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Mechanical and Water Absorption Properties of Mercerized Banana Fiber-Reinforced Polyester Composites for Sustainable Prosthetic Applications

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Abstract

The demand for sustainable and cost-effective materials in prosthetic socket fabrication has stimulated interest in natural fiber-reinforced composites. This study aims to evaluate the mechanical and water absorption properties of mercerized banana fiber-reinforced polyester composites and assess their suitability for prosthetic applications. Additionally, it explores the application of novel modeling approaches, such as the Log-Square Root Linear Model, to analyze water absorption kinetics. Banana fibers were treated with 12.5% NaOH for 30 minutes to enhance mechanical performance by removing lignin and hemicellulose. Polyester composites were fabricated with varying fiber contents, and mechanical properties, including tensile strength, tensile modulus, flexural modulus, and hardness, as well as water absorption behavior, were systematically analyzed. FTIR spectroscopy was used to assess fiber-matrix bonding. Treated banana fibers exhibited a 2300% improvement in tensile strength and an 860% increase in tensile modulus. Composites with 15% fiber content demonstrated optimal mechanical performance, with a 632% increase in tensile strength and a 33.61% improvement in flexural modulus compared to pure polyester. FTIR analysis confirmed enhanced bonding at the fiber-matrix interface. Water absorption analysis showed that composites with 10–15% fiber content had the lowest water diffusion coefficients, providing an optimal balance between reinforcement and moisture resistance. Mercerized banana fiber-reinforced polyester composites exhibit significantly enhanced mechanical properties, reduced water absorption, and strong environmental advantages, highlighting their potential as sustainable alternatives for prosthetic socket fabrication.

Keywords: Banana fiber; mercerization; polyester; prosthetic; sockets

1. Introduction

Prosthetic sockets are essential for providing support, comfort, and functionality to amputees (Patel & Mahato, 2022). Traditionally, synthetic fibers like glass, Kevlar, and carbon fibers have been used in prosthetic fabrication; however, these materials are expensive, non-biodegradable, and derived from petroleum-based sources, raising environmental and sustainability concerns (Gashawtena et al., 2021; Syduzzaman et al., 2020). Additionally, synthetic fibers often exhibit poor biocompatibility and inadequate bonding with resins, limiting their effectiveness in applications requiring long-term durability (Ahmed & Miah, 2024). These limitations have driven interest in natural fibers as renewable, cost-effective, and environmentally friendly alternatives (Sekhar et al., 2023).

Banana pseudo stem fibers have gained significant attention as a sustainable option due to their abundant availability in tropical regions like Nigeria, a major banana-producing country (Odusote et al., 2016a, 2016b). These fibers, often discarded as agricultural waste, offer excellent mechanical properties such as high specific strength, lightweight characteristics, and good interfacial bonding with resins, making them suitable for prosthetic applications (Kabir et al., 2023; Sukania, 2015). Using banana fibers for composite production not only addresses environmental concerns by recycling agricultural waste but also provides an economical solution for prosthetic manufacturing (Mohammed et al., 2024). For prosthetic applications, key aterial requirements include high tensile and flexural strength, good hardness, durability, and lightweight characteristics to ensure the material can withstand dynamic loads while maintaining user comfort (Badyankal et al., 2021; Odusote et al., 2016a, 2016b). Among polymer matrices, polyester resin is particularly promising due to its affordability, ease of processing, and compatibility with natural fibers. Despite its widespread use, research on banana fiber-reinforced polyester composites remains limited, particularly regarding their performance in prosthetic applications. Existing studies have largely focused on epoxy-based composites (Odusote et al., 2016b), leaving a gap in understanding how polyester compares in terms of mechanical properties and moisture resistance.

Moisture exposure is a critical issue for prosthetic sockets, as it can degrade composite materials, reduce user comfort, and shorten the device's lifespan, particularly in humid environments (Wernke et al., 2015). However, there is limited research on the water absorption and diffusion behavior of banana fiber-reinforced polyester composites. Furthermore, studies on modeling water absorption kinetics in such composites are scarce, despite their relevance for optimizing material design.

This study focuses on addressing these research gaps by investigating the mechanical properties, water absorption behavior, and water diffusion kinetics of banana fiber-reinforced polyester composites. Using advanced modeling techniques, such as the Log-Square Root Linear Model, this research aims to enhance understanding of the performance of polyester composites in prosthetic applications. By evaluating the optimal fiber content and treatment conditions, this study contributes to the development of sustainable, durable, and cost-effective materials for prosthetic socket fabrication.

