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RESEARCH

Comprehensive Studies on Mechanical Characteristics and Interfacial Behavior of Ramie/ Jute and Hybrid Fiber Epoxy Composites

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A B S T R A C T

In recent years, natural fiber composites have gained popularity as alternatives to synthetic composites because they are lighter, cheaper, eco-friendly, and biodegradable. Despite being sustainable, they still offer good strength and stiffness, making them suitable for various engineering and structural applications. In this research, composites reinforced with ramie, jute, and a combination of both fibers were produced employing the hand lay-up technique. A total of six distinct composite variants were fabricated and subsequently evaluated following ASTM testing standards.The composites were evaluated for density, tensile, flexural, interlaminar shear, impact, hardness and water absorption properties. Results showed that adding pure ramie fibers improved the overall mechanical performance. The hybrid RJRJ composite shows less water absorption and also demonstrated superior in tensile, flexural, ILSS, impact capability, and hardness examined alongside to the single fiber composite variant (SSSS) and other hybrid composites. When reinforced with the RJRJ fiber combination, the epoxy composite's tensile strength rose by 170%, reaching 45.23 MPa, while its flexural strength increased by 127%, attaining 68.24 MPa.The flexural modulus also rose by 42%, reaching 1.79 GPa. Fracture and debonding behavior from tensile tests were further analyzed using scanning electron microscopy. Overall, the study concludes that RJRJ hybrid composite are promising materials for medium-load structural applications to lessen dependence on depleting non-renewable sources through renewable material alternatives.

1. INTRODUCTION

Natural fibers, derived from plants or other living sources, offer several advantages over synthetic fibers: low cost and density, ready availability, lightweight nature, compostability, reusability, non-toxicity, and good mechanical properties. Ramie fiber is widely studied as a high-performance natural reinforcement due to its excellent mechanical and chemical properties [1]. Ramie, a bast fiber, exhibits very high cellulose content (typically 80–90%), low lignin, and relatively low hemicellulose. These characteristics contribute to its superior stiffness and strength compared to many other plant fibers [2]. Recent studies on ramie fiber tensile behavior report strengths typically ranging from 95–170 MPa with variability due to gauge length, extraction method, and testing conditions and moduli reaching tens of GPa, positioning ramie among the strongest natural fibers [3]. Tensile properties of ramie fibers depend strongly on harvesting time and extraction method. Optimized harvesting age and mechanical or chemical decortication enhance strength and reduce variability in properties [4]. To improve compatibility with polymer matrices, researchers frequently treat ramie fibers with alkaline NaOH, silane, or other chemical agents. These treatments remove surface impurities, roughen the fibers, and enhance interfacial bonding, resulting in higher composite strength [5]. Studies on thermally and chemically modified ramie fibers show that treatments such as biopolyurethane or silicon-polymer impregnation improve thermal stability, reduce moisture sensitivity, and enhance the mechanical performance of ramie-based composites [6]. Ramie fiber–reinforced epoxy laminates show substantial improvements in tensile, flexural, and impact properties compared to neat epoxy. Strength and stiffness increase with fiber volume fraction and proper consolidation [7]. Dynamic mechanical analysis (DMA) of ramie/epoxy composites reveals increased storage modulus and modified damping behavior compared to the neat matrix, indicating effective reinforcement and altered viscoelastic response across temperature [8]. Work on transparent ramie/epoxy composites demonstrates that, with careful control of fiber volume, orientation and resin refractive index, it is possible to obtain composites that combine adequate optical transmittance with enhanced mechanical performance [9]. Hybridization of ramie with glass or other natural fibers (such as hemp) has been shown to produce synergistic effects, where optimized stacking sequence and fiber ratio yield higher tensile, flexural and shear strengths than single-fiber systems at comparable reinforcement contents [10]. Recent review articles summarize that ramie fiber–reinforced polymers show promising mechanical, thermomechanical and even ballistic performance, suggesting potential applications in automotive, protective structures, and eco-friendly engineering components, while also emphasizing the need for standardized treatments and processing routes [11]. Jute/epoxy laminates demonstrate tensile strengths of 25–60 MPa and flexural strengths up to 80 MPa, with properties improving with fiber alignment, volume fraction (20–40%), and proper consolidation pressure[12]. Jute–banana/epoxy laminates show optimal tensile strength (45–65 MPa) at 1:1 ratio; banana adds toughness while jute provides stiffness [13]. Jute–flax polyester hybrids exhibit balanced tensile (35–55 MPa) and flexural (60–85 MPa) properties; flax reduces moisture absorption compared to pure jute [14]. Jute–hemp epoxy composites achieve tensile strengths of 40–70 MPa with improved impact resistance; hemp enhances fiber–matrix bonding over jute alone [15]. Jute–sisal laminates demonstrate synergistic flexural strength (70–90 MPa) at equal ratios; sisal contributes to better fatigue performance [16]. Jute/banana/flax three-fiber systems achieve balanced properties (tensile 50 MPa, flexural 80 MPa) suitable for automotive panels and furniture [17]. Natural fibers need different treatments based on their type, the desired properties, and the intended application. These treatments help improve features such as bonding with the matrix, surface wetting, roughness, and resistance to moisture [18]. Vachellia farnesiana fibers were extracted and treated with NaOH and HCl, where NaOH treatment improved cellulose content and reduced moisture, while HCl treatment degraded the fiber due to its acidic nature [19]. Treating Ficus macrocarpa bark fibers with alkali made their surface rougher (39.26) and improved their heat resistance up to about 378.87 °C. This shows that these natural fibers could be a sustainable and eco-friendly alternative to synthetic fibers in making polymer composites [20]. NaOH-treated coir and hemp fibers, when combined with SiO_2 and Al_2O_3 nanofillers, greatly improve the mechanical strength and antibacterial performance of hybrid nanocomposites [21]. Studies on hybrid composites made from kenaf and kapok fibers show that the fiber ratio plays a key role in determining their mechanical performance [22].

Table 1. Physical and mechanical characteristics of fibers and epoxy [23].

Description	Ramie fiber	Jute fiber	Epoxy
Density (g/cc)	1.5	1.38	1.15
Tensile strength(MPa)	1000	650	35-135
Tensile modulus (GPa)	61.4-128	24	3.4
Elongation(%)	2-4	1.5-1.8	1-8.5

Table 1 presents the physical-mechanical properties of ramie and jute fibers as well as the epoxy (resin). The results show that hybrid composition demonstrate significantly greater impact resistance compared to composites reinforced with only fiberglass. A significant body of literature is dedicated to investigating the mechanical properties of hybrid fiber polymer composites. Epoxy composites built with ramie, jute, and their hybrid combinations were employed in this work to study the hybridization effects on composite material behavior The hybrid specimens were tested for a setting of physical and mechanical attribute, including density, tensile, flexural, ILSS, impact, and hardness.

