a predetermined length between 6 and 10 mm. Additional processing was performed to eliminate any remaining particles and fibers shorter than 6 mm. This ensured the extraction of clean, uniform fibers suitable for the fabrication of composite materials. The extracted banana fibers differed in thickness between 0.2 and 0.3 mm, providing a variety of fiber sizes for the subsequent composite fabrication.

2.2.2 Roystonea-Regia fibre extraction

For the extraction of Roystonea-Regia fibers, the leaves and leaf stems of a nearby palm tree were collected and dried in the dark for three days. The greasy component of the collected material was extracted by compressing and washing it after an additional three days of soaking in water. After removing the oily material, the fine fibers were thoroughly washed with clean water to eliminate any remaining residues. In order to prepare the extracted fibers for sample preparation, they were washed and dried under the sun for one week [5]. The extracted Roystonea Regia fibers ranged in diameter from approximately 0.2–0.3 mm and in length from approximately 0.2–1.5 m. These dimensions reflect the characteristics of the fibers and provide insight into their possible application in the development and testing of composite materials.

2.2.3 Alkaline treatment

Banana fibers and Roystonea-Regia fibers were both subjected to an alkaline treatment to improve their properties. The fibers were chemically treated with a sodium hydroxide (NaOH) solution containing 5% sodium hydroxide. Due to its potential in delignification and reducing crystallinity of cellulose the Sodium Hydroxide solution is preferred in the investigation [21].

Fibers were submerged in a glass container containing an alkaline solution as part of the alkaline treatment procedure. Approximately two hours were spent soaking the fibers in the solution at room temperature. After the process of soaking, the fibers were thoroughly rinsed with water to eradicate any remaining alkali [22], [23].

Consequently, they were entirely dried. To ensure that the fibers dried properly, they were placed in an oven and heated to 60 °C. The alkaline treatment was intended to modify the surface properties of the fibers, thereby augmenting their compatibility with the polyester matrix and the overall performance of the hybrid composites.

2.3 *Hybrid composite fabrication*

The polyester hybrid composites were manufactured using the hand lay-up procedure. The composites were strengthened by varying proportions of Roystonea-Regia and banana fibers. During the fabrication process, a mold with dimensions of 260 mm length, 260 mm breadth, and 3 mm height (according to the ASTM standard) was utilized. To facilitate the removal of the cured samples from the mold, a silicone release agent was applied to its surfaces. To obtain a uniform consistency, the matrix resin, polyester reagent, was prepared and thoroughly mixed with 1% to 2 wt% Methyl Ethyl Ketone Peroxide (MEKP) hardener and 0.02 wt% cobalt catalyst. The mixture was then degassed to remove any air pockets.

Figure 3: Fabricated Laminate composite material.

In the first stage, the prepared matrix resin was poured into the mold to form the composite material's first layer. On top of the first layer, chopped Roystonea-Regia and banana fibers ranging in length from 6–10 mm were applied. Rolling the layer eliminated any air pockets. This procedure was repeated until the desired thickness of the composite was attained. Prior to compressing the final layer, a sheet of plastic (polythene) was inserted on top of the uncured topmost layer. A load of 50 kilograms was used to ensure a uniform thickness of 3 mm throughout the composite material. The material was then left to cure at ambient temperatures for 24 h. Finally, the composites were meticulously removed from the mold, as shown in Figure 3.

The proportions of Roystonea-Regia fiber and banana fiber used to create composite materials are depicted in Table 3. Composites containing only polyester and Roystonea-Regia fiber are designated (PR), while composites containing polyester, Roystonea-Regia fiber, and banana fiber are designated (PBR). In the preliminary study, it was discovered that combining more than 15 wt% Roystonea-Regia fiber with a polyester matrix led to improper fiber distribution or moisture. Therefore, the fiber composition was fixed at 15 wt% for this study.