2. Materials and Methods

2.1 Materials

The materials used in this study included banana pseudo-stems, unsaturated polyester resin, sodium hydroxide (NaOH), and distilled water. Banana pseudo-stems were locally sourced from Ayetoro, Yewa North, Ogun State, Nigeria. The polyester resin and its corresponding hardener were supplied by OrthoEx, Lagos, Nigeria. Sodium hydroxide was utilized for mercerization to enhance fiber-matrix bonding, while distilled water was used for washing the treated fibers to ensure complete removal of residual alkali. Banana pseudo-stems served as the reinforcement material, with polyester resin acting as the matrix for composite fabrication.

2.2 Methods

2.2.1 Fiber Preparation

Banana fibers were manually extracted from pseudo-stems to preserve their natural properties. The extracted fibers were treated with a 12.5% sodium hydroxide (NaOH) solution for 10–50 minutes to remove non-cellulosic materials such as lignin and hemicellulose. This mercerization process enhanced fiber compatibility with the polymer matrix. Following treatment, the fibers were rinsed thoroughly with distilled water until a neutral pH of 7 was achieved and were then oven-dried at 60°C to remove any remaining moisture. The dried fibers were handwoven into mats to improve fiber alignment and reduce void formation during composite fabrication (Figure 1a).

2.2.2 Composite Fabrication

Banana fiber-reinforced composites were fabricated using the hand lay-up method with unsaturated polyester resin as the matrix. The resin and hardener were mixed in a 10:1 ratio by weight. The fiber weight fractions were 5%, 10%, 15%, 20%, and 25%, with the remainder consisting of the matrix material. Pure polyester resin was labeled as Pp, and fiber-reinforced polyester composites were labeled as A, B, C, D, and E for 5%, 10%, 15%, 20%, and 25% fiber loadings, respectively (Figure 1b).

Rectangular molds with dimensions of 100 mm × 15 mm × 5 mm were prepared, cleaned, and coated with polyvinyl acetate as a mold-releasing agent. Woven and mercerized banana fiber mats were placed into the molds, and the resin-hardener mixtures were poured onto the fibers. A roller was used to ensure uniform resin infiltration and eliminate trapped air. A weight of 30 kg was applied to the mold for compression, reducing voids and improving structural integrity. Initial curing was performed at room temperature for 6 hours, followed by a 24-hour curing period to ensure complete polymerization.

(a) (b)

Figure 1: Banana fiber (a) Woven banana fibers. (b) Composite

2.2.3 Mechanical Testing

2.2.3.1 Tensile Testing

Tensile properties were evaluated following ASTM D3039 standards using an Instron Universal Testing Machine (Model 3369). Specimens were cut to dimensions of 150 mm × 25 mm × 3 mm. The specimens were clamped into the machine, and a crosshead speed of 5 mm/min was maintained during the test. Stress-strain data were recorded continuously until specimen failure. The tensile modulus (E) was calculated from the linear region of the stress-strain curve using the equation:

$$\mathrm{E} = \frac{\Delta\sigma}{\Delta\epsilon} \qquad (1)$$

Where $\Delta\sigma$ represent the change in tensile stress and $\Delta\epsilon$ represents the corresponding change in strain.

2.2.3.2 Flexural Testing

Flexural properties were assessed according to ASTM D790 using an Instron Universal Testing Machine (Model 3369) with a three-point bending fixture. Specimens were prepared with dimensions of 127 mm × 12.7 mm × 3 mm, and the support span was set to 80 mm to comply with ASTM guidelines. A crosshead speed of 2 mm/min was employed until either failure or significant deflection was observed. The flexural modulus (Ef) was calculated using equation (2) (Licari & Swanson, 2011):

$$\mathrm{E}_f = \frac{L^3 \mathrm{m}}{4bd^3} \qquad (2)$$

where L is the support span length, m is the slope of the load-deflection curve, b is the width, and d is the thickness of the specimen.

2.2.3.3 Hardness Testing

The hardness of the composites was evaluated using the Brinell hardness test, following ASTM E10 standards. A Monsanto Testing Machine was employed, equipped with a 10 mm steel ball indenter and applying a load of 3000 kgf for 10–15 seconds. The Brinell Hardness Number (BHN) was calculated using equation (3) (Karabudi & K, 2021):

$$\mathrm{BHN} = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \qquad (3)$$

where P represents the applied force (3000 kgf), D is the diameter of the indenter (10 mm), and d is the measured diameter of the indentation.