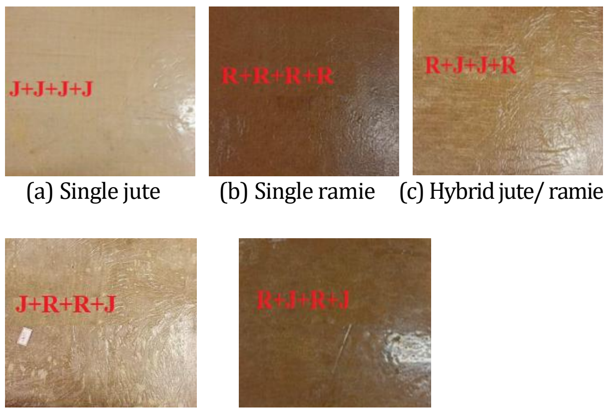
2. MATERIALS AND METHODS

2.1 Raw-material

This study aims to, composite specimen are fabricated using woven ramie and jute fibers as reinforcement material. The 250 GSM(gram per square meter) woven fabrics were procured from Vruksha Composites, Guntur, Andhra Pradesh, while the resin epoxy with hardener were provided by Ultrananotech India-Ltd., Bengaluru. Ramie (6–8% NaOH) and jute (5–6% NaOH) fibers were soaked for 2 to 3 hrs, washed with distilled water to neutral pH, and dried at 60 to 80°C for 24 hrs. This removes hemicellulose or lignin and roughens the surface for better fiber–matrix interfacial adhesion.

2.2 Composition fabrication

The hand lay-up method was first employed for slabs processing and then made compact with a light compression mould. Hand lay-up is cheap and easy for making small composite samples like your ramie/jute ones, but it has clear downsides that affect quality. It depends heavily on the worker's skill, causing uneven resin spread and varying thickness between batches. It's also slow and not good for mass production since everything is done by hand. Air gets trapped when brushing resin, creating small holes (voids) that weaken the material. These holes cut strength by 20-30% and make layers peel apart easily, especially in wet conditions with natural fibers. Fibers can shift, wrinkle, or twist during manual placement, messing up the planned layers. This drops stiffness and strength by 10-25% and hurts impact performance in hybrids like yours. Using rollers helps some, but issues remain. Table 2 shows total six kinds of groups prepared with differing fiber loading. Epoxy resin LY556 and HY951 hardener were blended in a 10:1 ratio , (with accelerator) is then stirred at 400–500 RPM and poured onto the woven fabric fibers arranged in the mold , then mixed with 4 layers of ramie, jute and hybrid fiber to produce laminates measuring 300 × 300 × 3 mm^3 as shown in the Figure 1. Excess resin on the fiber mat is then compacted using a roller, which also removes trapped air bubbles. A release agent is sprayed on the inner surface of the top mold plate. All variants use hand lay-up followed by initial room-temperature curing at 22–27°C under weighted plates, 10 kg/m^2 for 24 hours to achieve gelation and handling strength. Apply the same post-cure to all variants after demolding, ramp to 60°C hold 2 hours, then 80–100°C hold 2–4 hours, followed by slow oven cooling. This enhances cross-linking and mechanical properties while minimizing voids, tailored to common epoxy systems like LY556, then oven-cured and cut using a water abrasive jet machine in accordance with ASTM specifications.



(a) Single jute (b) Single ramie (c) Hybrid jute/ ramie (d) Hybrid jute/ramie (e) Hybrid jute/ramie

Fig. 1. Fabrication of Single and hybrid natural filler composites.

Table 2. Composite classification.

Sl No	Composites	Volume fraction V_f(%)	V_m(%)
1	Epoxy		100
2	J+J+J+J	24.15	75.85
3	R+R+R+R	22.22	77.78
4	R+J+R+J	12.08J+11.11R=23.19	76.81
5	J+R+R+J	12.08J+11.11R=23.19	76.81
6	R+J+J+R	12.08J+11.11R=23.19	76.81

3. EXPERIMENTAL METHODS

3.1 Density

The composite's theoretical density can be ascertained based on the weight fractions of its individual components using the corresponding equation (1)

$$\rho_{th} = \frac{1}{(W_{fj}/\rho_{fj})+(W_{fr}/\rho_{fr})+(W_m/\rho_m)} \quad (1)$$

In this context, W= weight fraction and ρ = density, with subscripts f_{j}=jute fiber, f_{r}=ramie fiber, m=matrix, and ρ_{th} = theoretical composite density. The composite density was experimentally determined using either the archimedes-principle or the water immersion method in accordance with ASTM (D792-91) standards. The void content was assessed following the procedures outlined in ASTM (D2734-70). The volume fraction of voids (V_v) was determined using equation (2), in which ρ_{th} and ρ_{exp} correspond to the theoretical and measured composite densities, respectively.

$$V_v = \frac{\rho_{th}-\rho_{exp}}{\rho_{th}} \quad (2)$$

3.2 Tensile strength

Tensile tests followed ASTM D3039-14 using flat, straight-sided specimens on an Instron 1195 Universal Testing Machine at a crosshead speed of 2 mm/min. Three replicate specimens were tested for each composite type, and the average values determined the reported tensile strength and modulus.

3.3 Flexural strength

Flexural strength refers to the highest tensile stress a composite can endure during bending before it breaks. Rectangular samples were evaluated using a Universal Testing Machine (Instron 1195) as per ASTM D790 guidelines. Each specimen measured 100X 12.7 X 4 in mm, and testing was conducted using a 10 kN load cell with 2 mm per minute of loading rate. The resulting flexural strength was calculated using the relevant equation(3) for this test.

$$\frac{3PL}{2bt^2} \quad (3)$$

In this equation, P represents load , L is the distance between supports (span length), b = width and, t = thickness of the specimen. Flexural strength was evaluated by testing three replicate samples from each composite category and reporting the average result.

3.4 Inter laminar shear strength (ILSS)

Short beam shear testing was performed at ambient temperature to measure the interlaminar shear strength (ILSS) of the composites, utilizing a Universal Testing Machine (Instron 1195) and adhering to ASTM D2344-84 standards. Test specimens had dimensions of 45 × 10 × 4 mm and were loaded at a crosshead speed of 2 mm/min. This test method is designed to minimize bending stresses, ensuring that failure primarily occurs along the interlaminar plane. ILSS was calculated as per equation (4), and the flexural property was averaged over three tested specimens for each composite category.

$$\frac{3P}{4bt} \quad (4)$$

3.5 Impact strength

Low-velocity impact testing was performed using a pendulum impact tester to evaluate the notch impact strength of the specimen. V-notched specimens were broken by a pendulum hammer, and the energy absorbed, indicated on the dial, was normalized by the cross-section of specimen's area to determine impact resistance. The tests followed the ASTM D256 standard, with specimens sized 64X12.7X4 in mm, featuring a notch depth of 10 mm.

3.6 Micro-hardness test

Micro-hardness was measured using a Leitz tester equipped with a diamond indenter shaped as a right square pyramid with a 136° apex angle.

The indenter was pressed into the specimen surface under a set load, and after removal, the lengths of the two indentation diagonals (X-Y) were measured. The arithmetic mean of these diagonals (L) was calculated as shown in equation (5). In this study, a load of 24.54 N was used. The Vickers hardness number was then calculated based on these measurements using equation (5).

$$H_v = 0.1889 \frac{F}{L^2} \; and \; L = \frac{X+Y}{2} \qquad (5)$$

In this context, F represents load in newtons (N), while L denotes the mean length of the square indentation in millimeters (mm). The values X and Y correspond to the lengths of the horizontal and vertical diagonals. Three identical samples were tested, and their average hardness was reported as the composite's representative value.

