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An Experimental Study on the Hardness, Inter Laminar Shear Strength, and Water Absorption Behavior of Habeshian Banana Fiber Reinforced Composites

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ABSTRACT

The current study examines the effect of NaOH treatment on the hardness, inter-laminar shear strength (ILSS) and water absorption behavior of epoxy composites reinforced with banana pseudostem fibers. Using the hand-lay-up method, six distinct samples are created that are composed of layers of woven and short banana fibers in both a plain and hybrid form. Plain- treated woven composites reveal the highest hardness and ILLS properties followed by the hybrid and short fiber composites. The random orientation of the fiber structure in short fiber composites results in the largest moisture absorption; this behavior is further supported by elucidating the kinetic parameters and diffusion coefficient parameters. SEM analysis confirms the improved surface of the NaOH-treated composite material.

摘要

本研究考察了NaOH处理对香蕉假茎纤维增强环氧复合材料硬度、层间剪切强度（ILSS）和吸水性能的影响. 使用手工叠放方法，制作了六个不同的样品，这些样品由编织和短香蕉纤维层组成，既有普通的也有混合的形式. 普通处理的机织复合材料显示出最高的硬度和ILLS性能，其次是混合纤维和短纤维复合材料. 短纤维复合材料中纤维结构的随机取向导致最大的吸湿性; 通过阐明动力学参数和扩散系数参数进一步支持了这种行为. SEM分析证实了经NaOH处理的复合材料的表面得到了改善.

KEYWORDS
Banana fiber; sandwich composites; water absorption; ILSS, hardness

关键词
香蕉纤维; 夹层复合材料; 吸水性; 硬度

Introduction

In light of ever-increasing regulations and societal demands for material recyclability and environmental sustainability, manufacturers and research institutions are embracing a paradigm shift toward

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the development of composites sourced from renewable origins (L. Wang, Toppinen, and Juslin 2014). Plant fibers [PFs], encompassing flax, ramie, jute, hemp, banana, and sisal, have emerged as compelling prospects due to their inherent biodegradability, renewability, and cost-effectiveness (Azanaw and Ketema 2022). Furthermore, PFs exhibit commendable specific modulus and strength while concurrently maintaining a superior strength-to-weight ratio compared to glass fibers (Hu et al. 2023). This unique attribute facilitates the fabrication of lighter components, thereby fostering reduced emissions and heightened fuel efficiency in transport applications (Shambhu et al. 2023). Consequently, the eco-advantages and weight reductions render PF composites competitive counterparts to synthetic fiber-reinforced materials. Additionally, natural fibers present certain limitations, including suboptimal wettability, elevated moisture absorption, and limited interface adhesion with specific polymeric matrices (Martel, Salgado, and Silva 2022).

The hydrophilic nature of natural fibers can indeed influence their mechanical properties, necessitating consideration in their application (Kusmono, Hestiawan, and Jamasri 2020). Few works carried out on studying about water absorption have stated that increased coir fiber content results in increased water absorption because it contains more hydroxyl groups, according to investigations on the water absorption of coir/polypropylene composites submerged in distilled and saline water. Proper encapsulation of fibers can reduce water absorption. Composites with 30 wt.% fibers exhibit higher water absorption than 10 wt.% and 20 wt.% counterparts, likely due to increased cellulose content. Saline water immersion shows lower water absorption than distilled water (Khuntia and Biswas 2020). A 20-day experiment, all non-woven bamboo fiber reinforced composites exhibited Fickian-like moisture transmission behavior. Notably, the sodium bicarbonate (NCTB) composite had a lower saturation point compared to others, while the Silane treated (SiTB) composite showed a higher saturation point. Moisture transmission improved during the initial 12 days and then remained constant for all composites (Chalapathi, Venkata, and Song 2022). At 23°C and 60°C, water absorption tests were performed on bamboo composite samples in accordance with ASTM D5229M–14 standard. The three-month study revealed maximum water absorption of 0.5% relative to the dry sample mass, indicating the composites' high resistance to water ingress even in extreme conditions. A quasi-equilibrium state was achieved for both temperatures after 170 h of immersion. Samples at 60°C exhibited slightly higher water absorption, attributed to temperature-induced influences on moisture diffusion within the composites (Alireza, Smith, and Hebel 2020).

Additionally, few studies have examined other crucial characteristics of hybrid reinforcement and natural fiber reinforced polymers (NFRP), such as hardness and inter-laminar shear strength (ILSS), in the literature. These qualities are typically investigated in composites containing synthetic fibers. However, in hybrid composites, the presence of an extra phase directly affects these properties, having a noticeable impact on the interface and between the layers of the various fiber types (Almeida et al. 2013; Alves, Prado, and de Paiva 2021). In this context, this work evaluates the hardness, inter-laminar shear strength, and water absorption properties of novel banana fiber composites derived from Ethiopia, comprising layers of woven and short banana fibers in a hybrid form, as well as different combinations of treated and untreated banana fibers fabricated with a hand-lay-up approach.

Materials and methods

Materials

For this study, fresh banana fiber is obtained directly from the pseudo stem, which is abundant in the region of Arbamich, Ethiopia. The extraction process involves manual labor, where an individual layer of pseudo stem is carefully placed on an inclined flat wooden surface, and the pulp is meticulously removed using a bamboo stick. Subsequently, the extracted fiber undergoes a two-day drying period in natural sunlight. For the experimental materials, The World Fiberglass and Waterproofing Engineering facility in Addis Ababa, Ethiopia, provided the LAPOX L-12 epoxy resin, K-6 hardener, and silicon releasing agent. The Atomic Educational Materials Supplier, which is also based in Addis Ababa, Ethiopia, provided the distilled water and sodium hydroxide flakes.

Composite fabrication

In this investigation, the composite material was crafted with utmost precision using the hand lay-up technique, maintaining a consistent fiber-to-matrix weight ratio of 40:60. A well-crafted mold made of mild steel, measuring 170 × 400 mm, was employed and coated with a protective layer of polyethylene plaster to ensure a barrier between the materials. The fibers, both chemically treated and untreated, were carefully chopped into 15 mm lengths. Before the chopping process, the fibers underwent meticulous combing to align them in a parallel fashion, ensuring a uniform and well-ordered arrangement. To ensure ease of separation, a silicon releasing agent was uniformly applied to the mold surface. The resin was then diligently mixed with the hardener in a precise 10:1 weight ratio. The composite fabrication involved a systematic layering process, where alternating layers of resin and fibers were added step by step until the desired quantity of materials filled the mold. After placing each layer of fiber, thorough rolling was carried out to remove any trapped air bubbles, ensuring an impeccable end product. To prevent any void formation during the curing process, the mold was sealed with a plaster-coated wooden board, and static pressure was applied. A total of six distinct samples were prepared as shown in Figure 1 for different composite types, including untreated/treated short banana fiber composites (UTSB/TSB), untreated/treated woven banana fiber composites (UTWB/TWB), and untreated/treated woven-short-woven banana fiber composites (UTWSWB/TWSWB).