2.2.3.3 Fourier transform Infrared (FTIR) spectrometry of resins and composites

Buck Scientific M530 Infrared Spectrophotometer was used for the FTIR analysis. The instrument was equipped with a detector of deuterated triglycine sulphate and beam splitter of potassium bromide (KBr). The software of the Gram A1 was used to obtain the spectra. An approximately of 1.0g of samples was properly placed on the salt pellet mixed with KBr. FTIR spectrum was obtained at 4,000 – 600 cm-1 frequency regions at 4 cm-1 resolution in 32 scans. FTIR spectrum was displayed as transmitter values. Zero transmittance means that the sample absorbed all the radiation while 100% transmittance means that the sample absorbed the same amounts of radiation as the reference. The transmittance at different absorption peaks was obtained and corroborates the functional groups present in the sample.

2.2.4 Kinetics of Water Absorption and Diffusion Behaviors

The diffusion phenomenon of the banana fiber-reinforced composites was studied through a water absorption method. The kinetics of water absorption was evaluated using Peleg's model, the Power Law model, and a newly developed Log-Square Root Linear Model , represented by Equations (4) - (6), respectively as reported by Azeez and Onukwuli (2018).

2.2.4.1 Peleg's Model

The kinetics of water absorption was initially modeled using Peleg's model of equation (4), which characterizes the rate and capacity of water absorption (Piergiovanni, 2011). Peleg's model is particularly suitable for this study as it captures the two-phase water absorption behavior typical of natural fiber composites (Nóbrega et al., 2010): an initial rapid absorption phase (dominated by diffusion) followed by a slower phase (due to fiber swelling, relaxation, and matrix interactions). The model's ability to predict the equilibrium water absorption (i.e., when the composite reaches moisture balance with the environment) is crucial for assessing the material's suitability for prosthetic applications, where moisture resistance is key to long-term performance:

$$M_t - M_0 = \frac{t}{k_1 + k_2 t} \quad (4)$$

Where M_t, M_0 and M_m are the water content at specific time *t,* initial water absorption and the equilibrium water content (EWC), respectively. $k_1$and k_2 are Peleg rate constant which relates to initial absorption rate and Peleg capacity constant relate to maximum attainable water content, respectively.

2.2.4.2 Development of the Custom Kinetic Model

The Log-Square Root Linear Model was specifically developed to account for both the initial rapid absorption, driven by diffusion, and the subsequent slower absorption phases, linked to fiber swelling, relaxation, and matrix interactions. This model is represented by the following equation (6):

$$M(t) = a\sqrt{t} + b\,log(t+1) + dt + c \quad (6)$$

Where *M(t)* represents the water absorption (%) at time t, a√t: Captures the Fickian-like diffusion that is dominant during the early stages of absorption, b log(t + 1) accounts for linear growth, reflecting sustained absorption due to fiber swelling or voids opening up in the matrix and *c* is a constant that accommodates the baseline offset. The model parameters (a, b, d, c) were obtained for each group using non-linear curve fitting and were evaluated against the data to assess their accuracy in representing the experimental behavior.

2.2.4.3 Water Diffusion Coefficient

The water diffusion coefficient (Dwf) was calculated to evaluate the rate of water ingress during short-term exposure, using equation (7) as adapted from (Azeez et al., 2023; Azeez & Onukwuli, 2018):

$$D_{wf} = \pi \left[\frac{h}{4M_m}\right]^2 [S]^2 \quad (7)$$

Where $S = \frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}$, M_m is the maximum percentage of water content, *h* is the fiber thickness, M_1 and M_2 are percentage of water content at respective time $t_1$and $t_2$selected in the linear portion of the plot of water sorption (M_t) versus $\sqrt{t}$.*S* was evaluated as gradient plot of M_t against$\sqrt{t}$ based on equation (7).

3.0 Result and Discussion

3.1. Tensile properties of mercerized banana fibers

The tensile properties of banana fibers improved significantly after treatment with 12.5% NaOH, with the optimal results observed at 30 minutes of treatment (***Table 1***). Untreated fibers exhibited a tensile strength of 217.95 N/mm², which increased by over 2300% to 5256.31 N/mm² at 30 minutes, which may be due to the removal of lignin and hemicellulose, leading to enhanced fiber-matrix bonding (Mishra et al., 2003; Rosa et al., 2009). The tensile modulus also showed a marked increase from 4537.28 MPa to 43588.57 MPa, representing an 860% improvement, linked to increased crystallinity of the fibers (Sreekumar et al., 2008). Tensile strain improved from 0.00467 mm/mm to 0.10621 mm/mm, indicating increased flexibility due to the removal of non-cellulosic components (Mishra et al., 2003). However, at treatment times beyond 30 minutes, tensile strength, modulus, and strain began to decrease, indicating over-treatment, which leads to fiber damage and performance degradation, consistent with findings by Bledzki et al. (2010). Thus, 30 minutes is identified as the optimal treatment time to enhance tensile properties while avoiding fiber degradation.