3.7 SEM (Scanningelectron microscope)

The eroded surfaces of the composite specimens were directly examined using a Tescan Vega scanning electron-microscope to analyze their surface morphology. Each specimen was affixed to an aluminum stub with silver paste to ensure stable mounting. To improve surface conductivity and minimize charging effects during imaging, a thin platinum coating was applied to the samples through vacuum sputtering prior to capturing the micrographs.

4. RESULT AND DISCUSSION

4.1 Density test

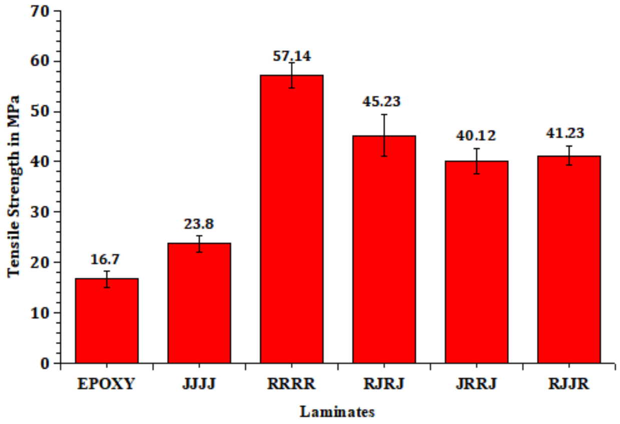
Table 3. Theoretical (ρ_{th}) and Experimental-density(ρ_{exp}) values of Single-Hybrid composites.

Composites	ρ_{th} (g/cm^3)	ρ_{exp} (g/cm^3)	Void (%)
Epoxy	1.150	1.141	0.782
JJJJ	1.268	1.236	2.523
RRRR	1.319	1.291	2.122
RJRJ	1.295	1.280	1.158
JRRJ	1.295	1.275	1.544
RJJR	1.295	1.272	1.776

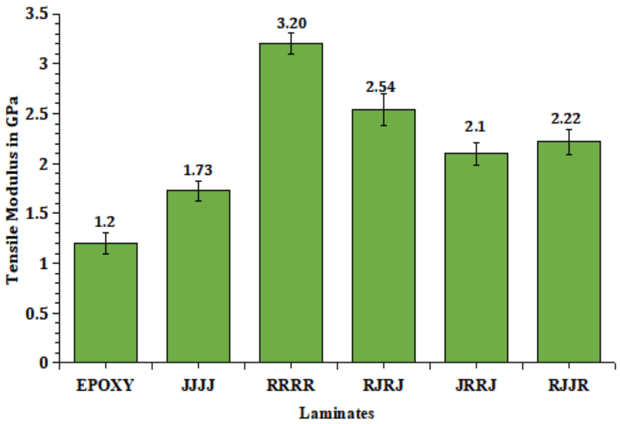
The densities of ramie and jute fibers are higher than that of neat epoxy, which results in an overall increase in composite density upon fiber reinforcement. As shown in Table 3, the RRRR composite exhibited the highest density (1.319 g/cm^3) due to the greater density of ramie fiber compared to JJJJ (1.268 g/cm^3) and neat epoxy (1.15 g/cm^3). The JJJJ composite had a higher density than epoxy but lower than RRRR, whereas hybrid stacking sequences such as RJJR showed nearly identical densities (1.295 g/cm^3) regardless of layer arrangement. The highest void content (2.523 %) was observed in JJJJ composites, attributed to the presence of lumens in jute fibers that naturally introduce voids and hinder effective fiber–matrix bonding, leading to incomplete wetting. Conversely, hybrid composites (RJJR, RJRJ, and JRRJ) displayed reduced void content, attributable to the smaller lumen diameter of ramie fibers and enhanced fiber–matrix bonding, which improved epoxy matrix wetting around the fibers [24].

4.2 Tensile strength

Tensile testing was conducted according to ASTM D3039 specifications, and the resulting stress–strain data were analyzed to determine the tensile strength and modulus of the different laminate configurations. As shown in Figures 2(a) and 2(b), the ramie-reinforced laminate (RRRR) demonstrated the improved tensile potential of 57.40 MPa and 3.20 GPa of modulus, indicating superior load-bearing capability among the tested composites. This improvement is attributed to the increased number of fiber layers, which facilitates a more homogeneous stress distribution throughout the matrix. The jute composite (JJJJ) recorded the lowest tensile strength (23.8 MPa) and modulus (1.73 GPa). Hybrid laminates such as RJRJ and JRRJ showed intermediate values of 45.23 MPa and 40.12 MPa with moduli of 2.54 GPa and 2.10 GPa, respectively. Ramie fibers, with their high strength and modulus positioned at the outer and middle layers, effectively resisted the applied load, while the jute core absorbed and evenly distributed stresses. The variations in mechanical performance arise from the efficiency of stress transfer between fiber and matrix. The tensile fracture surfaces of the RJRJ, JJJJ, and RJJR single and hybrid natural fiber composites are shown in Figure 3. Composites with higher jute content exhibit localized matrix strain due to insufficient reinforcement, whereas hybrid composites may experience effective wetting, fine fiber packing, and less entanglement, which improves stress transfer and overall tensile efficiency [25].



(a) Tensile strength



(b) Tensile modulus

Fig. 2. Tensile strength and modulus of single and hybrid natural filler composites.

(a) Tensile fractured specimen (RJRJ)

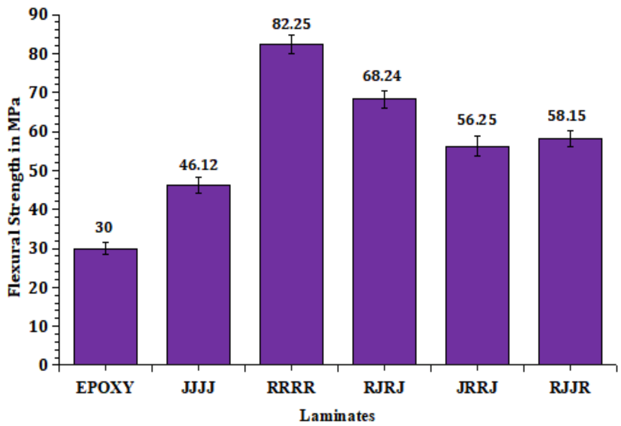
(b) Tensile fractured specimen (JJJJ)

(c) Tensile fractured specimen (RJJR)

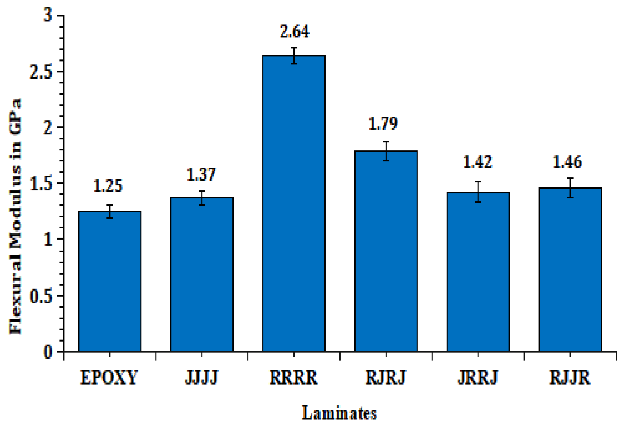
Fig. 3. Tensile fractured specimen of single and hybrid filler composite.