Table 3: Matrix fiber composition

Nomenclature	Matrix (wt.%)	Roystonea-Regia Fiber (wt.%)	Banana Fiber (wt.%)
PR	85	15	-
PBR1	85	10	5.0
PBR2	85	05	10
PBR3	85	7.5	7.5

3 Experimentation

3.1 *Water absorption behavior*

The water absorption behavior of untreated and alkali-treated polyester composites was evaluated in accordance with ASTM D-570 [24]. To evaluate the kinetics of water absorption, samples with varying fiber weight ratios were immersed at room temperature in a beaker of distilled water. The samples were removed from the water at regular intervals of 24 h, rubbed with tissue paper to remove surface moisture, and then weighed using a precision electronic balance. Using the following equation, the percentage of water absorption was computed [Equation (1)]:

$$\%\ Water\ Absorption = \frac{M_t - M_o}{M_o} \quad (1)$$

Where

M_o = Initial weight of the specimen before immersion in water

M_t = Weight of the specimen after immersion in water

By analyzing the water absorption behavior and calculating the liquid ingestion rate, we were able to gain insight into the composite's ability to absorb water and its resistance to moisture ingress. These results provide important information regarding the composite's durability and applicability.

3.2 *Density and void fraction*

The room-temperature density of the polymer, fiber, and composite was determined using the ASTM D792 standard method, which is based on Archimedes' principle [25]. In order to implement Archimedes' principle, each sample was first weighed in air and then in water. Utilizing a digital scale available in the laboratory, precise weight measurements were obtained. Since the scale lacked a built-in attachment for sample suspension, an improvised apparatus was created. By placing the assembly on the pan of the electronic balance, it was possible to ascertain the density of the sample relative to either air or water temperature. The composite's theoretical density (ρth) was calculated using the following formula [Equation (2)]:

$$\rho_{th} = (f_{fibre} \times \rho_{fibre}) + (f_{resin} \times \rho_{resin}) \quad (2)$$

where

f_{fiber} = Fraction of fiber content

f_{resin} = Fraction of resin content

ρ_{fiber} = Density of fiber

ρ_{resin} = Density of resin

The actual density (ρact) was calculated as follows Equation (3):

$$\rho_{act} = \left(\frac{A}{A-B}\right) \times \rho_{dw} \quad (3)$$

where

A = Weight of the sample in air

B = Weight of the sample in the distilled water

ρ_{dw} = Density of distilled water (0.997 g/cm³)

The volume fraction of voids (V_v) was determined using the formula [Equation (4)]:

$$V_v = \frac{\rho_{th} - \rho_{act}}{\rho_{th}} \quad (4)$$

The presence of voids in composite materials can have a significant impact on their mechanical properties. Increased void content can result in decreased fatigue resistance, increased susceptibility to moisture and erosion, and greater strength property variation. Understanding the void content is therefore essential for accurately evaluating the quality of composites. A rise in the vacuum volume fraction (V_v) is undesirable because it has a negative effect on the properties of composites [25]–[27].

3.3 *Mechanical characterization*

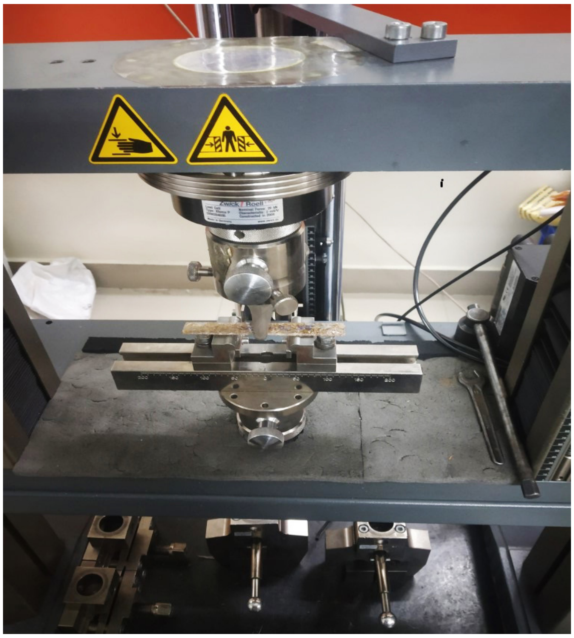
A series of experiments, including tensile strength, flexural strength, and impact strength, were performed to evaluate the mechanical properties of the composites. For these tests, Z020 AllroundLine universal testing equipment with a 25 kN load capacity, and testing speed ranging from 0.00005 to 3000 mm/min was rented from KONSPEC in Mangalore. Figure 4(a) and (b) depict tensile testing according to ASTM D638 [28] with a gauge length of 80mm, while Figure 5(a) and (b) depict flexural testing according to ASTM D790 [29] with a gauge length of 52 mm. At a constant strain rate of 2 mm/min, both experiments were conducted. To evaluate the impact strength, a ZWICK/ROELL HIT50P Pendulum Impact Tester of 50J maximum