Table 1: Tensile properties of banana fiber treated with 12.5% NaOH

Time (min)	Tensile strength (N/mm²)	Tensile modulus (MPa)	Tensile strain (mm/mm)
0	217.9451	4537.28	0.00467
10	426.132	16326.53	0.00682
20	1325.024	37732.38	0.09656
30	5256.312	43588.57	0.10621
40	1314.384	34614.25	0.091582
50	1273.410	15177.3	0.00332

3.2 Tensile Properties of Polyester Composites

The tensile properties of pure polyester (Pp) composites were evaluated, and the results are presented in ***Table 2***. High tensile strength and modulus are crucial for prosthetic socket materials as they ensure durability and resistance to deformation under dynamic loads. Pure polyester (Pp) exhibited a baseline tensile strength of 1.595 MPa. The addition of mercerized banana fibers significantly enhanced the tensile properties, with the maximum tensile strength observed at 15% fiber loading (C), reaching 11.68 MPa, a 632% improvement compared to pure polyester. This substantial increase is attributed to the mercerization process, which removes impurities such as lignin, enhances fiber surface roughness, and improves fiber-matrix bonding, allowing efficient stress transfer between the fibers and the matrix (Hurtado-Figueroa et al., 2023; Rosa et al., 2009). The tensile modulus also peaked at 15% fiber loading, achieving 681.63 MPa, representing a 202.62% increase over pure polyester. This improvement reflects the reinforcement effect of banana fibers, which acted as load carriers within the matrix, enhancing the composite's stiffness. At higher fiber loadings, however, the tensile properties declined. At 20% fiber content (D), the tensile strength dropped sharply to 0.43 MPa, likely due to fiber agglomeration, which creates weak spots and inhibits stress distribution. At 25% fiber loading (E), the tensile strength partially recovered to 5.82 MPa, but remained below the optimal value at 15% fiber loading. Excessive fiber content can disrupt matrix continuity and create voids, which reduce the composite's mechanical performance (Hamidi et al., 2009; Irawan et al., 2011). These results indicate that 15% fiber loading is the optimal level for improving tensile properties, consistent with findings in other natural fiber-reinforced composites (Livchak et al., 2020; Sosa & Millare, 2023). The observed decline beyond this point highlights the importance of balancing fiber content with processing techniques to minimize defects.

3.3 Flexural Properties of Polyester Composites

The flexural properties of pure polyester (Pp) and its composites were assessed and are summarized in ***Table2***. Flexural properties are critical for prosthetic socket materials as they indicate the material's ability to resist deformation under bending loads. Pure polyester exhibited a flexural stress of 21.90 MPa and a flexural modulus of 567.10 MPa. With the incorporation of banana fibers, significant improvements were observed, particularly at 15% fiber loading (C), where the flexural modulus reached 757.45 MPa, a 33.61% increase over pure polyester. This improvement can be attributed to the mercerized fibers' reinforcement effect, which enhances the material's stiffness under bending loads (Musa et al., 2010). However, similar to the tensile properties, the flexural modulus and stress decreased at higher fiber loadings. At 20% fiber content (D), the flexural modulus dropped to 456.10 MPa, and at 25% fiber loading (E), it further reduced to 646.51 MPa. This decline is attributed to poor fiber dispersion and void formation, which compromise the composite's structural integrity. Excess fiber content often leads to resin starvation, where the matrix is insufficient to encapsulate all the fibers effectively, reducing load-bearing capacity (Hart-Smith, 2014). These results align with previous studies on natural fiber-reinforced composites, which report that moderate fiber content yields optimal flexural performance, while excessive fiber loading reduces the composite's effectiveness (Ahmed & Miah, 2024). The optimal flexural performance at 15% fiber loading suggests a strong fiber-matrix interface and efficient load transfer

Table 2: Tensile and Flexural Properties of Polyester and its Composite

		Tensile Properties				Flexural Properties			
Composite Type	Specimen	Maximum Tensile Stress (MPa)	Tensile Strain at Maximum Strain (%)	Tensile Modulus (MPa)	% Variation in Modulus Compared to Pure Resin	Maximum Flexural Stress (MPa)	Flexural Strain at Maximum Stress (%)	Flexural Modulus (MPa)	% Variation in Modulus Compared to Pure Resin
Pure Polyester	Pp	1.595	0.00708	225.28	-	21.90	0.0386	567.10	-
5% fiber	A	6.92	0.03047	227.11	+0.81%	11.16	0.0957	116.62	-79.44%
10% fiber	B	5.06	0.01904	265.84	+18.01%	11.38	0.0650	175.08	-69.12%
15% fiber	C	11.68	0.01714	681.63	+202.62%	10.68	0.0141	757.45	+33.61%
20% fiber	D	0.43	0.00702	61.25	-72.82%	18.70	0.0410	456.10	-19.60%
25% fiber	E	5.82	0.01179	493.76	+119.15%	19.45	0.0301	646.51	+14.00%

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composites, which report that moderate fiber content yields optimal flexural performance, while excessive fiber loading reduces the composite's effectiveness (Ahmed & Miah, 2024). The optimal flexural performance at 15% fiber loading suggests a strong fiber-matrix interface and efficient load transfer.