4.3 Flexural strength

A three-point bend test was used to determine the flexural characteristics of the composites, with the outcomes shown in Figure 4. Among all laminates, the RRRR configuration exhibited the higher flexural strength (82.25 MPa) and elastic modulus (2.64 GPa), while the JJJJ laminate recorded the lowest values (46.12 MPa and 1.37 GPa, respectively). The hybrid laminates showed intermediate performance, with RJRJ achieving the highest flexural strength (68.24 MPa) compared to JRRJ (56.25 MPa) and RJJR (58.15 MPa).The enhanced flexural performance of the hybrid laminates is due to the balanced fiber distribution, which improves load-bearing capacity. The slight increase in hybrid laminate strength is attributed to strong interfacial bonding, minimal fiber entanglement, and minor incomplete wetting of fibers in the epoxy matrix. Similar trends were observed in earlier studies on hybrid natural fiber composites [26].



(a) Flexural strength



(b) Flexural modulus

Fig. 4. Flexural strength and modulus of single and hybrid natural fillers composite.

Table 4. Comparison of tensile strength of hybrid natural fillers composite.

Hybrid fiber	Reinforcement	Stacking of fiber	Tensile strength (MPa)	Tensile modulus (GPa)	Reference
Jute/Ramie	Bi directional	JJJJ	23.8	1.73	Current study
		RRRR	57.14	3.20	
		RJRJ	45.23	2.54	
		RJJR	41.23	2.22	
		JRRJ	40.12	2.10	
JF/BaF/CF/Palf	Bi directional	JF/CF/Palf	71.3	3.4	[27]
		JF/BaF/Palf	74	3.8	
		JF/BaF/CF	77.5	3.7	
		JF/CF/Palf	79.2	3.0	
		JF/BaF/Palf	85.8	3.5	
		JF/BaF/CF	83.6	3.2	

The current study was evaluated against earlier research on epoxy-based hybrid composites. Most prior studies have focused on the influence of jute fiber(JF)/coir fiber (CF)/banana fiber (BaF)/pine apple leaf (Palf) epoxy hybrids and various stacking sequences of 7 mm thickness, on tensile behavior. The findings of this work show that both jute fiber and hybrid jute–ramie composites perform better than neat epoxy. The tensile strength of the JF/CF/BaF/Pal hybrid composite is comparable to that of a four-layer Jute–ramie system, while the JF/BaF/Palf configuration exhibits a higher tensile modulus than the Jute–ramie counterpart is presented in Table 4.

The flexural properties obtained in this study were compared with previously reported results, as summarized in Table 5. Most existing literature focuses on hybrid composites containing natural fibers. Among these, JF/BaF/Palf hybrids have shown superior flexural strength compared to jute–ramie epoxy composites. Likewise, their elastic modulus was found to be higher than that of the hybrid epoxy composites examined in the present work.

Table 5. Comparison of Flexural strength of hybrid natural fillers composite.

Hybrid fiber	Reinforcement	Stacking of fiber	Flexural strength (MPa)	Flexural modulus (GPa)	Reference
Jute/Ramie	Bi directional	JJJJ	46.12	1.37	Current study
		RRRR	82.25	2.64	
		RJRJ	68.24	1.79	
		RJJR	58.15	1.46	
		JRRJ	56.25	1.42	
JF/BaF/CF/Palf	Bi directional	JF/CF/Palf	127.4	4.2	[27]
		JF/BaF/Palf	129.6	3.9	
		JF/BaF/CF	130.3	4.3	
		JF/CF/Palf	131.9	4.0	
		JF/BaF/Palf	134.5	4.1	
		JF/BaF/CF	132.2	4.2	

4.4 ILSS (Inter Laminar Shear Strength)

The ramie fiber–reinforced laminate (RRRR) exhibited the highest interlaminar shear strength (ILSS) of 76.62 MPa due to the superior stiffness and load-bearing capability of ramie fibers, which effectively resist shear deformation within the laminate as shown in figure 5. In contrast, the jute laminate (JJJJ) showed a lower ILSS of 46.68 MPa, while the hybrid configuration RJRJ, containing alternating layers of ramie and jute, achieved the highest ILSS among hybrid laminates

(67.82 MPa). The remaining hybrids, JRRJ and RJJR, exhibited ILSS values of 60.52 MPa and 61.13 MPa, respectively.The improved ILSS of hybrid laminates is attributed to reduced void formation in the matrix and strong interfacial bonding between layers, especially at higher fiber loadings. The low void content minimizes delamination and enables effective stress transfer across the laminae. The interlaminar shear behavior of hybrid composites is mainly influenced by fiber–matrix adhesion, fiber loading, orientation, and void content, which together determine the laminate's resistance to shear failure [28].

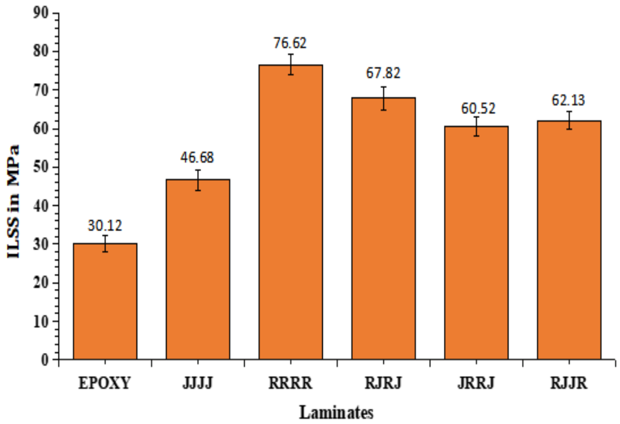


Fig. 5. ILSS of single and hybrid composites.

4.5 Impact strength

Figure 6 shows that the laminates' impact strength reflects matrix– fiber bonding efficiency. The RRRR composite exhibited the highest impact strength (51.68 kJ/m^2) due to the excellent stiffness and energy absorption capability of ramie fibers. In contrast, the JJJJ laminate showed the lowest value (20.4 kJ/m^2), attributed to the hemicellulose content in jute fibers, which reduces bonding strength. Among the hybrid laminates, RJRJ displayed the highest impact value (32.5 kJ/m^2), followed by RJJR (28.64 kJ/m^2) and JRRJ (26.52 kJ/m^2).The impact resistance of hybrid composites surpassed that of single-fiber jute laminates, mainly due to the inclusion of ramie fibers, which enhance interfacial adhesion and delay crack propagation. Failure during the impact test typically initiates with fiber–matrix debonding, followed by crack growth, fiber breakage, and pull-out. Overall, the presence of ramie fibers improves bonding quality and energy absorption, leading to higher impact performance [29].

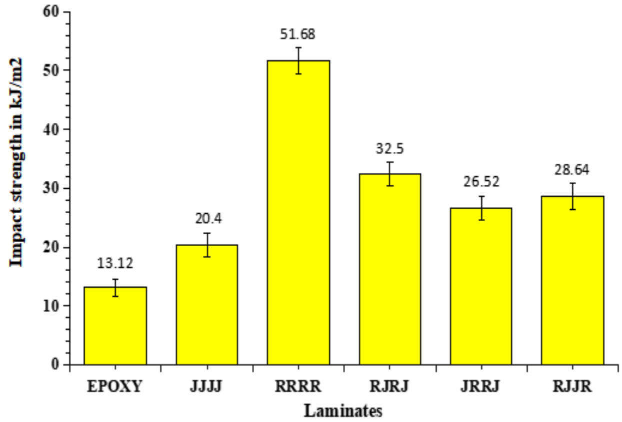


Fig. 6. Impact strength of single and hybrid natural filler composites.