(a)

(b)

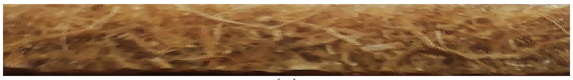
Figure 4: (a) Specimen for tensile testing and (b) Set up for tensile testing.

(a)



(b)

Figure 5: (a) Specimen for flexural testing and (b) Set up for flexural testing.



(a)

(b)

Figure 6: (a) Specimen for impact testing and (b) Set up for impact testing.

energy compliant with ASTM D256 [30] was used [Figure 6(a) and (b)]. The test specimens for tensile strength measured 160 × 20 × 3 mm, whereas the test specimens for flexural strength measured 125 × 15 × 3 mm. The specimens for impact testing measured 65 × 10 × 3 mm.

3.4 *Scanning Electron Microscopy (SEM) analysis*

Using a Hitachi SU3500 SEM operating at 30 kV, the morphology of the fragmented specimens was examined. A thin coating of gold material was applied to the specimens in order to increase their conductivity and facilitate imaging under an SEM [22]. The surface structure and morphology of composite materials can be visualized with high resolution via SEM analysis. By examining the fracture surfaces, we can obtain insight into the failure mode, fiber-matrix interaction, and reinforcement fiber distribution within the composite matrix. Utilizing SEM analysis provides valuable visual data and permits a thorough characterization of the composite microstructure. This analysis contributes to a comprehensive evaluation of the composite material by aiding in the comprehension of its mechanical properties and the efficiency of the fiber-matrix interface.

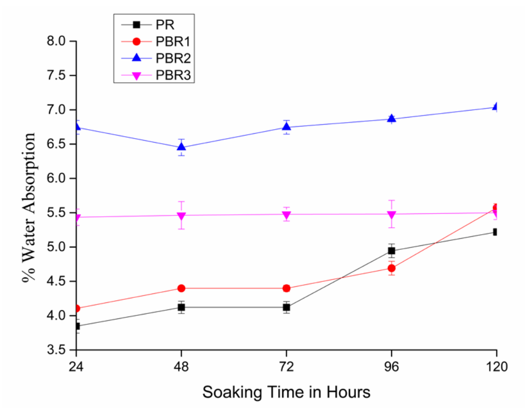


Figure 7: Percentage of water absorption for different soaking hours.

4 Results and Discussion

4.1 *Water absorption analysis*

Commonly used in natural fiber-reinforced composites, lignocellulosic fibers have a propensity to absorb moisture, resulting in dimensional instability and changes in mechanical properties. Understanding the water absorption characteristics of natural fiber composites is essential for determining their durability in particular applications. Through micro-gaps between polymer chains, capillary action within the fiber-matrix interstitial spaces, and defects at the fibre-matrix interfaces, water molecules enter these composites. The principal site of moisture absorption is the interface between the fiber and matrix, as well as the fiber itself through hydrogen bonding [31]–[34]. The water absorption results of the study's prepared hybrid composites are displayed in Table 4. Figure 7 depicts the percentage of water absorption over time for banana fiber hybridized with various proportions of Roystonea-Regia (PBR1, PBR2, and PBR3). The results indicate that hybridization has a significant impact on the composites' water absorption. This is due to the hydroxide treatment of the fiber's exterior surface, which increases its water resistance. The composition PBR1 (10 wt% Roystonea-Regia and 5 wt% banana) has the highest resistance to water absorption compared to the others. As the amount of banana fiber increases more prone to moisture absorption which may be due to the banana fiber having more cellulosic content than Roystonea-Regia. The findings also indicate that the fibers absorb the most water after 24 h of immersion, with a significant weight gain up to 144 h. As shown in Table 4, variations in water absorption are observed after this point. The prolonged exposure to water reveals that water absorption reaches a saturation point, indicating that the fibers have attained their maximal capacity to absorb moisture. After 144 h of immersion, saturation behavior is observed. The decreased water absorption observed in hybrid composites, particularly with the optimized composition of 10 wt% Roystonea-Regia and 5 wt% banana (PBR1), demonstrates their potential for use in applications where moisture resistance is essential. The ability of alkali-treated fibers to restrict water ingress contributes to the enhanced dimensional stability and durability of these composites, making them suitable for industries and mechanically resilient materials.