3.4 Hardness Properties of Mercerized Banana Fiber-Polyester Composites

Brittleness, as measured by the BHN, indicates the material's resistance to localized deformation. Pure polyester had a BHN of 15.29, serving as a baseline for comparison (***Figure 2***). With the addition of banana fibers, the BHN values varied depending on fiber content. At 15% fiber loading (C), the BHN reached its highest value of 15.94, representing a 4.25% improvement over pure polyester. This improvement highlights the enhanced fiber-matrix bonding achieved through mercerization, which increases the composite's resistance to indentation by improving fiber-matrix interaction (Hurtado-Figueroa et al., 2023). At lower fiber contents, such as 5% (A) and 10% (B), the BHN decreased to 13.52 and 14.08, showing reductions of 11.57% and 7.91%, respectively, compared to pure polyester. These reductions suggest insufficient fiber reinforcement at lower loadings, which limits the enhancement of hardness. However, at higher fiber loadings, such as 20% (D) and 25% (E), the BHN values decreased significantly, with the latter dropping to 4.67, a 69.45% reduction compared to pure polyester. The drastic decline at 25% fiber loading is attributed to excessive fiber content, which leads to poor fiber dispersion, increased void formation, and insufficient matrix to hold the fibers firmly (Hyde et al., 2020). These results emphasize the need to optimize fiber content to balance hardness and processability.

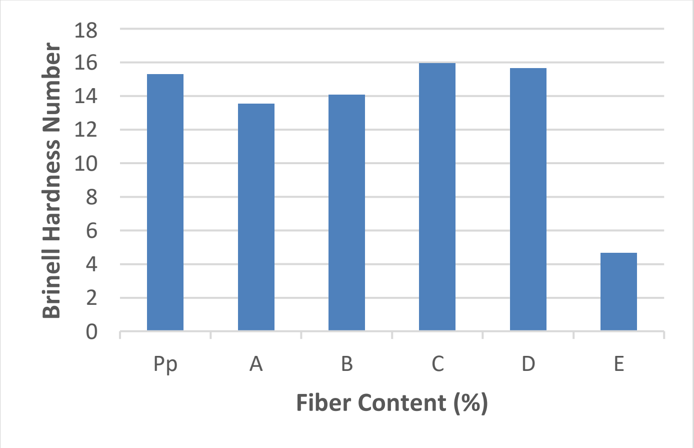

Figure 2: Hardness Properties of Polyester and its Composites

3.5 Fourier Transform Infrared (FTIR)

FTIR analysis reveals significant shifts in absorption peaks, indicative of enhanced interfacial bonding between the fibers and the polyester matrix. A notable observation is the shift in the absorption peak from 770.815 cm⁻¹ to 857.034 cm⁻¹ **(Figure 3a vs Figure 3b)**, corresponding to C–H bending vibrations in phenyl ring substitutions. This shift suggests chemical interactions between the mercerized banana fibers and the polyester resin, leading to improved compatibility and bonding. Such enhancements in interfacial adhesion are crucial for the mechanical integrity of composites, as they facilitate effective stress transfer between the matrix and the reinforcing fibers. Further, the absorption peaks at 1038.005 cm⁻¹ and 1185.327 cm⁻¹, associated with C–O–C stretching vibrations, shift to 1051.730 cm⁻¹. This change indicates the presence of ether linkages, characteristic of polyester resins, and reflects the successful integration of the banana fibers within the polymer matrix. The interaction between the hydroxyl groups of the cellulose fibers and the ester groups of the polyester resin enhances the chemical bonding at the interface, contributing to the composite's overall performance. Additionally, the shift in the absorption peak from 1620.970 cm⁻¹ to 1642.189 cm⁻¹, corresponding to C=C stretching vibrations, signifies alterations in the unsaturated polyester's double bonds. This shift may result from the polymerization process and the interaction with the mercerized fibers, leading to a more cross-linked and robust network within the composite material.