4.6 Micro-hardness test

Hardness is a crucial property that reflects a composite's ability to resist permanent deformation or surface damage. In this work, microhardness was measured by applying an indentation load perpendicular to the fiber orientation, as illustrated in Figure 7. The RRRR laminate exhibited the highest hardness value (79 Hv) due to the superior stiffness of ramie fibers, while the JJJJ laminate showed the lowest hardness (52 Hv), reflecting the softer nature of jute fibers. Hybrid laminates demonstrated intermediate hardness values of 65, 59, and 61Hv for RJRJ, JRRJ, and RJJR, respectively. These results indicate that ramie reinforcement enhances indentation resistance and improves load transfer within the matrix. The improved hardness in hybrid composites is attributed to better compaction during loading, effective matrix–fiber contact, and the higher modulus. contribution from ramie fibers, which collectively increase surface resistance to deformation [30].

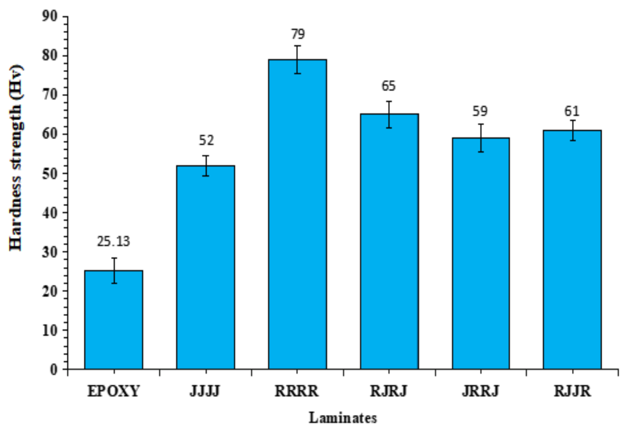


Fig. 7. Hardness test of single and hybrid composites.

4.7 Water absorption test

The Figure 8 shows that all laminates absorb more water as soaking time increases from 1 to 28 days, but the rate and magnitude vary with stacking sequence. Weight gain rises from about 2.6–2.9% at 1 day to roughly 7.5–8.1% at 28 days for all sequences, indicating typical Fickian-type diffusion in jute/ramie epoxy laminates reported in literature [31]. The curves are almost parallel, suggesting that soaking time is the dominant factor, while fiber layup has a secondary effect. At every time point, the fully jute laminate (JJJJ) shows the highest water uptake (2.9%, 6.1%, 7.2%, 8.1%), consistent with jute's higher hemicellulose and lignin content and hence higher hydrophilicity compared to ramie.

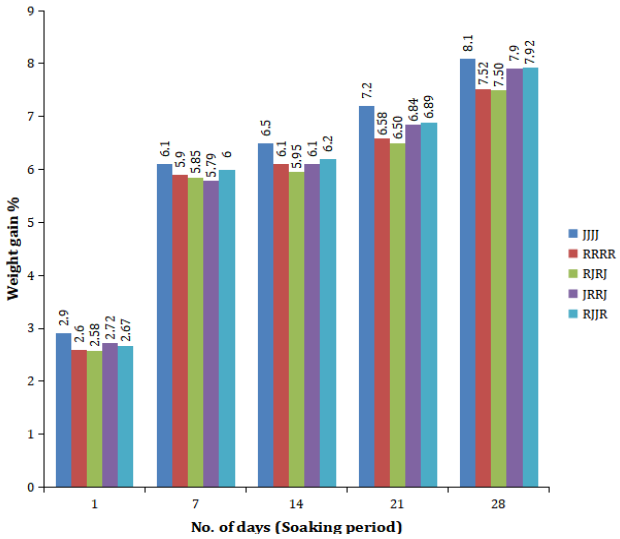
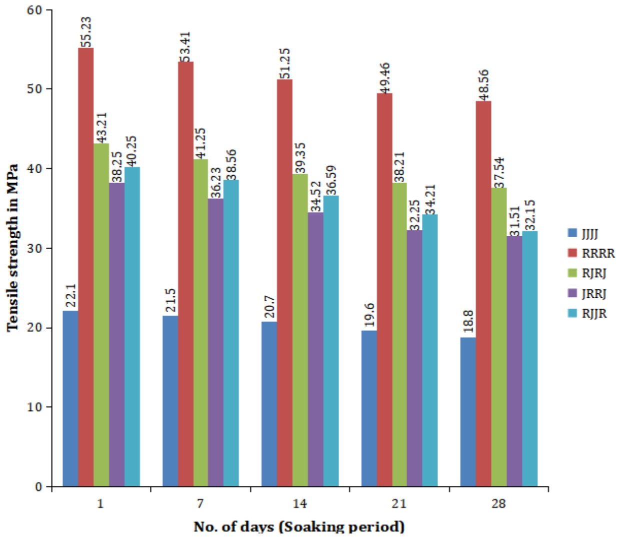


Fig. 8. Water absorption of single and hybrid composites.

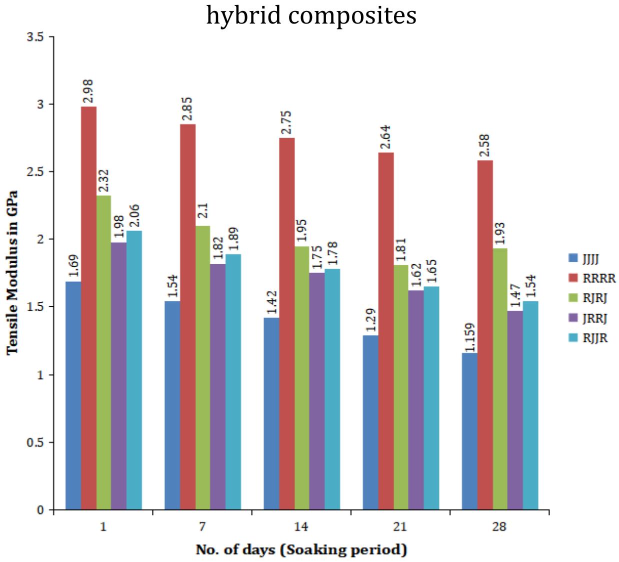
The fully ramie laminate (RRRR) consistently shows the lowest absorption (2.6%, 5.9%, 6.58%, 7.52%), matching reports that ramie, with higher cellulose and lower amorphous content, takes up less moisture than jute. Hybrid sequences (RJRJ, JRRJ, RJJR) lie between JJJJ and RRRR at each soaking time, confirming that combining ramie with jute can reduce overall water uptake relative to pure jute while still using jute as a partial reinforcement. The small differences among the three hybrid layups suggest that total ramie/jute content influences moisture uptake more strongly than the exact ply order, though outer layer choice (e.g., ramie faced vs jute faced) may slightly affect early time absorption. Among all compositions, the 50% sisal / 50% PALF hybrid shows the lowest moisture uptake, while still keeping good mechanical properties, making it the best compromise for applications where water resistance is important [32]. Hybridizing EFB (empty fruite bunches) composites with woven jute improves fibre–matrix adhesion, which lowers water absorption and thickness swelling compared with jute-only laminates. The epoxy matrix further limits moisture uptake due to its inherent water-resistant nature [33].