Density

Based on ASTM D2734–09 and a specimen measuring 25.4 × 25.4 mm, the void in the composite was identified. The theoretical to real density ratio is used to express it. Archimedes' principle was applied to ascertain the composite's true density. It describes an object that is submerged entirely or partially in the fluid and is buoyant up to a height equal to the weight of the displaced fluid. Both prior to and following the composite's immersion in water, the volume of each sample was measured using the

Figure 1. Different types of composites prepared using the hand lay-up technique.

displaced water level. Product life is shortened and mechanical qualities are hindered by voids in composite structures.

$$\rho_a = \frac{\rho_w W_a}{w_a - w_w} \tag{1}$$

$$v_r = \frac{\rho t - \rho a}{\rho t} \tag{2}$$

where, ρ_a is actual density, ρ_w is density of water, W_a is weight in air, w_w is weight in the water, v_r is void ratio, and ρt is theoretical density.

Vickers hardness test

The hardness test involves measuring of indentation dimension lifted on the sample after application of constant loaded indenter for specific time. The hardness of the specimens was measured by Vickers hardness testing machine (HVS-50) with test force of 10 kgf and 10 sec of dwelling time. The average diagonal length of two indentations was calculated on the flat surface by indenting it two times at different positions. A surface-projected diagonal length of each sample impression was measured right after unloading with an upright optical device. Load during hardness test is kept at 10 kg (99.1N).

Inter laminar shear strength (ILSS)

To determine the maximum inter laminar shear strength (ILSS) of composite specimens, short beam shear tests are performed in accordance with ASTM D2344 standard. A 4:1 span-to-thickness ratio and a 1 mm/min crosshead speed were used in the tests. The ILSS value was calculated from below equation

$$\text{ILSS} = \frac{3xPm}{4xbxd} \tag{3}$$

Water absorption

Water absorption test is performed to estimate the composite behavior in wet environment. The test was performed as per ASTM D570 with specimen dimension 76 × 25.4 × 3.5 mm by immersing the specimens in water for 8 days as shown in Figure 2. The specimen weights were noted before immersing in the water and the specimen weights were measured for every 24 h for a period of 8 days. The digital balance with accuracy of 0.0001 g was used to measure the weight. The percentage of water gain is calculated using Equation 3.

(a) (b)

Figure 2. (a) Specimens for water absorption test and (b) specimens immersed under test.

$$w_g\% = \frac{w_t - w_i}{w_i} * 100 \tag{4}$$

where, $w_g\%$is the percentage of water gain, $w_i$is the initial weight and w_t is the weight of the sample after soaked in the water.

Scanning electron microscopy (SEM) and X-ray diffraction

The test surfaces are examined using a JEOL JSM 6380 LA scanning electron microscope. Specimens are sputtered using a JFC-1600 auto finer coater JEOL. The crystallinity of the chemically treated and untreated banana fiber epoxy composites was investigated using the XRD test. The test was conducted in conscious scanning mode, with a 2θ = 5–55° angular range and a 2 deg./min scan speed.

Results and discussion

X-ray diffraction

The low intensity peaks at 18° indicate the amorphous constituents such as hemicellulose content, poor order, and disorientation of crystalline lattices at the fiber surface due to the presence of waxy and impurities in untreated banana fiber (Gopinathan et al. 2017). The higher peaks observed at 22° defines the regular chemical structure and ordered arrangement of their segments. The enhancement in the peak after treatment infers the increase in crystallinity percentage which can be calculated using Segal equation (Das et al. 2017). The crystallinity percentage increased from 58% to 59% after treatment from the below Segal equation.

$$\mathrm{CI} = \frac{I_{Cr} - I_{am}}{I_{Cr}} X100 \tag{5}$$

Density and void content estimation

Since voids are a reinforced composite's inherited behavior, creating a composite that is void-free is difficult. It must, however, be within a narrow range because even a small increase in vacancy percentage has a substantial impact on the reinforced composite's mechanical behavior. The theoretical density of all the composites is noted to be 1.25 kg/m^3 while the experimental density of UTSB, TSB, UTWSWB, TWSWB, UTWB and TWB are noted to be 1.224, 1.226, 1.226, 1.228, 1.226, and 1.227, respectively. Furthermore, the void content estimations of all the composites lie within a range of 2.8–3.1% indicating a good quality composite. With the largest void fraction, the UTSB composite specimen looks to be the most porous when compared to the other specimens. This can be caused by a variety of factors, including reduced fiber crystallinity, poor fiber-resin adhesion, and uneven fiber distribution during composite processing. TSB has a void content of 2.92%, while UTSB has a porosity of 3.1%. As a result, the alkalization of the fiber lowers the porosity level in the composite structure. In addition, when compared to the UTWB specimens, TWB showed a lower void fraction. Because of the weave architecture's ease of handling and placement of fiber during composite processing, the amount of void caused by fiber aggregation was reduced. The TWB composite exhibits the least amount of porosity because the fiber's surface modification and weave structure enhance the fiber's bonding with the matrix. The composite composed of chopped fibers and woven face has a void percentage that is lower than that of its chopped fiber counterpart but higher than that of its woven fiber counterpart. The density values of the Banana/Epoxy composite in the present work (ranging from 1.224 to 1.228) are consistent with those of natural composites like Areca/Epoxy, Flax/Epoxy, and Cyrtostachys renda/Kenaf (Table 1). Synthetic composites generally exhibit slightly higher density values, suggesting that the present work aligns more closely with the characteristics of natural composites (Balogun

Table 1. Comparison of density with different composites.

Composite	Wt.%	Density	Reference
Areca/Epoxy	20	1.612	(Praveena et al. 2022)
	30	1.499	
	40	1.401	
	50	1.301	
Flax/Epoxy	0	1.11	(Ismail et al. 2022)
	30	1.17	
	40	1.21	
	50	1.23	
Woven/Non-woven flax	-	1.29	(Shamsuyeva, Winkelmann, and Endres 2019)
Flax/carbon	-	1.34	
Flax/Glass	-	1.45	
Cyrtostachys renda/Kenaf	50/0	1.22	(Loganathan et al. 2021)
	35/15	1.26	
	25/25	1.27	
	15/35	1.27	
	0/50	1.28	
Jute/Glass	0/100	1.435	(Raghavendra, Shakuntala Ojha, and Pal 2014)
	100/0	1.183	
	50/50	1.2	
UTSB/Epoxy	60/40	1.224	Present work
TSB/Epoxy		1.226	
UTWSWB/Epoxy		1.226	
TWSWB/Epoxy		1.228	
UTWB/Epoxy		1.226	
TWB/Epoxy		1.227	

et al. 2022; Ismail et al. 2022; Loganathan et al. 2021; Praveena et al. 2022; Raghavendra, Shakuntala Ojha, and Pal 2014; Shamsuyeva, Winkelmann, and Endres 2019).