The broad absorption band observed between 3281.960 cm⁻¹ and 3789.141 cm⁻¹, attributed to O–H stretching vibrations, shifts to a range of 3263.151 cm⁻¹ to 3790.003 cm⁻¹. This shift indicates the presence of hydrogen bonding interactions between the hydroxyl groups of the banana fibers and the polyester matrix, further enhancing interfacial adhesion. Hydrogen bonding plays a significant role in natural fiber-reinforced composites, as it contributes to the mechanical strength and stability of the material. These FTIR findings align with existing literature on natural fiber-reinforced polyester composites. For instance, Barrera-Fajardo et al. (2024) reported that alkaline treatment of banana fibers improved their physicochemical properties and adhesion behavior with unsaturated polyester matrices, as evidenced by shifts in FTIR absorption peaks corresponding to functional groups involved in fiber-matrix interactions. Similarly, studies on other natural fibers, such as flax, have demonstrated that surface treatments lead to significant changes in FTIR spectra, indicating enhanced interfacial bonding with polymer matrices (Singh et al., 2024). These chemical modifications are crucial for improving the mechanical properties and durability of natural fiber-reinforced composites. In summary, the FTIR analysis of mercerized banana fiber-polyester composites reveals critical chemical interactions that enhance interfacial bonding. These findings are consistent with existing literature and underscore the importance of chemical treatments in optimizing the performance of natural fiber-reinforced polymer composites.

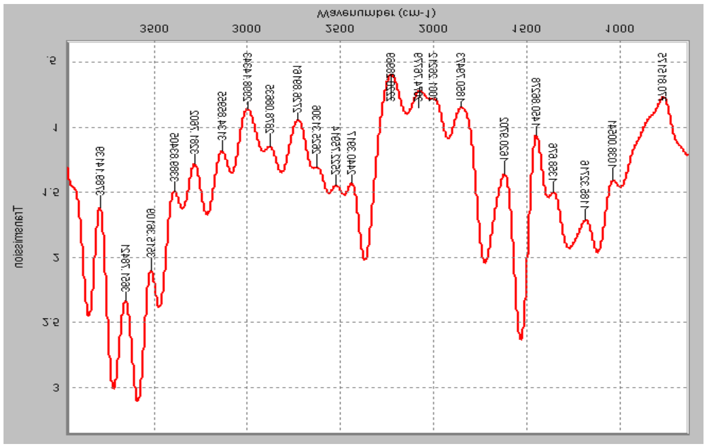

Figure 3a: FTIR spectrum of unsaturated polyester resin

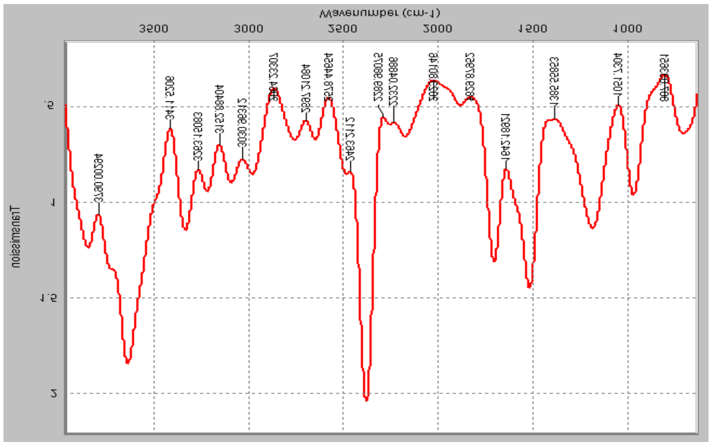

Figure 3b: FTIR spectrum of polyester composites

3.6 Water Absorption Analysis

3.6.1 Water Absorption of Mercerized Banana Fiber Composites

The water absorption behavior of banana fiber reinforced polyester composites were obtained over a 21 hours immersion period as presented in ***Figure 4***, respectively. The water absorption behavior of pure polyester (Pp) and its composites reinforced with mercerized banana fibers is illustrated in Figure 3a. The results demonstrate a progressive increase in water uptake with fiber content and immersion time, consistent with the hydrophilic nature of natural fibers. The water absorption of pure polyester (Pp) was the lowest among all specimens, reaching a maximum of approximately 0.8% after 21 hours. This low value can be attributed to the hydrophobic nature of the polyester resin, which inherently resists water penetration. In contrast, fiber-reinforced composites exhibited higher water absorption, which increased with fiber content due to the hydrophilic properties of the mercerized banana fibers. Specimen E (25% fiber content) showed the highest water uptake of approximately 4.5% after 21 hours, while Specimen A (5% fiber content) had the lowest absorption among the composites, at around 1.5%.

The rapid increase in water absorption during the initial 9 hours suggests a diffusion-controlled process, where water molecules penetrate the composite through microvoids and imperfections in the matrix. This is followed by a slower phase as the system approaches equilibrium. This two-phase behavior has been reported in other natural fiber composites, such as banana and sisal fiber-reinforced polyester, where the diffusion of water molecules is initially driven by capillary action and later slowed by fiber swelling and fiber-matrix interactions (Pothan & Thomas, 2004).