4.8 Tensile strength and modulus of water absorption of single and hybrid composites

Strength decreases because the specimens absorb more water at longer soaking times, and swelling occurs as a higher number of micro-cracks forms. When axial loads act on the specimens, they weaken the fibre–matrix interface. Figure 9 (a) and (b) show the tensile strength and modulus after immersion.



(a) Tensile strength of water absorption of single and hybrid composites



(b) Tensile Modulus of water absorption of single and hybrid composites

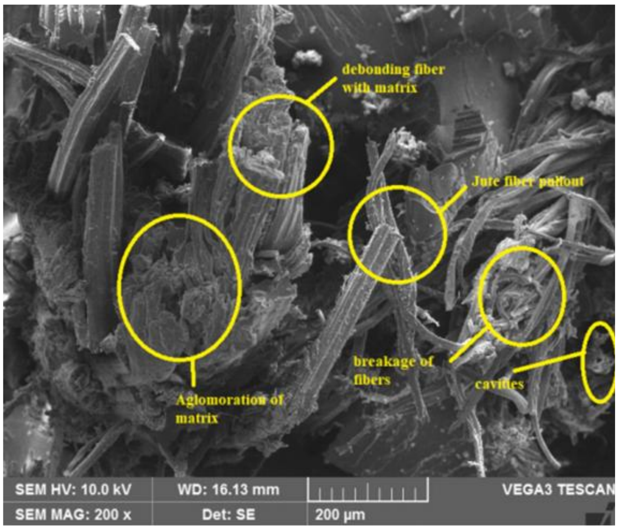
Fig. 9. Tensile strength and modulus of Water absorption of single and hybrid composites.

The result illustrates how water molecules penetrate and move by capillary action through the micro-cracks, especially at the specimen surface. For the four-layer single jute fibre composite, tensile strength decreases by 21% from 23.8 MPa (dry) to 18.80 MPa (28-day immersion), while tensile modulus drops by 33% from 1.73 GPa to 1.159 GPa. For ramie, tensile strength and modulus decrease by 15% and 21%, from 57.14 MPa to 48.56 MPa and from 3.20 GPa to 2.528 GPa, respectively. Jute shows a relatively higher percentage reduction in tensile strength and modulus than ramie. The hydroxyl and other polar groups present in jute fibre make the composite strongly hydrophilic [34], causing incompatibility and low wettability with the hydrophobic polymer matrix and, consequently, weak interfacial properties [35]. The hybrid jute–ramie composites show 17–24% and 23–30% reductions in tensile strength and modulus, respectively. This study concludes that hybrid jute–ramie reinforced epoxy improves the composite's water-resistance, which in turn enhances tensile strength and modulus compared with single jute fibre composites.

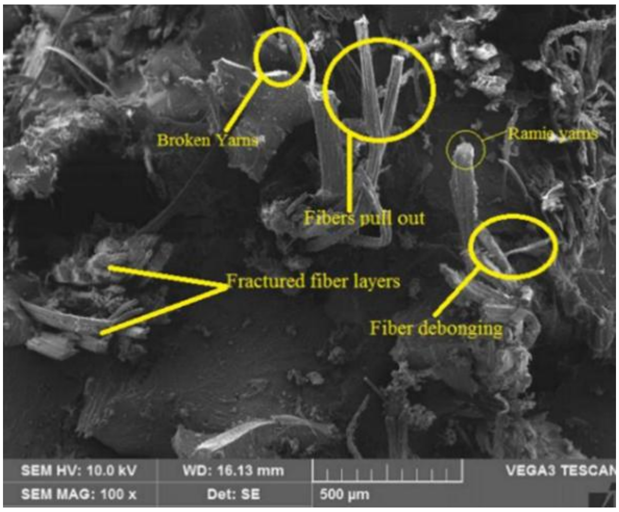
These composites typically gain 3-8% weight in water after prolonged exposure, as cellulose in ramie and lignin in jute attract moisture via hydrogen bonding. This swells fibers, weakens fiber-matrix bonds, and drops tensile strength by 15-30% while increasing ductility slightly. Moisture leads to hydrolysis of epoxy matrix and interfacial debonding, accelerating creep and fatigue failure under cyclic loads. In outdoor applications, UV aging further embrittles fibers, reducing impact toughness by up to 40% over 6-12 months. Long-term aging shows initial stiffening from post-cure, followed by 20-25% modulus loss after 1-year immersion due to plasticization. Hybrid stacking improves resistance somewhat via balanced properties, but treatments like alkali or silane are essential for automotive or structural viability.

4.9 Surface morphology

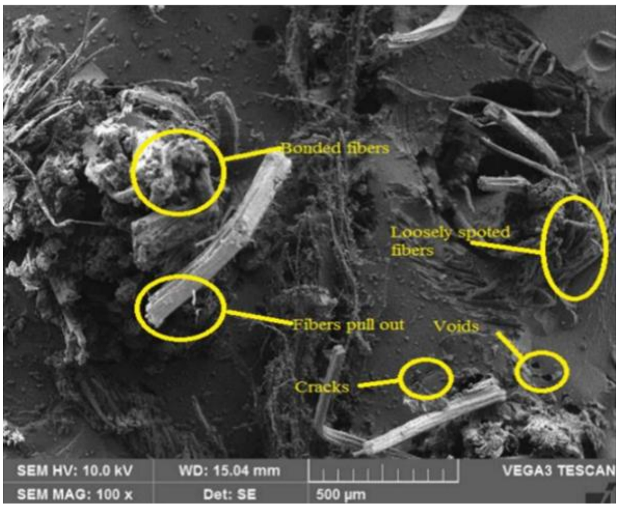
Figure 10a–e presents the SEM images illustrating the tensile fracture morphology of composites reinforced with single jute, single ramie, and hybrid jute–ramie fibers. SEM -out, matrix cracking, void formation, and interfacial debonding play a crucial role in determining the degree of adhesion between the fibers and the polymer matrix [36].



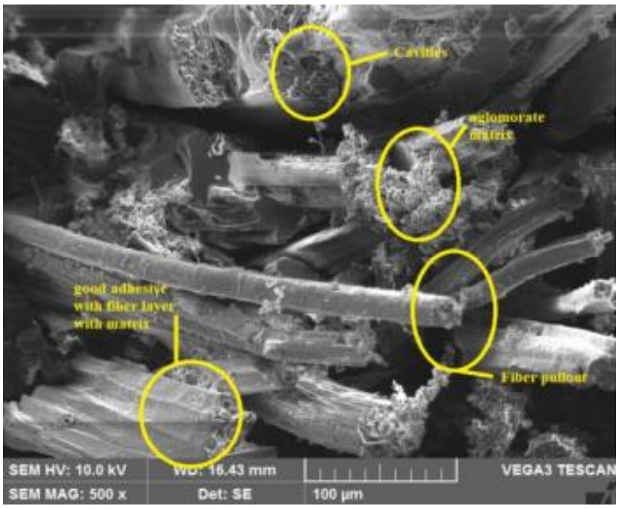
(a) JJJJ composite



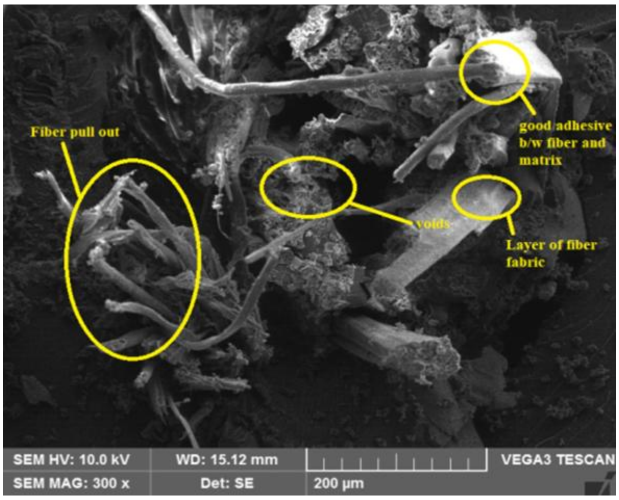
(b) RRRR composite



(c) RJRJ hybrid composite



(d) RJJR hybrid composite



(e) JRRJ hybrid composite

Fig. 10. SEM images tensile test of single and Hybrid fiber composites.