Hardness of composites

The Vickers hardness test results of the composites exhibit pronounced variations contingent on their treatment and composition. The untreated short banana composite demonstrated a lower hardness value of 32.5 as shown in Figure 3, whereas the sodium hydroxide-treated counterpart exhibited a noteworthy enhancement to 39.9, indicative of improved interfacial adhesion between fibers and matrix. The treatment of banana fibers with sodium hydroxide induces notable alterations in their chemical composition and surface characteristics. This treatment involves the elimination of non-

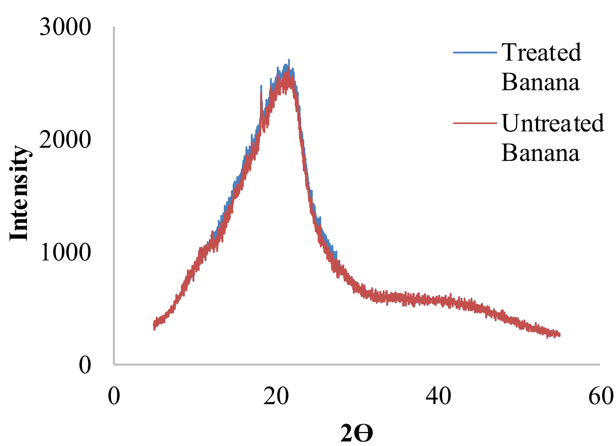

Figure 3. XRD graph of untreated and treated banana fiber epoxy composites (Gebremaryam et al. 2023).

cellulosic components and impurities, yielding a more pristine and uniform fiber structure. Consequently, the treated fibers exhibit enhanced affinity to the matrix material, culminating in heightened load-bearing capacity and hardness. Short banana fibers, as their name implies, possess reduced length compared to woven fibers. Similarly, the untreated woven banana composite manifested higher hardness of 47.35, attributed to the superior reinforcement of longer fibers and their organized arrangement within the matrix.

Following sodium hydroxide treatment, the woven banana composite exhibited a remarkable surge in hardness to 70.75, owing to the establishment of a cleaner and more uniform fiber structure. Woven composites, with their well-organized fiber layout, demonstrate elevated overall strength and hardness. The hybrid composite, comprising a blend of untreated woven and short banana fibers, displayed a hardness of 41.5, suggesting synergistic effects resulting from this unique combination of fibers. Upon sodium hydroxide treatment, the hybrid composite further elevated its hardness to 62.8, underscoring the treatment's salutary influence on fiber-matrix adhesion. The woven short woven banana hybrid composite is an amalgamation of woven and short fibers, showcasing synergistic effects by harnessing the advantages of both fiber types. This unique combination results in variable hardness values compared to composites with single-fiber reinforcements. Notably, the composite composed of a woven face and a short fiber mid-layer exhibited enhanced hardness compared to its short fiber counterpart, yet it displayed lower hardness than the woven fiber composite with an equivalent fiber loading. This suggests that the partial replacement of short fiber with woven fabric enhances the composite's ability to resist localized plastic deformation. This in good agreement with they reported the maximum hardness 70 HV perceived by jute-coconut fiber hybrid epoxy composite with 85% jute fiber contribution (Singh et al. 2021). A key factor in defining the properties of composites is the strength of the connection at the fiber–matrix interface between the fibers and the matrix. A robust interface ensures efficient stress transfer, leading to heightened hardness. Treatments like sodium hydroxide treatment can bolster fiber-matrix adhesion, thus augmenting hardness and overall composite performance (Fangueiro and Rana 2016). In summation, the Vickers hardness outcomes underscore the paramount impact of treatment and composite composition on the mechanical properties, with sodium hydroxide treatment affording substantial gains in adhesion and hardness. This suggests that the chemical treatment has significantly improved the hardness of the banana fiber polyester composite. The Vickers hardness values of the Banana/Epoxy composite (ranging from 32.23 to 70.75) are comparable to those of synthetic composites, as seen in the CFRP/epoxy, TWSWB/Epoxy, and TWB/Epoxy composites (Table 2). The results indicate that the treated woven and hybrid

Table 2. Comparison of vickers hardness with different composites.

Composite	Wt.%	Vickers hardness	Reference
Orange peel/formaldehyde	4/1	23,6	(Tasdemir et al. 2019)
	3/1	24.1	
	2/1	25.2	
	1/1	25.9	
Titanium hydride/polystyrene	0/100	19.87	(Cherkashina et al.)
	20/80	24.42	
	40/60	29.26	
	60/40	36.17	
CFRP/epoxy	–	100.28	(Ghani, Fuad, and Mahmud 2018)
GFRP/epoxy	–	74.67	
Hybrid A	–	76.28	
Hybrid B	–	80.27	
Hybrid C	–	62.91	
Hybrid D	–	79.12	
Hybrid E	–	76.92	
Hybrid F	–	76.29	
Hybrid G	–	75.61	
UTSB/Epoxy	60/40	32.23	Present work
TSB/Epoxy		40.22	
UTWSWB/Epoxy		41.54	
TWSWB/Epoxy		62.81	
UTWB/Epoxy		47.49	
TWB/Epoxy		70.75	

composites show a hardness response similar to synthetic composites, implying a potential for the use of natural composites in specific applications. Additionally, the treated composites have shown similar hardness value to few works (Madgule et al. 2023) inferring the removal of hemicellulose and lignin enhances the bonding and surface property of composites.

Ilss

Delamination's arise as a consequence of the diminished transverse and inter-laminar shear strength exhibited by Fiber-Reinforced Composite (FRC) materials. Upon impact, these delamination's tend to propagate outward from the locus of contact with the impacting object. The low inter-laminar shear strength found in polymer composites can be attributed to the use of untreated fibers, resulting in poor bonding and weak adhesion with the polymer matrix. As shown in Figure 4, TWB has shown a 400% increase in value compared to the short fibers, indicating treatment of fiber enhances adhesion by increasing surface acidic functional groups and expanding the surface area. This improved adhesion leads to higher inter-laminar shear strength and overall mechanical performance of the composite material. Our findings reveal a discernible reduction in the magnitude of short fibers (UTSB, TSB), owing to a pronounced plasticizing influence exerted upon the matrix, leading to a concomitant attenuation of the fiber-matrix interconnectivity (Bieniaś et al. 2020). The mechanical characteristics of the hybrid composites (UTWSWB and TWSWB) are a direct outcome of the amalgamation of fiber orientation and the type of reinforcement employed, with fiber orientation wielding the most pronounced impact (Alves, Prado, and de Paiva 2021). Comparatively, ILSS values of banana/carbon reinforced composites (Kore et al. 2021) have shown lower values compared to the present work, whereas the carbon/epoxy composites have shown a higher value more than 200% (Sun, Lu, and Guo 2019) implying that synthetic fiber composites display better performance under ILSS loading conditions. Additionally, the ILSS values of the Banana/Epoxy composite (ranging from 4 to 17) are lower compared to the referenced works (Table 3), suggesting room for improvement in the inter-laminar strength of the composites. Further research or modification of the composite formulation may be needed to enhance the inter-laminar shear strength for better performance (Cheon and Kim 2021; Gu et al. 2023; Lakshmaiya et al. 2022; Natrayan et al. 2022; Zareei, Geranmayeh, and Eslami-Farsani 2019).

Water absorption

Natural fibers demonstrate a pronounced propensity for moisture, leading to its absorption, accompanied by swelling and delamination of the composite material. The presence of hemicellulose plays

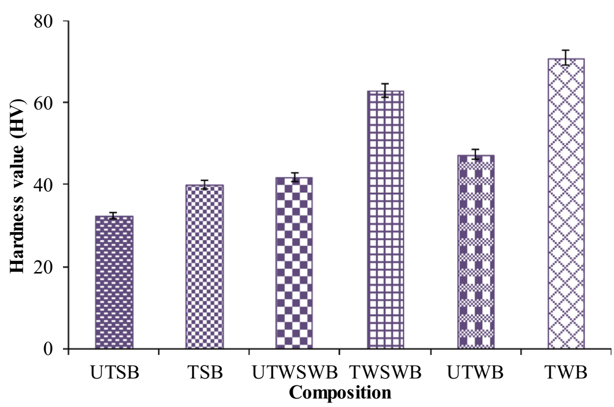

Figure 4. Vickers hardness test results of short, woven and hybrid composites.