Table 4: Water absorption of hybrid composites

Soaking Time in Hours	% Water Absorption			
	PR	PBR1	PBR2	PBR3
24	3.49	4.11	6.74	5.43
48	4.12	4.39	6.45	5.46
72	4.12	4.39	6.74	5.48
96	4.95	4.69	6.87	5.48
120	5.22	5.57	7.03	5.50

4.2 *Density and void fraction*

The results of the composites' density and void fraction are presented in Table 5. These parameters play a crucial role in determining the suitability of composites for industrial applications, especially when the desired properties of lightweight, environmentally friendly, and mechanically robust materials are taken into account. The banana fibers are combined with Roystonea-Regia fibers and the theoretical density of the composites changes. As the percentage of banana fibers in the composite increases, so does its density. This is because banana fibers have a greater density than other fibers. This trend is supported by the experimental findings, which indicate that the composite density increases as the banana fiber content rises. Notably, the actual density of composites is marginally lower than their theoretical density. This is due to the introduction of trapped gases during the manual lay-up fabrication technique [35]. Despite this minor variation, the composites continue to exhibit a favorable density range, making them lightweight materials suitable for a variety of applications. The void fraction in hybrid composites varies depending on the fiber composition. PBR2 (5 wt% Roystonea-Regia and 10 wt% Banana) has a lower vacancy fraction than the other compositions tested. This suggests a more compact and densely packed structure within the composite, which contributes to improve mechanical properties and resistance to moisture absorption [36].

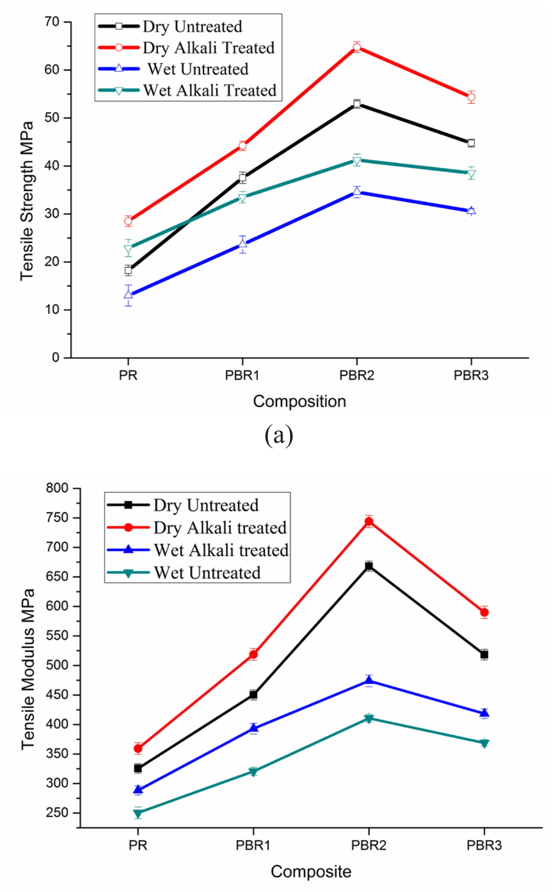
Table 5: Density and void fraction of composites

Sample	Theoretical Density (g/cm^3)	Actual Density (g/cm^3)	% Volume Fraction of Voids
PR	1.39	1.33	4.25
PBR1	1.43	1.36	4.17
PBR2	1.45	1.40	3.53
PBR3	1.44	1.38	4.17

The density and vacancy fraction results demonstrate the potential of these composites as lightweight alternatives for industries that prioritize eco-friendly materials with superior mechanical performance. The meticulous selection and optimization of fiber compositions can further increase density and reduce voids, resulting in the development of high-quality composites with superior properties.