Figure 10 a depicts that in the single four-layer jute composite, fiber pull-out and interfacial debonding are evident on the fractured surface. Fiber pull-out is recognized as one of the primary failure mechanisms in natural fiber-reinforced polymer composites (NFRPCs) subjected to tensile loading [37]. Debonding, on the other hand, indicates the extent of fiber embedding within the matrix [38]. The SEM micrograph reveals poor interfacial bonding between the jute fibers and the epoxy resin, which corresponds to the relatively low tensile strength of 23.8 MPa. Similar findings have shown that woven jute-reinforced polyester composites exhibit lower damage resistance and tolerance compared to jute/glass hybrid laminates [39]. Figure 10b reveals that the single ramie composite exhibits less fiber pull-out than the jute composite, indicating a stronger interfacial bond between ramie fibers and the epoxy matrix and resulting in a higher tensile strength of 57.14 MPa. The SEM images of hybrid jute–ramie composites (Figure 10c–e) show that configurations with ramie on the outer layers, such as RJRJ and RJJR, display reduced fiber pull-out compared to JRRJ. Overall, all hybrid stacking arrangements demonstrated improved tensile performance relative to the single jute composite. The growing use of natural fiber hybrids is largely due to their capability to enhance the mechanical characteristics of composites [40].

Fiber pullout dominates in jute-rich layers, indicating poor matrix adhesion due to hydrophilic surfaces and voids, which correlates with 15-25% lower interlaminar shear strength. Matrix cracking and delamination appear at interfaces, linked to high void content (2-4%) from hand lay-up, reducing flexural modulus by 20%. River marks and hackles on ramie fibers signal brittle cleavage, supporting higher tensile strength (up to 50 MPa) but sensitivity to misalignment, which drops impact energy by 30% in misaligned hybrids. Good hybrids show fewer gaps and more fibrillation, explaining their 10-15% better toughness via balanced load transfer. SEM analysis of fractured surfaces from tensile, flexural, and impact tests reveals key failure mechanisms that directly explain the observed mechanical performance variations across ramie/jute hybrid layups.

5. CONCLUSION

The experimental investigation into the physical and mechanical characteristics of ramie/jute fiber-reinforced epoxy hybrid composites yielded the following findings:

- Epoxy composite specimens reinforced with ramie, jute, and ramie/jute hybrid woven fibers treated with NaOH solution were fabricated successfully using a straightforward hand lay-up process.
- The composite properties were significantly influenced by fiber loading. In single-fiber composites, the void content increased (2.523% for JJJJ and 2.122% for RRRR), whereas in the hybrid composite (1.158% for RJRJ), it decreased due to enhanced fiber–matrix interfacial bonding.

- Both tensile and flexural strengths improved with hybrid fiber incorporation (RJRJ: 45.23 MPa) and declined with other hybrid and higher jute fiber concentration (JJJJ: 23.8 MPa). These trends are associated with improved wetting, fiber arrangement, minimal entanglement, and efficient stress transfer between the fibers and the matrix.
- The ramie/jute hybrid composite (RJRJ) demonstrated the highest interlaminar shear strength of 67.82 MPa, compared with other hybrid and 46.68 MPa for the single jute composite. Its impact strength (32.5 kJ/m^2) and microhardness (65 Hv) also exceeded those of the jute composite (20.4 kJ/m^2 and 52 Hv, respectively). Water abosrption is also shown in less compare to other hybrid and single jute composites. The high strength and modulus ramie fibre provided at the top and middle layers withstood the applied load.

The RJRJ stacking sequence exhibited the highest mechanical strength among the hybrid composites. Stacking configuration plays a key role in determining composite performance. Based on the results, the hybrid composite is suitable for non-structural industrial applications, such as interior components in automotive and furniture products. Although they have some issues, such as absorbing moisture, producing odor, and low weather resistance, researchers have to work on to reduce these problems and improve their performance.

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REFERENCES

[1] C. Thiyagu and U. Narendrakumar, “Mechanical and ballistic performance of ramie fiber-reinforced polymer composites: A review,” *Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science*, vol. 238, no. 15, pp. 7661–7675, Feb. 2024, doi: 10.1177/09544062241230224.

[2] P. S. Khoo *et al.*, “Tensile properties of ramie fibre: Effect of harvesting day and extraction method,” *Materials Today Proceedings*, Apr. 2023, doi: 10.1016/j.matpr.2023.04.247.

[3] A. P. Wulandari *et al.*, “Tensile Strength Improvements of Ramie Fiber Threads through Combination of Citric Acid and Sodium Hypophosphite Cross-Linking,” *Materials*, vol. 16, no. 13, p. 4758, Jun. 2023, doi: 10.3390/ma16134758.

[4] A. Samir, F. H. Ashour, A. a. A. Hakim, and M. Bassyouni, “Recent advances in biodegradable polymers for sustainable applications,” *Npj Materials Degradation*, vol. 6, no. 1, Aug. 2022, doi: 10.1038/s41529-022-00277-7.

[5] S. O. Handika *et al.*, “Enhancing thermal and mechanical properties of ramie fiber via impregnation by Lignin-Based polyurethane resin,” *Materials*, vol. 14, no. 22, p. 6850, Nov. 2021, doi: 10.3390/ma14226850.

[6] D. K. Debeli, M. Tebyetekerwa, J. Hao, F. Jiao, and J. Guo, “Improved thermal and mechanical performance of ramie fibers reinforced poly(lactic acid) biocomposites via fiber surface modifications and composites thermal annealing,” *Polymer Composites*, vol. 39, no. S3, Mar. 2018, doi: 10.1002/pc.24844.

[7] C. Liu, D. Zou, Q. Huang, S. Li, X. Zheng, and X. Li, “Optical and mechanical properties of RaMIe Fiber/Epoxy Resin transparent composites,” *Journal of Renewable Materials*, vol. 11, no. 10, pp. 3613–3624, Jan. 2023, doi: 10.32604/jrm.2023.028111.

[8] T. Raja *et al.*, “Dynamic Mechanical Analysis of Banyan/Ramie Fibers Reinforced with Nanoparticle Hybrid Polymer Composite,” *Advances in Polymer Technology*, vol. 2022, pp. 1–10, Aug. 2022, doi: 10.1155/2022/1560330.