Table 3. Comparison of ILSS with different composites.

Composite	Wt.%	ILSS	Reference
Carbon/Kevlar/Epoxy	52.77	58	(Gu et al. 2023)
	55.16	54	
	51.03	49	
Aluminium/Basalt/Jute/Aluminium –	50/50		(Zareei, Geranmayeh, and Eslami-Farsani 2019)
A		17	
B		10	
C		14	
D		13.7	
Carbon/MWCNTs/Polyamide	0 (CNTs)	35	(Cheon and Kim 2021)
	1	48	
	2	40	
	3	40	
	4	24	
Flax/Oil Palm Nanofiller/Epoxy	0	38	(Lakshmaiya et al. 2022)
	2	41	
	4	47	
	6	45	
Flax/Polyester	20/80	31.83	(Natrayan et al. 2022)
	20/77.5	34.31	
	20/70	29.91	
	20/67.5	28.89	
	20/60	18.69	
UTSB/Epoxy	60/40	4	Present work
TSB/Epoxy		6	
UTWSWB/Epoxy		10	
TWSWB/Epoxy		14	
UTWB/Epoxy		14	
TWB/Epoxy		17	

a pivotal role in this absorption process, exerting a significant influence on the morphology and properties of the composites, which, in turn, may be further susceptible to microbial attacks that are triggered by the presence of moisture. The observed curves below exemplify Fickian behavior, wherein water migrates from regions of highest concentration to those of lowest concentration within the composite (Chunhong, Shengkai, and Zhanglong 2016). The infiltration of water into the composites is facilitated through diverse mechanisms such as diffusion, micro-cracks, and capillary action (Dhakal, Zhang, and Richardson 2007). As moisture permeates the fibers, it initiates the formation of hydrogen bonds with the fibers, leading to a reduction in the interfacial adhesion between the fiber and the matrix. Consequently, this instigates the swelling of fibers, inducing stress at the interface and causing micro-cracks, thereby intensifying the transport of water through capillary action and micro-cracks. Moreover, a higher rate of water addition can result in debonding due to leaching of water-soluble substances (Azwa et al. 2013). The initial absorption curves as shown in Figure 5, exemplify a linear Fickian behavior up to a certain threshold, beyond which the absorption rate reaches

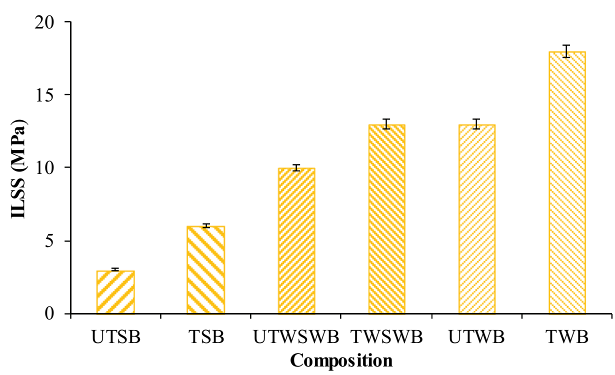

Figure 5. ILSS graph of composites.

saturation (Hrabalova et al. 2010). The heightened absorption rate was ascribed to the innate predilection of natural fibers toward water sorption. Once absorbed, water permeates the inter-fibrillar spaces within the cellulosic structure and further infiltrates cracks and voids through capillary action, leading to a gradual attenuation in the rate of absorption over time (Chunhong, Shengkai, and Zhanglong 2016). The curves evince a diminished absorption rate in the treated composites compared to their untreated counterparts. NaOH treatment has effectively curtailed the presence of amorphous constituents, particularly hemicellulose and lignin, both renowned for their proclivity toward water uptake. Consequently, the treated composites display a diminished absorption rate. Furthermore, the treatment substantially enhances interface wicking, owing to augmented wettability and adhesion, thus efficaciously thwarting water ingress (Kusmono, Hestiawan, and Jamasri 2020). The curves manifest an initial diminishment in water absorption rate for short fibers, compared with heightened water absorption exhibited by woven and hybrid composites. This discernible contrast can be ascribed to the interconnected architecture of fibers in woven and hybrid composites, which confers greater ease to water permeation through these fibrils. Moreover, the curves evince a progressive escalation in the water absorption rate for short fibers due to the presence of voids, serving as conduits for water flow facilitated by capillary action (Baghaei et al. 2014). The saturated curves divulge that woven composites evince a reduced rate of absorption when compared to the hybrid and short fibers. This variance can be attributed to the heightened prevalence of voids within woven composites, thus engendering more expedient water movement (Kanaginahal et al. 2023). The behavior of water absorption in the present work is noted to be similar to works referenced in (Karthik et al. 2023; Oun et al. 2022), showing a Fickian behavior. The increasing trend toward a static absorption of water indicates that, after a certain point, the molecules reach stability. This information is essential for understanding the water resistance and durability of the composite material.

Kinetic of water absorption

The diffusion behavior by composite material can be analyzed mathematically from shape of absorption curve (Chunhong, Shengkai, and Zhanglong 2016).

$$\frac{M_t}{M_s} = kt^n \tag{6}$$

Where M_t is water gain at any time t, M_s is water gain at saturation point, k is the slope of $\frac{M_t}{M_s}$ verse √t curve, n is constant. The value of coefficient n shows different diffusion behavior exhibited by material. Diffusion is considered Fickian when $n = 0.5$ and it follows Fick's law. Diffusion is considered abnormal when $n > 1$. The diffusion is non-Fickian when n is between 0.5 and 1. The polymer-water interaction is shown by the value k, while the diffusion mode is indicated by the constant n (Sreekumar et al. 2008). In order to get the value of kinetic parameter k and n from experimental data the above equation rearranged as follows.

$$\log\left(\frac{M_t}{M_s}\right) = logk + nlog(t) \tag{7}$$

The values of n, k and diffusion coefficient are depicted in Table 4. The UTWB, TWB, and TWSWB composites exhibited a Fickan diffusion process, as indicated by their diffusion exponent n being near to 0.5. UTWSWB exhibits a non-Fickan mechanism since its n value falls between 0.5 and 1, whereas UTSB and TSB exhibit a case-II diffusion mechanism as their n values approach 1.

When comparing the NaOH-treated banana fiber composite to the untreated composite with the same fiber architecture, the value k was lower. This suggests that, in comparison to its untreated counterpart, the treated banana fiber composite interacted well with water molecules. In general, the woven fiber composite and short fiber core sandwiched by the woven fiber face have a lower value of k,

Table 4. Kinetic parameters and diffusion coefficient values different banana fiber epoxy composites.