The observed trend of increasing water absorption with fiber content aligns with findings from previous studies. For instance, Sundramurthy Venkatesa Prabhu et al. (2022) reported a similar increase in water uptake for teff straw fiber-reinforced polyester composites, attributing it to the high cellulose content in natural fibers, which enhances water retention. Sekhar et al. (2023) also noted that the degree of water absorption in natural fiber composites is influenced by fiber treatment, fiber-matrix bonding, and void content. In this study, the mercerization process likely improved the bonding between the fibers and the matrix, reducing water ingress compared to untreated fibers but not eliminating it completely. The higher water absorption observed in composites with greater fiber content is due to the increased availability of hydrophilic sites in the fibers, which readily interact with water molecules. Moreover, the presence of voids or microcracks at the fiber-matrix interface can exacerbate water ingress. Similar behavior was reported by Masoodi and Pillai (2012) in jute fiber composites, where the hydrophilic fibers significantly increased water uptake relative to the pure resin.

Excessive water absorption can compromise the mechanical performance and durability of composites, leading to dimensional instability and degradation over time. For prosthetic socket applications, this could result in discomfort, reduced strength, or premature failure. However, the water absorption of polyester composites in this study was relatively low compared to values reported for epoxy composites, which often exhibit higher water uptake due to a less effective fiber encapsulation (Karthick et al., 2018).

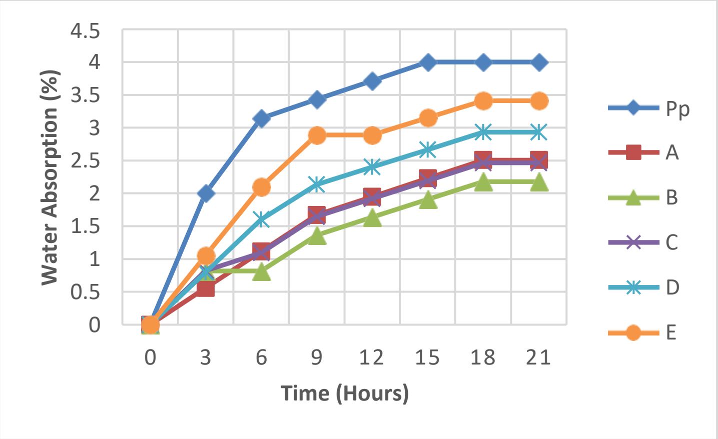

Figure 4: Water absorption (%) against time for polyester composites.

3.6.2 Water Absorption Kinetics

3.6.2.1 Peleg's Model

The Peleg's model was employed to evaluate the water absorption kinetics of the composites. The initial absorption rate constant (k1) indicated that pure resin sample (Pp) had higher initial absorption rates, while fiber-reinforced composites showed reduced rates due to the physical barrier effect of the fibers. This reduction aligns with findings from other studies on natural fiber composites, such as those involving teff straw (S. Venkatesa Prabhu et al., 2022). ***Table 3*** summarizes the Peleg constants k1 (initial absorption rate) and k2 (capacity constant).

Table 3: Peleg's Model Parameters for Water Absorption

omposite ype	**mple**	**leg onstant (*k_1*)**	**Rate**	**leg onstant (*k_2*)**	**Capacity**
re Polyester		057		043	965
fiber		039		028	939
% fiber		037		025	931
% fiber		038		026	959
% fiber		031		031	969
% fiber		035		035	970

3.6.2.3 Log-Square Root Linear Model

The LSRLM demonstrated superior fitting for both polyester composites, as indicated by higher R² values (***Figures5***). This model effectively captures the multi-phase behavior of water absorption, accounting for both the initial rapid uptake and the slower phase governed by fiber swelling and matrix relaxation. The higher accuracy of this model is particularly relevant for prosthetic applications where prolonged exposure to moisture must be anticipated. The need for complex models that go beyond simple Fickian diffusion has been highlighted in recent studies (Azeez et al., 2023; S. Venkatesa Prabhu et al., 2022). ***Table 4*** presents the model parameters for each composite as evaluated from ***Figure 5*** for polyester.