4.3 *Tensile test results*

The results of the tensile test provide valuable information regarding the efficacy of composites under various moisture conditions. Figure 8(a) and (b) illustrate the influence of water absorption on the tensile strength and tensile modulus of composites. When untreated fibers are exposed to moisture, there is a significant 43% reduction in tensile strength. This indicates that moisture absorption has a negative effect on the composites' mechanical properties. However, when composites that have been treated with alkali are tested, the reduction in tensile strength is reduced to 22%. This enhancement is due to the alkali treatment of fibers, which reduces their capacity to absorb moisture and increases the bonding between fiber and matrix [37], [38]. In addition, the hybridization of Roystonea-Regia fibers with banana fibers affects the tensile properties of the composites further. Figure 9 depicts a reduction in tensile results spanning from 17–18% due to the



(b)

Figure 8: Tensile test results (a) Tensile Strength, (b) Tensile Modulus.

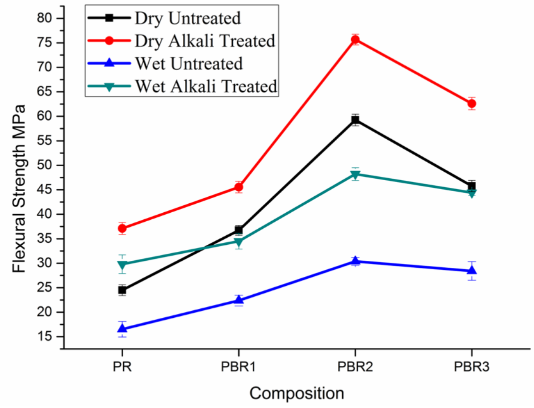
incorporation of banana fibers. Among all the evaluated hybrid combinations, 10 wt% Roystonea-Regia and 5 wt% banana proved to be the most effective. This combination exhibits superior tensile performance in comparison to other compositions.

The enhanced tensile properties can be attributed to the interactions between the two fiber types, resulting in a tension-resistant structure with reinforced tensile properties. Intriguingly, the higher hydrophilicity of banana fibers, which results from their higher moisture content, may contribute to their inferior overall compositional properties. However, the optimal hybrid composition effectively balances the advantages of Roystonea-Regia fibers and the moisture resistance attained via alkali treatment. These results emphasize the significance of fiber treatment and hybridization in optimizing the tensile properties of composites, particularly in environments with high levels of moisture. By employing suitable fiber treatments and selecting hybrid compositions with care, it is possible to increase the tensile strength and moisture resistance of composites, making them suitable for applications that require lightweight, ecologically friendly, and mechanically durable materials.