Composition	Slope (n)	Intercept (k)	Diffusion coefficient ($cm^2\ s^{-1}$)
UTSB	1.105	1.246	3.95×10^{-8}
TSB	0.959	1.078	3.16×10^{-8}
UTWB	0.549	0.605	9.72×10^{-8}
TWB	0.486	0.534	8.94×10^{-8}
UTWSWB	0.676	0.764	9.09×10^{-8}
TWSWB	0.532	0.600	7.01×10^{-8}

indicating that the short banana fiber composite did not have as good of an interaction with water molecules as the woven fiber outer layer and composite (W. Wang, Sain, and Cooper 2006).

Diffusion coefficient (D) is an important factor that tells us the amount of water molecules can pass unit area per unit time. It obtained from initial slope of $\frac{M_t}{M_s}$ verse square root time curve (Chunhong, Shengkai, and Zhanglong 2016).

$$\frac{M_t}{M_s} = \frac{4}{h}\left(\sqrt{\frac{D * t}{\pi}}\right) \tag{8}$$

Where h is the thickness of specimen. From experimental data $\frac{M_t}{M_s}$ was calculated and corresponding graph was sketched below.

The value of D calculated from initial slope of $\frac{M_t}{M_s}$ displayed in Table 4 is in good agreement reported by other author where the value of D for natural fiber composite lies within range of 10^{-8} to 10^{-9} cm^2/s (Panthapulakkal and Sain 2007). As shown in Figure 6, untreated banana fiber composite had higher diffusion coefficient compared with chemical treated fiber composites that have the same fiber architecture. This implies lesser amounts of water molecules can pass unit area per unit time for treated fiber composite. Treated fiber composites also had good interfacial bond with matrix and less amount – OH ions this may reduce affinity to moisture. When compared to short fiber, the weaved fiber composite showed a higher diffusion coefficient value, indicating that a large amount of water molecules initially egressed into the composite structure. This happens due to the weave structure, where interlace of warp and weft yarns in a 0/90° direction takes place. This may restrict the shrinkage of resin in two dimensions when

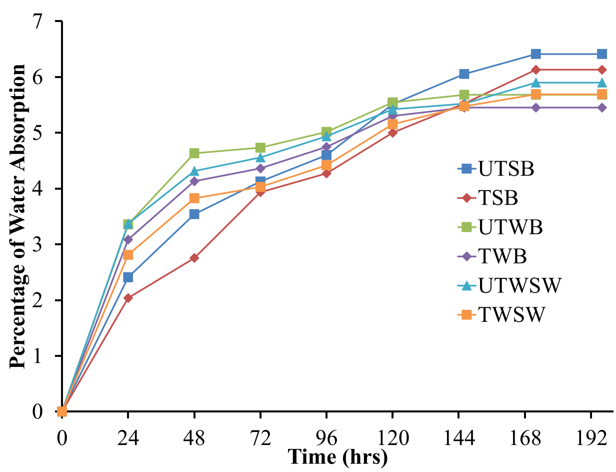

Figure 6. Moisture absorption curves of composites.

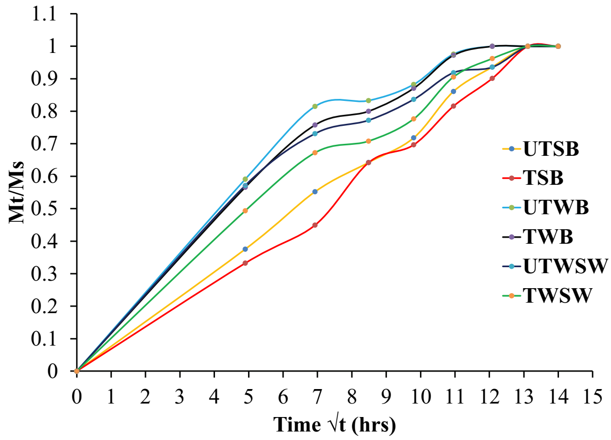

Figure 7. Water uptake of treated and untreated banana fiber composites.

curing (Li-Rong and Yee 2002a). The restraint of resin in two dimensions induces residual stress and micro-voids on the surface of the composite structure (Xiaogang, Gillespie, and Bogetti 2000). Consequently, when woven fiber composites are immersed in water, the quick filling of micro-voids on the surface contributes to the fast rate of absorption within the first short initial period of time. Following the fullness of surface voids, woven fiber composite easily relieves residual stress, hence reaching a saturated state at a fast rate compared with short fiber composite counter parts (Li-Rong and Yee 2002b; Tang et al. 2005). However, in the case of short banana fiber composites, due to the random orientation of the short fibers, the resin may not be restrained in a specific direction during curing, hence the low probability of surface void development and residual stress. But the difficulty of short fiber handling and distribution during composite processing may cause increased internal void formation due to agglomeration, hence the gradual holding of more water at saturation. The structure and hydrophilic qualities of the untreated fiber may also have contributed to the maximum diffusion coefficient that the composites have displayed. When submerged in water, raw fibers dissolve more readily than treated fibers, which are shielded against breakdown. This is because raw fiber has a higher water absorption capacity due to its hydrophilic lignin concentration. However, treated fibers absorb water less readily due to the removal of lignin and hemicellulose during from the NaOH treatment (Ronald Aseer et al. 2013). Nevertheless, the diffusion coefficient of a short fiber core surrounded by an outside layer of woven banana fiber is similar to that of a woven composite; this could indicate that the outer face of the composite influences the diffusion of water molecules significantly (Figure 7). In summary, the present work exhibits characteristics similar to natural composites in terms of density and Vickers hardness. However, there is a need for improvement in inter-laminar shear strength. The water absorption behavior aligns with previous studies, providing valuable insights into the composite material's stability and resistance to moisture.

Scanning electron micrographs

The scanning electron micrographs of freeze fracture specimens post-water absorption tests are presented in Figure 8. SEM images clearly show that the fibers are deteriorated by water absorption. The composite structure of UTSB and TSB, respectively, is shown in Figure 8a,b. The images highlight the voids that were developed due to uneven fiber and matrix adhesion. Extreme deterioration of the fibers is evident from the micrographs, indicating that the fibers are completely ingress with water and thereby revealing higher moisture absorption as compared with woven composites. The treated fibers