Table 4: Log-Square Root Linear Model Parameters for mercerized banana fiber composites

mposite pe	**mple**	**√t term)**	**(log(t + 1) m)**	**m)**	**(t nstant)**	
re Polyester		796	58	58	004	98
fiber		271	52	14	013	92
% fiber		71	982	071	017	80
% fiber		459	86	79	014	89
% fiber		590	60	70	008	97
% fiber		527	.297	10	003	94

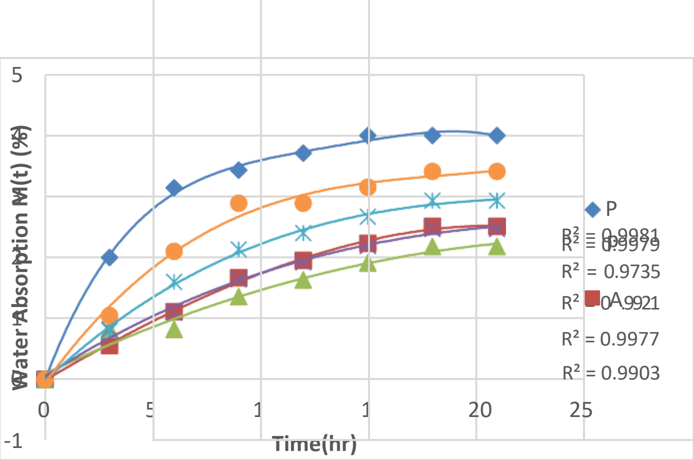

Figure 5: LSRLM for Polyester Composites

3.5.2.4 Water Diffusion Coefficient

From ***Table 5***, the diffusion coefficients revealed that polyester composites exhibited reduced water uptake with fiber reinforcement, showing lower Dwf values compared to pure resin. The Dwf of polyester composites varied with fiber content, demonstrating the influence of reinforcement on water transport. Pure polyester exhibited the highest Dwf (0.0072 cm²/hr), while the lowest diffusion coefficient was observed at 10% fiber content (0.0028 cm²/hr), indicating enhanced fiber-matrix bonding and reduced porosity. Beyond 10%, the Dwf increased, reaching 0.0061 cm²/hr at 25% fiber content, likely due to void formation and fiber agglomeration. These findings suggest that 10-15% fiber content offers the best water resistance for polyester composites, balancing reinforcement and matrix integrity. Higher fiber contents may require additional treatments to improve moisture stability for applications like prosthetic sockets.

Table 5: Diffusion Coefficient for Water Absorption

Composit e Type	**Sa mpl e**	**Slope (S) (g/cm² √hr)**	**Diffusion Coefficient (D_{wf}) (cm²/hr)**
Pure Polyester	Pp	0.013	0.0072
5% fiber	A	0.009	0.0041
10% fiber	B	0.007	0.0028
15% fiber	C	0.008	0.0036
20% fiber	D	0.010	0.0049
25% fiber	E	0.012	0.0061

4.0. Conclusion

This study demonstrates the effectiveness of mercerized banana fibers as reinforcements for polyester composites, showing significant improvements in mechanical properties and moisture resistance. Optimized NaOH treatment (12.5% for 30 minutes) enhanced fiber tensile strength, modulus, and flexibility by removing lignin and hemicellulose. Composites with 15% fiber content exhibited optimal performance, achieving a 632% increase in tensile strength, a 33.61% improvement in flexural modulus, and the highest hardness, attributed to improved fiber-matrix bonding. FTIR analysis confirmed enhanced interfacial adhesion through chemical interactions between the fibers and the polyester matrix. Water absorption and diffusion analysis highlighted that 10-15% fiber content minimizes moisture ingress, balancing reinforcement and matrix integrity. These findings support the potential of mercerized banana fiber-polyester composites for prosthetic applications, offering improved durability, mechanical performance, and moisture resistance. Future studies should focus on advanced treatments and fabrication methods to further enhance their performance.

Declaration Statement

The authors agreed with total interest to submit the manuscript entitled, 'Mechanical and Water Absorption Properties of Mercerized Banana Fiber-Reinforced Polyester Composites for Sustainable Prosthetic Applications' for publication in your reputable Institution without conflict of interest, be it design and implementation, respect towards society, resources and research output and conduct without deceptive acts.

Conflict of Interest

The authors declare no conflict of interest.

Author Contribution

Sodiq Fakorede - Conceptualized the study, wrote the original article, and edited and reviewed the manuscript. Taofik Oladimeji Azeez - Supervised the study. Kennedy Ejeta - Reviewed and edited the manuscript.

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Nomenclature

Tensile Strength (σ): Measured in MPa (MegaPascal) or N/mm².
Tensile Modulus (E): Measured in MPa (MegaPascal).
Flexural Modulus (E_f): Measured in MPa (MegaPascal).
Hardness (BHN): Brinell Hardness Number (unitless).
Water Absorption (M): Percentage (%).
Water Diffusion Coefficient (D_wf): cm²/hr.

Fiber Weight Fractions (Wt%): Percentage (%) by weight of fibers in the composite.

Fiber Length (L): Measured in mm (millimeter).ΔG= Free energy change, kJ/mol;

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