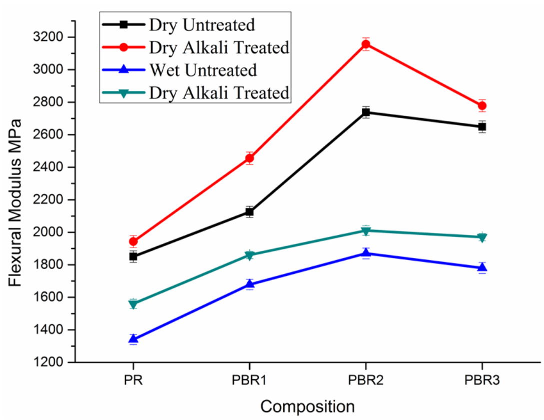
4.4 *Flexural test results*

The flexural test results shown in Figure 9(a) and (b) provide useful information regarding the flexural strength and flexural modulus of the composites under dry and water-absorbent conditions. These findings shed light on the behavior of composites under bending loads and the effect of moisture on their mechanical properties. When scrutinizing the dry samples, it is evident that the flexural strength increases proportionally when banana fibers are added. This improvement can be attributed to a combination of factors. First, the presence of banana fibers permits a greater burden transfer to the fibers, thereby enhancing the composites' overall strength. In addition, the interface zone between the fibers and matrix exhibits improved adhesion, which contributes to enhance flexural strength. Additionally, the cellulose fibers present in the composites provide additional support for bending stresses, enhancing the flexural properties synergistically with the banana fibers. Nonetheless, the results indicate that water absorption decreases the flexural strength of composites. Without alkali treatment, water absorption causes a 46% reduction in flexural strength. However, when composites are treated with an alkali, the decrease in flexural strength is reduced to 28%. This enhancement is a result of the alkali treatment's ability to reduce moisture absorption and increase the fibers' resistance to moisture. In addition, by employing hybrid compositions, the detrimental effect of water absorption on flexural strength can be mitigated further. The composition containing 10 wt% Roystonea-Regia and 5 wt% banana exhibits the most favorable results, with a 19–26% reduction in flexural strength. This indicates that hybridization of fibers provides additional advantages in terms of moisture resistance and overall flexural performance.

The lower flexural strength observed under moist conditions can be attributed to the penetration of water



(a)



(b)

Figure 9: Flexural test results (a) Flexural Strength, (b) Flexural Modulus.

molecules into the fiber-matrix interface. This causes fiber enlargement and the formation of spaces between the fibers and the matrix, which ultimately results in fiber detachment. The separation of fibers into fibrils caused by moisture-induced degradation of fibers further contributes to the decrease in flexural strength of damp hybrid composites.

These results highlight the significance of moisture resistance in attaining optimal flexural properties for composites. Alkali treatment and the selection of hybrid compositions are essential for enhancing the composites' resistance to moisture absorption and minimizing the detrimental impacts on flexural strength [38]–[41]. This makes composites suitable for applications requiring high strength-to-weight ratio, ecologically favorable, and mechanically robust materials [42], [43].

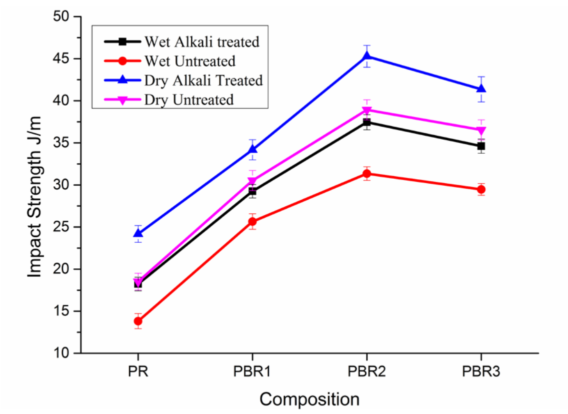


Figure 10: Effect of water absorption on Impact Strength.

4.5 *Impact test results*

As depicted in Figure 10, the impact test results cast light on the impact strength of the hybrid composites under wet and dry conditions. It is evident that the impact strength of composites in wet conditions is substantially lower than in dry conditions. This can be attributed to the formation of an increased number of micro cracks as water molecules diffuse into the fiber-matrix contact zone. As a consequence, the bond between the fibers and the matrix weakens, resulting in diminished impact strength. Further analysis reveals that water absorption reduces the impact strength of composites containing 15 wt% Roystonea-Regia fibers by 25% compared to dried composites. Nonetheless, by employing the hybridization strategy, this reduction can be reduced to a range of 14% to 17%.

Notably, the hybrid composition consisting of 10 wt% Roystonea-Regia and 5 wt% banana exhibits superior impact resistance in comparison to other compositions. These findings emphasize the significance of moisture resistance in maintaining composites' optimal impact strength. The diffusion of water molecules into the contact zone results in the formation of micro cracks, thereby compromising the fiber-matrix bond. Thus, the impact resistance of damp hybrid composites is diminished. The negative impact of water absorption on impact strength can, however, be effectively mitigated by incorporating banana fibers and the appropriate hybrid composition. The implications of these findings for industries pursuing moderate weight and ecologically friendly, and mechanically robust materials are substantial. By contemplating the hybridization of fibers and employing moisture-resistant techniques, such as alkali treatment, composites can maintain their impact strength even in environments with high levels of moisture [38], [39], [44]. This assures their suitability for applications where impact resistance is crucial and contributes to the development of lightweight and resilient materials across a variety of industries.