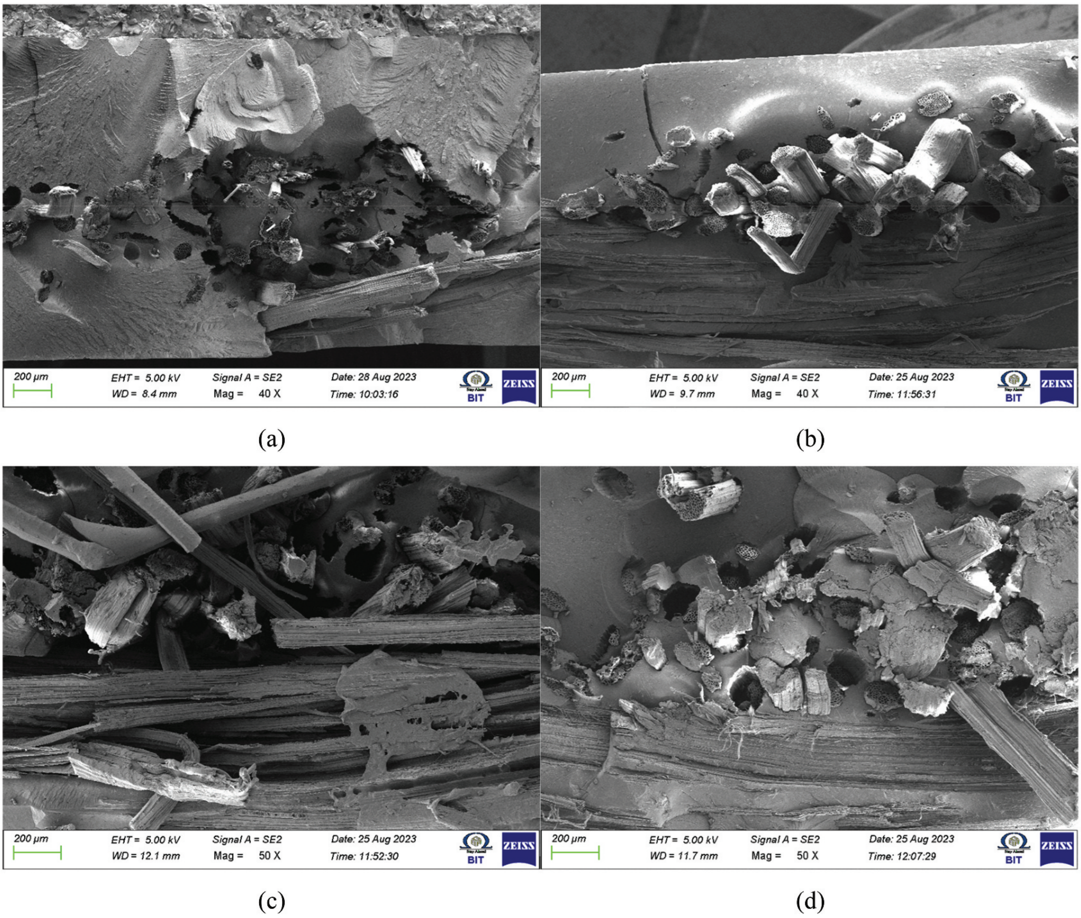

Figure 8. SEM micrographs of (a) UTSB, (b) TSB, (c) UTWSWB and (d) TWSWB.

have demonstrated superior adhesion, resulting in reduced fiber pullouts and consequently indicating a lower rate of water absorption relative to untreated fibers. In the untreated fibers, matrix failure is noticeable, stemming from voids, whereas the treated fibers exhibit crack propagation along the fiber–matrix interface. This suggests that failure occurred subsequent to fiber breakage, wherein the load was borne and transferred to the interphase. However, the interphase exhibited insufficient bonding to sustain the load post-failure that led to crack formation. SEM micrographs of UTWSWB and TWSWB are shown in Figure 8c,d, respectively. Comparing the UTWSWB and TWSWB composites to the UTSB and TSB composites, it is evident that the former exhibit superior resistance to moisture absorption since the fibers remains intact despite moisture absorption. The images depict a higher frequency of fiber pullouts alongside reduced resin content on the surface, suggestive of inadequate bonding. Conversely, treated fibers exhibit robust adhesion, characterized by diminished fiber pullouts and breakages. In the UTWSWB samples, the greater presence of voids signifies inferior bonding between the fiber and matrix, while the TWSWB samples display fewer voids and minimal crack propagation, indicative of superior load-bearing capabilities.

Conclusions

In the current study, three alternative methods of layering banana fibers – short fiber, woven fiber, and mix of short and woven fiber – are used to create banana fiber composites. Effects of NaOH fiber treatment is also performed on the three different banana fiber composites. Hardness, ILSS and water absorption properties of composites is investigated. Results infer that the TWB composite exhibited hardness of 70.75 HV owing to the establishment of a cleaner and more uniform fiber structure. The UTWSWB hybrid composite, displayed a hardness of 41.5, suggesting synergistic effects resulting from this unique combination of fibers while TWSWB composite reveals a hardness of 62.8 HV mainly attributed to the treatment's salutary influence on fiber-matrix adhesion. UTSB and TSB composites reveal lowest hardness of 32.5 and 39.9 HV, respectively. ILSS results were in line with the hardness ones wherein the UTSB and TSB reveal low inter-laminar shear strength due to poor bonding and weak adhesion with the polymer matrix. TWB reveals higher ILSS compared with all other composite types owing to the treatment of fibers and woven pattern enabling the structure to offer more resistance to shear forces. Water absorption results indicate that short fiber composites are more susceptible to water uptake as compared with woven or hybrid composites.

Highlights

- Banana fibers derived from Ethiopia are utilized for fabricating novel composites
- Composites are prepared by using short and woven banana fibers in plain and hybrid form
- Effect of NaOH treatment is investigated on the developed composites
- Treated woven composites reveal good hardness and inter-laminar shear strength
- Short banana fiber composites possess higher affinity for moisture absorption

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Authors' contributions

Kiran Shahapurkar, Gezahgn Gebremaryam – Conceptualization, Gezahgn Gebremaryam, Kiran Shahapurkar, Gangadhar Kanaginahal – Methodology, C. Venkatesh, Manzoore Elahi M Soudagar – Supervision, Mohammad Yassin, Kiran Shahapurkar – Writing – original draft, Kiran Shahapurkar, S. Ramesh, Nik-Nazri Nik-Ghazali – Investigation, Manzoore Elahi M Soudagar, Yasser Fouad, M.A.Kalam – Review and Editing.

Data availability statement

All the data used for the study is available in the manuscript.

References

Alireza, J., I. F. C. Smith, and D. E. Hebel. 2020. "Application of Sustainable Bamboo-Based Composite Reinforcement in Structural-Concrete Beams: Design and Evaluation." *Materials* 13 (3): 696.

Almeida, J. H. S., S. Campos Amico, E. Cocchieri Botelho, and F. Dani Rico Amado. 2013. "Hybridization Effect on the Mechanical Properties of Curaua/Glass Fiber Composites." *Composites Part B Engineering* 55:492–497. https://doi.org/10.1016/j.compositesb.2013.07.014.

Alves, J. L. C., K. S. Prado, and J. M. F. de Paiva. 2021. "Compressive and Interlaminar Shear Strength Properties of Biaxial Fibreglass Laminates Hybridized with Jute Fibre Produced by Vacuum Infusion." *Journal of Natural Fibers* 18 (11): 1772–1787.

Azanaw, A., and A. Ketema. 2022. "Extraction and Characterization of Fibers from Ethiopian Finger Euphorbia (Euphorbia Tirucalli) Plants." *Journal of Natural Fibers* 19 (15): 11885–11895. https://doi.org/10.1080/15440478.2022.2046674.

Azwa, Z. N., B. F. Yousif, A. C. Manalo, and W. Karunasena. 2013. "A Review on the Degradability of Polymeric Composites Based on Natural Fibres." *Materials & Design* 47:424–442. https://doi.org/10.1016/j.matdes.2012.11.025.

Baghaei, B., M. Skrifvars, M. Salehi, T. Bashir, M. Rissanen, and P. Nousiainen. 2014. "Novel Aligned Hemp Fibre Reinforcement for Structural Biocomposites: Porosity, Water Absorption, Mechanical Performances and Viscoelastic Behaviour." *Composites Part A, Applied Science and Manufacturing* 61:1–12. https://doi.org/10.1016/j.compositesa.2014.01.017.

Balogun, O. P., K. Kanayo Alaneme, A. Adesoji Adediran, I. Oluwole Oladele, J. Ajibade Omotoyinbo, and K. Fah Tee. 2022. "Evaluation of the Physical and Mechanical Properties of Short Entada Mannii-Glass Fiber Hybrid Composites." *Fibers* 10 (3): 30.

Bieniaś, J., P. Jakubczak, M. Droździel, and B. Surowska. 2020. "Interlaminar Shear Strength and Failure Analysis of Aluminium-Carbon Laminates with a Glass Fiber Interlayer After Moisture Absorption." *Materials* 13 (13): 2999.

Chalapathi, K., M. N. P. Venkata, and J.-I. Song. 2022. "Impact of Surface Treatments and Hybrid Flame Retardants on Flammability, and Thermal Performance of Bamboo Paper Composites." *Journal of Natural Fibers* 19 (6): 2152–2162.

Cheon, J., and M. Kim. 2021. "Impact Resistance and Interlaminar Shear Strength Enhancement of Carbon Fiber Reinforced Thermoplastic Composites by Introducing MWCNT-Anchored Carbon Fiber." *Composites Part B Engineering* 217:108872. https://doi.org/10.1016/j.compositesb.2021.108872 .

Chunhong, W., L. Shengkai, and Y. Zhanglong. 2016. "Mechanical, Hygrothermal Ageing and Moisture Absorption Properties of Bamboo Fibers Reinforced with Polypropylene Composites." *Journal of Reinforced Plastics & Composites* 35 (13): 1062–1074.

Das, D., M. Mukherjee, A. K. Pal, and K. G. Anup. 2017. "Extraction of Xylem Fibers from Musa Sapientum and Characterization." *Fibers and Polymers* 18:2225–2234. https://doi.org/10.1007/s12221-017-1187-5.

Dhakal, H. N., Z. Y. Zhang, and M. O. W. Richardson. 2007. "Effect of Water Absorption on the Mechanical Properties of Hemp Fibre Reinforced Unsaturated Polyester Composites." *Composites Science and Technology* 67 (7): 1674–1683. https://doi.org/10.1016/j.compscitech.2006.06.019.

Fangueiro, R., and S. Rana. 2016. "Natural Fibres: Advances in Science and Technology Towards Industrial Applications." *Springer Dordrecht* 12:183–196. https://doi.org/10.1007/978-94-017-7515-1 .

Gebremaryam, G., K. Shahapurkar, V. Chenrayan, F. Althoey, H. M. Hadidi, M. E. M. Soudagar, V. Tirth, et al. 2023. "Influence of Layering Pattern, Fibre Architecture, and Alkalization on Physical, Mechanical, and Morphological Behaviour of Banana Fibre Epoxy Composites." *International Journal of Polymer Science* 6023056. https://doi.org/10.1155/2023/6023056.

Ghani, A., A. Fuad, and J. Mahmud. 2018. "Hardness, Tensile and Microstructure Assessment of Carbon/Glass Hybrid Composite Laminate." *Journal of Mechanical Engineering (JMechE)* 15 (2): 91–105.

Gopinathan, P., K. S. Subramanian, G. Paliyath, and J. Subramanian. 2017. "Genotypic Variations in Characteristics of Nano-Fibrillated Cellulose Derived from Banana Pseudostem." *Bio Resources* 12 (4): 6984–7001.

Gu, Q., Z. Quan, M. Shen, Y. Xie, and J. Yu. 2023. "Fabrication and Braiding Angle Effect on the Improved Interlaminar Shear Performances of 3D Braided Sandwich Hybrid Composites." *Journal of Materials Research and Technology* 25:5795–5806. https://doi.org/10.1016/j.jmrt.2023.07.019.

Hrabalova, M., A. Gregorova, R. Wimmer, V. Sedlarik, M. Machovsky, and N. Mundigler. 2010. "Effect of Wood Flour Loading and Thermal Annealing on Viscoelastic Properties of Poly (Lactic Acid) Composite Films." *Journal of Applied Polymer Science* 118 (3): 1534–1540.

Hu, H., X. Cheng, Z. Liu, X. Chen, R. Piao, and C. Xiang. 2023. "Influence of Bamboo Fibers Weight Fraction on the Quasi-Static and Dynamic Compressive Responses of Epoxy Matrix Composites." *Journal of Natural Fibers* 20 (2): 2246646. https://doi.org/10.1080/15440478.2023.2246646.

Ismail, A. S., M. Jawaid, N. Hisham Hamid, R. Yahaya, M. Sain, and S. Noorbaini Sarmin. 2022. "Dimensional Stability, Density, Void and Mechanical Properties of Flax Fabrics Reinforced Bio-Phenolic/epoxy Composites." *Journal of Industrial Textiles* 52:15280837221123594. https://doi.org/10.1177/15280837221123594.

Kanaginahal, G. M., S. Hebbar, K. Shahapurkar, M. A. Alamir, V. Tirth, I. M. Alarifi, M. Sillanpaa, and H. C. Ananda Murthy. 2023. "Leverage of Weave Pattern and Composite Thickness on Dynamic Mechanical Analysis, Water

Absorption and Flammability Response of Bamboo Fabric/Epoxy Composites." *Heliyon* 9 (1): E12950. https://doi.org/10.1016/j.heliyon.2023.e12950.

Karthik, A., V. Vijayan, Z. Ahmad, S. Rajkumar, S. Sharma, K. P. Sharma, R. Singh, C. Li, and M. E. Sayed. 2023. "Study on the Physicomechanical, Fracture-Deformation, Interface-Adhesion, and Water-Absorption Properties of Twill Fabric Cotton-Bamboo/epoxy Composites." *Journal of Materials Research and Technology* 24:8429–8442. https://doi.org/10.1016/j.jmrt.2023.05.102.

Khuntia, T., and S. Biswas. 2020. "An Investigation on the Flammability and Dynamic Mechanical Behavior of Coir Fibers Reinforced Polymer Composites." *Journal of Industrial Textiles* 51 (10): 1616–1640. https://doi.org/10.1177/1528083720905031.

Kore, S., R. Spencer, H. Ghossein, L. Slaven, D. Knight, J. Unser, and U. Vaidya. 2021. "Performance of Hybridized Bamboo-Carbon Fiber Reinforced Polypropylene Composites Processed Using Wet Laid Technique." *Composites Part C Open Access* 6:100185. https://doi.org/10.1016/j.jcomc.2021.100185 .

Kusmono, H. Hestiawan, and Jamasri. 2020. "The Water Absorption, Mechanical and Thermal Properties of Chemically Treated Woven Fan Palm Reinforced Polyester Composites." *Journal of Materials Research and Technology* 9 (3): 4410–4420. https://doi.org/10.1016/j.jmrt.2020.02.065.

Lakshmaiya, N., S. Kaliappan, P. P. Patil, V. Ganesan, J. Arockia Dhanraj, C. Sirisamphanwong, T. Wongwuttanasatian, S. Chowdhury, S. Channumsin, and M. Channumsin. 2022. "Influence of Oil Palm Nano Filler on Interlaminar Shear and Dynamic Mechanical Properties of Flax/epoxy-Based Hybrid Nanocomposites Under Cryogenic Condition." *Coatings* 12 (11): 1675.