4.6 *SEM analysis*

SEM permits a thorough examination of fiber surface morphology. Chemical treatments can effectively eliminate impurities and reduce hydrophilicity in polyester-hybrid natural fiber composites. SEM analysis was used to compare the surface morphology of untreated and treated polyester natural fiber composites. In comparison to their alkali-treated counterparts, untreated fiber-reinforced composites exhibit more extensive fiber degradation. Figure 11(a) and (f) depict the fracture surface of dried, untreated hybrid fibers, revealing weak fiber-matrix adhesion and crack formation during tensile fracture. In contrast, alkali treatment coarsens the surface of the fibers, resulting in an enhanced interface between the matrix and fibers, as shown in Figure 11(b). Chemical treatments result in an increase in surface porosity and roughness, which improves the mechanical interlocking adhesion between fibers and the matrix, especially when used in composite production [Figure 11(e)]. A narrower spectrum of mechanical properties is observed in wet hybrid composites compared to their dry counterparts.

This phenomenon is caused by the formation of hydrogen bonds between water molecules and cellulose upon immersion of composite specimens in water. The penetration of water molecules into the fiber-matrix region causes dimension changes in composite specimens, thereby diminishing the interfacial bonding and reducing the tensile properties. In addition, fiber enlargement results in fiber detachment from the matrix, which weakens fiber-matrix adhesion [Figure 11(c), (d), (g), and (h)]. The SEM analysis provides significant insight into the fracture surfaces of hybrid Roystonea-Regia/banana composites. The comparison between untreated, dried composites and treated composites demonstrates the significance of alkali treatment for enhancing the interface and overall mechanical properties. In addition, the study of wet

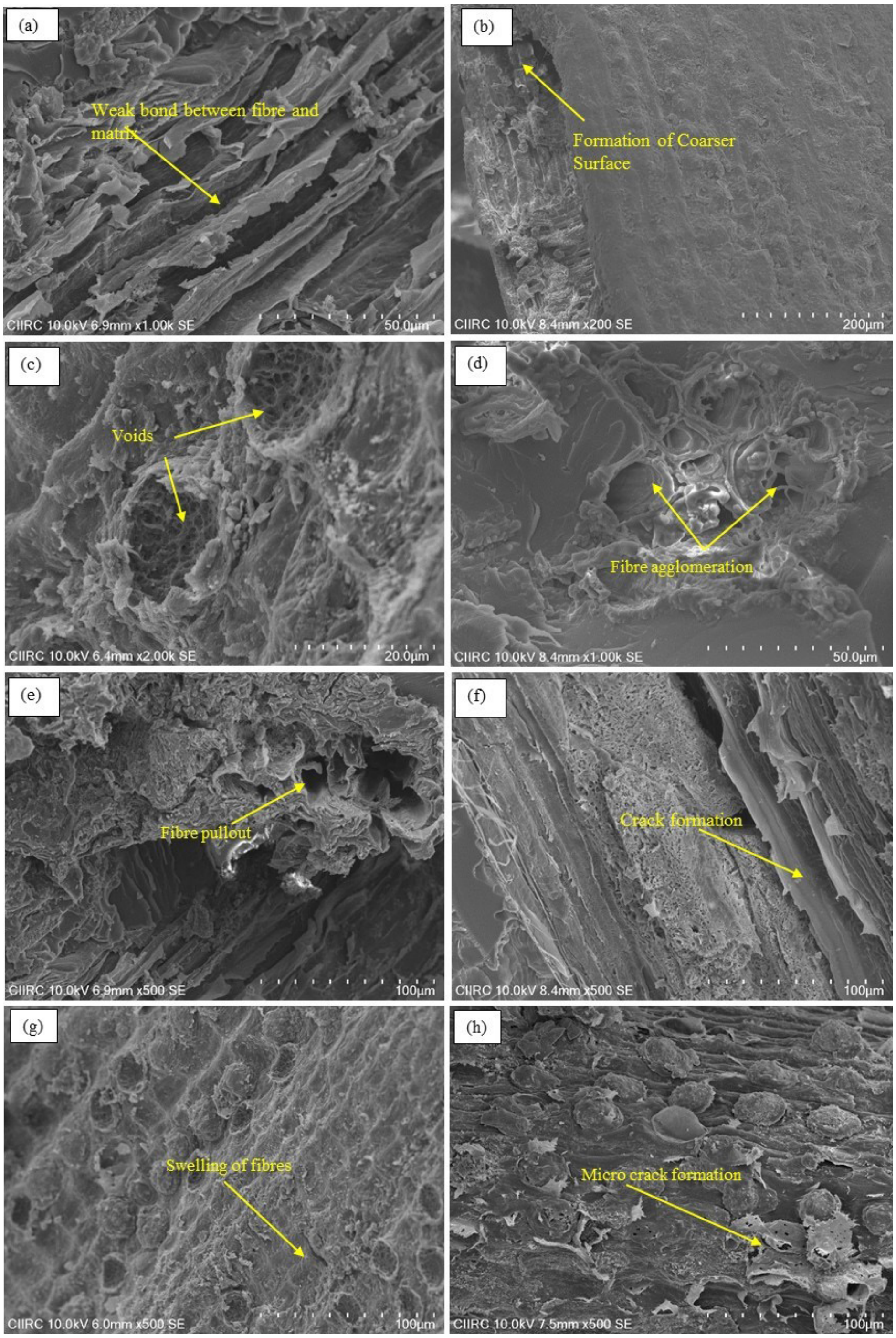


Figure 11: Tensile fracture surface of (a) Dry untreated Composites PBR1, (b) Dry treated composites PBR1 (c) Water absorbed treated Composites PBR1, (d) Water absorbed untreated composites PBR1, (e) Dry treated composites PBR2, (f) Dry untreated composites PBR2, (g) Water absorbed treated Composites PBR2, (h) Water absorbed untreated Composites PBR2.

composites reveals the detrimental impacts of water absorption on interfacial adhesion and mechanical performance [45]–[47]. These findings contribute to the comprehension of the microstructural changes that occur in composites and support the development of mechanically tough materials for a variety of industrial applications.

5 Conclusions

This article investigated the properties of Roystonea-Regia and banana fiber-based hybrid composites. The composites' density, void fraction, tensile strength, flexural strength, impact strength, and water absorption were analyzed using a variety of characterization techniques. The inclusion of Banana fibers improved the composite's density; however, trapped gases during manufacture lowered it marginally. Hybrid fiber compositions with 10 wt% Roystonea-Regia and 5 wt% banana had the lowest void fraction. Roystonea-Regia and banana lignocellulosic fibers absorb moisture, altering composites' dimensional stability and mechanical qualities. Alkali treatment made fibers less water-permeable, reducing water absorption during hybridization. 10 wt% Roystonea-Regia and 5 wt% banana absorbed the least water. Further incorporation of banana fibers enhanced the mechanical properties of composites in dry conditions. The absorption of water affected composites' mechanical properties. Water reduces the mechanical strength of untreated fibers. However, alkali treatment reduced this loss, while hybridization of Roystonea-Regia with banana fibers improved it further. The composition of 10 wt% Roystonea-Regia and 5 wt% banana produced the greatest results, likely due to the banana fiber's hydrophilicity and moisture effect. SEM examination revealed fiber surface morphology and the impact of chemical treatments, fiber-matrix bonding, and water absorption.

Overall, the hybrid composites exhibited optimistic properties, making them suitable for applications requiring lightweight, eco-friendly, and mechanically robust materials. The incorporation of banana fibers, alkali treatment, and fiber hybridization all improved the mechanical performance and water resistance of composites. These findings contribute to the development of sustainable composites for a variety of industrial applications, particularly those that prioritize lightweight materials with increased durability.

Author Contributions

All authors equally contributed to Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

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