Li-Rong, B., and A. F. Yee. 2002a. "Moisture Diffusion and Hygrothermal Aging in Bismaleimide Matrix Carbon Fiber Composites: Part II—Woven and Hybrid Composites." *Composites Science and Technology* 62 (16): 2111–2119.

Li-Rong, B., and A. F. Yee. 2002b. "Moisture Diffusion and Hygrothermal Aging in Bismaleimide Matrix Carbon Fiber Composites—Part I: Uni-Weave Composites." *Composites Science and Technology* 62 (16): 2099–2110.

Loganathan, T. M., M. T. H. Sultan, M. Jawaid, Q. Ahsan, J. Naveen, A. Umaira Md Shah, A. Rahim Abu Talib, and A. Azriff Basri. 2021. "Physical, Mechanical, and Morphological Properties of Hybrid Cyrtostachys Renda/Kenaf Fiber Reinforced with Multi-Walled Carbon Nanotubes (MWCNT)-Phenolic Composites." *Polymers* 13 (19): 3448.

Madgule, M., P. Deshmukh, K. Perveen, M. Obaid Qamar, A. Razak, and A. W. Wodajo. 2023. "Experimental Investigation on Mechanical Properties of Novel Polymer Hybrid Composite with Reinforcement of Banana Fiber and Sugarcane Bagasse Powder." *Advances in Mechanical Engineering* 15 (10): 16878132231203810.

Martel, W. D. N. D. R., I. P. Salgado, and F. A. Silva. 2022. "The Influence of Fiber Treatment on the Morphology, Water Absorption Capacity and Mechanical Behavior of Curauá Fibers." *Journal of Natural Fibers* 19 (2): 642–657. https://doi.org/10.1080/15440478.2020.1758863.

Natrayan, L., S. Kaliappan, S. B. Sethupathy, S. Sekar, P. P. Patil, S. Raja, G. Velmurugan, and D. Bayisa Abdeta. 2022. "Investigation on Interlaminar Shear Strength and Moisture Absorption Properties of Soybean Oil Reinforced with Aluminium Trihydrate-Filled Polyester-Based Nanocomposites." *Journal of Nanomaterials* 2022:7588699. https://doi.org/10.1155/2022/7588699.

Oun, A., A. Manalo, O. Alajarmeh, R. Abousnina, and A. Gerdes. 2022. "Long-Term Water Absorption of Hybrid Flax Fibre-Reinforced Epoxy Composites with Graphene and Its Influence on Mechanical Properties." *Polymers* 14 (17): 3679.

Panthapulakkal, S., and M. Sain. 2007. "Studies on the Water Absorption Properties of Short Hemp—Glass Fiber Hybrid Polypropylene Composites." *Journal of Composite Materials* 41 (15): 1871–1883.

Praveena, B. A., N. Santhosh, A. Buradi, H. V. Srikanth, G. Shankar, K. Ramesha, N. Manjunath, S. N. Karthik, M. Rudra Naik, and S. Praveen Kumar. 2022. "Experimental Investigation on Density and Volume Fraction of Void, and Mechanical Characteristics of Areca Nut Leaf Sheath Fiber-Reinforced Polymer Composites." *International Journal of Polymer Science* 2022:6445022. https://doi.org/10.1155/2022/6445022.

Raghavendra, G., S. K. A. Shakuntala Ojha, and S. K. Pal. 2014. "Mechanical Properties of Woven Jute–Glass Hybrid-Reinforced Epoxy Composite." *Journal of Composite Materials* 48 (28): 3445–3455.

Ronald Aseer, J., K. Sankaranarayanasamy, P. Jayabalan, R. Natarajan, and K. Priya Dasan. 2013. "Morphological, Physical, and Thermal Properties of Chemically Treated Banana Fiber." *Journal of Natural Fibers* 10 (4): 365–380. https://doi.org/10.1080/15440478.2013.824848.

Shambhu, V. B., P. Shrivastava, T. Nageshkumar, M. Jagadale, L. Kanta Nayak, and D. Babu Shakyawar. 2023. "Development of Gender-Friendly Power Ribboner for Extraction of Green Ribbon/Bast from Jute Plants." *Journal of Natural Fibers* 20 (2): 2250076. https://doi.org/10.1080/15440478.2023.2250076.

Shamsuyeva, M., J. Winkelmann, and H.-J. Endres. 2019. "Manufacture of Hybrid Natural/Synthetic Fiber Woven Textiles for Use in Technical Biocomposites with Maximum Biobased Content." *Journal of Composites Science* 3 (2): 43.

Singh, C. P., R. Vardhan Patel, M. Faizul Hasan, A. Yadav, V. Kumar, and A. Kumar. 2021. "Fabrication and Evaluation of Physical and Mechanical Properties of Jute and Coconut Coir Reinforced Polymer Matrix Composite." *Materials Today: Proceedings* 38:2572–2577. https://doi.org/10.1016/j.matpr.2020.07.684.

Sreekumar, P. A., P. Albert, G. Unnikrishnan, K. Joseph, and S. Thomas. 2008. "Mechanical and Water Sorption Studies of Ecofriendly Banana Fiber-Reinforced Polyester Composites Fabricated by RTM." *Journal of Applied Polymer Science* 109 (3): 1547–1555. https://doi.org/10.1002/app.28155.

Sun, Y., Y. Lu, and X. Guo. 2019. “The Effects of Sample Preparation on the Interlaminar Shear Strength Test Values of Unidirectional Carbon Fiber-Reinforced Epoxy Composites.” *Polymers & Polymer Composites* 27 (4): 228–234.
Tang, X., J. D. Whitcomb, Y. Li, and H.-J. Sue. 2005. “Micromechanics Modeling of Moisture Diffusion in Woven Composites.” *Composites Science and Technology* 65 (6): 817–826.
Tasdemir, H. M., A. Sahin, F. K. Ahmet, and M. Guru. 2019. “Production of Useful Composite Particleboard from Waste Orange Peel.” *Journal of Chemical Technology & Biotechnology* 53 (5–6): 517–526. https://doi.org/10.35812/CelluloseChemTechnol.2019.53.52.
Wang, W., M. Sain, and P. A. Cooper. 2006. “Study of Moisture Absorption in Natural Fiber Plastic Composites.” *Composites Science and Technology* 66 (3–4): 379–386.
Wang, L., A. Toppinen, and H. Juslin. 2014. “Use of Wood in Green Building: A Study of Expert Perspectives from the UK.” *Journal of Cleaner Production* 65:350–361. https://doi.org/10.1016/j.jclepro.2013.08.023.
Xiaogang, H., J. W. Gillespie Jr, and T. Bogetti. 2000. “Process Induced Stress for Woven Fabric Thick Section Composite Structures.” *Composite Structures* 49 (3): 303–312.
Zareei, N., A. Geranmayeh, and R. Eslami-Farsani. 2019. “Interlaminar Shear Strength and Tensile Properties of Environmentally-Friendly Fiber Metal Laminates Reinforced by Hybrid Basalt and Jute Fibers.” *Polymer testing* 75:205–212. https://doi.org/10.1016/j.polymertesting.2019.02.002.