[9] M. R. A. Refaai, S. Narayanasamy, V. C. Das, D. V. S. S. S. V. Prasad, N. Nalini, and S. Thanappan, “Mechanical properties of Ramie/HEMP hybrid composites influenced by stacking arrangement and NAOH treatment,” *Advances in Polymer Technology*, vol. 2022, pp. 1–9, May 2022, doi: 10.1155/2022/8737669.

[10] H. Ahmad *et al.*, “Investigating mechanical properties of composites reinforced with jute/cotton natural fibers in hybridized epoxy/vinylester and epoxy/polyester resins,” *Polymer Composites*, vol. 46, no. 10, pp. 9400–9409, Feb. 2025, doi: 10.1002/pc.29565.

[11] C. Tezara *et al.*, “The effect of hybridisation on mechanical properties and water absorption behaviour of woven Jute/Ramie reinforced epoxy composites,” *Polymers*, vol. 13, no. 17, p. 2964, Aug. 2021, doi: 10.3390/polym13172964.

[12] G. Sathishkumar *et al.*, "Experimental study on mechanical performance and microstructural characterization of optimized sisal fiber reinforced polyester composites," *Scientific Reports*, vol. 15, no. 1, p. 36348, Oct. 2025, doi: 10.1038/s41598-025-20177-5.

[13] Balamurugan, R. Girimurugan, M. Muthuraj, S. K. H. Ahammad, N. Vijayakumar, and M. Appadurai, "Experimental study of mechanical properties of sisal/jute fibers hybrid sandwich composite," *Materials Today Proceedings*, vol. 68, pp. 1742–1749, Jan. 2022, doi: 10.1016/j.matpr.2022.09.437.

[14] Md. Z. Islam, E. C. Sabir, and Md. Syduzzaman, "Experimental investigation of mechanical properties of jute/hemp fibers reinforced hybrid polyester composites," *SPE Polymers*, vol. 5, no. 2, pp. 192–205, Jan. 2024, doi: 10.1002/pls2.10119.

[15] R. V. Patel, A. Yadav, and J. Winczek, "Physical, mechanical, and thermal properties of natural Fiber-Reinforced epoxy composites for construction and automotive applications," *Applied Sciences*, vol. 13, no. 8, p. 5126, Apr. 2023, doi: 10.3390/app13085126.

[16] V. Raghunathan *et al.*, "Influence of Chemical Treatment on the Physico-mechanical Characteristics of Natural Fibers Extracted from the Barks of Vachellia Farnesiana," *Journal of Natural Fibers*, vol. 19, no. 13, pp. 5065–5075, Feb. 2021, doi: 10.1080/15440478.2021.187535.

[17] J. Tengsuthiwat, V. A, V. R, Y. G. T. G, S. M. Rangappa, and S. Siengchin, "Characterization of novel natural cellulose fiber from Ficus macrocarpa bark for lightweight structural composite application and its effect on chemical treatment," *Heliyon*, vol. 10, no. 9, p. e30442, Apr. 2024, doi: 10.1016/j.heliyon.2024.e30442.

[18] P. Alam, C. Robert, and C. M. Ó. Brádaigh, "Tidal turbine blade composites - A review on the effects of hygrothermal aging on the properties of CFRP," *Composites Part B Engineering*, vol. 149, pp. 248–259, May 2018, doi: 10.1016/j.compositesb.2018.05.003.

[19] B. A. Praveena *et al.*, "Investigation of moisture absorption and mechanical properties of natural fibre reinforced polymer hybrid composite," *Materials Today Proceedings*, vol. 45, pp. 8219–8223, Jan. 2021, doi: 10.1016/j.matpr.2021.04.254.

[20] Y. K. Yadav, G. Dixit, and S. Dixit, "Natural fiber reinforced rPET/polyester composites: a review on development, mechanical performance, and sustainable management," *Polymer-Plastics Technology and Materials*, vol. 62, no. 14, pp. 1823–1843, Jul. 2023, doi: 10.1080/25740881.2023.2237100.

[21] V. Raghunathan *et al.*, "Influence of Chemical Treatment on the Physico-mechanical Characteristics of Natural Fibers Extracted from the Barks of Vachellia Farnesiana," *Journal of Natural Fibers*, vol. 19, no. 13, pp. 5065–5075, Feb. 2021, doi: 10.1080/15440478.2021.187535.

[22] G. B. Vaggar, E. C. Dsouza, A. D. Kamath, S. Bhat, and P. D, "Mechanical Characterization and Engineering Applications of Kapok & Kenaf Fiber Based Materials: A Review," *Journal of Advance And Future Research*, vol. 3, no. 7, Jan. 2025, doi: 10.56975/jaafr.v3i7.500605.

[23] P. Jagadeesh, M. Puttegowda, Y. G. T. Girijappa, S. M. Rangappa, and S. Siengchin, "Carbon fiber reinforced areca/sisal hybrid composites for railway interior applications: Mechanical and morphological properties," *Polymer Composites*, vol. 43, no. 1, pp. 160–172, Oct. 2021, doi: 10.1002/pc.26364.

[24] Md. H. Hasan *et al.*, "Synergistic effect of chemically treated eco-friendly Luffa and glass fiber reinforcement for layered hybrid polymer composites: A novel approach," *SPE Polymers*, vol. 6, no. 2, Feb. 2025, doi: 10.1002/pls2.70007.

[25] G. S. Kumar *et al.*, "Mechanical and Dynamic Properties of Banana Fiber-Reinforced Polyester Composites: A Multi-Analytical Characterization Study," *Engineering Reports*, vol. 7, no. 6, Jun. 2025, doi: 10.1002/eng2.70200.

[26] T. O. Ogundana, B. O. Bolaji, O. T. Oginni, F. A. Onuh, I. A. Olumoroti, and M. O. Olagunju, "Effect of treatment processes on the morphology and mechanical properties of natural Fiber-Reinforced epoxy composites," *Journal of Engineering Research Innovation and Scientific Development*, vol. 3, no. 1, pp. 72–81, Mar. 2025, doi: 10.61448/jerisd31257.

[27] S. S. Kumar *et al.*, "Investigation and machine learning-based prediction of mechanical properties in hybrid natural fiber composites," *Scientific Reports*, vol. 15, no. 1, p. 33700, Sep. 2025, doi: 10.1038/s41598-025-18944-5.

[28] G. Subbiah *et al.*, "Effect of porcelain particles on sisal/ramie fibre-reinforced hybrid polymer composites: Antibacterial and structural analysis," *Results in Engineering*, vol. 27, p. 105831, Jun. 2025, doi: 10.1016/j.rineng.2025.105831.

[29] R. Y. Venkataravanappa, A. Lakshmikanthan, N. Kapilan, M. P. G. Chandrashekarappa, O. Der, and A. Ercetin, "Physico-Mechanical property evaluation and morphology study of Moisture-Treated Hemp–Banana Natural-Fiber-Reinforced green composites," *Journal of Composites Science*, vol. 7, no. 7, p. 266, Jun. 2023, doi: 10.3390/jcs7070266.

[30] M. M. Hossain, P. K. Singha, H. T. Sadia, H. Rahman, T. Islam, and A. K. Das, "Mechanical properties of raw jute and coir Fiber-Reinforced Polyester composites through Fiber orientation: A study on tensile, impact, and hardness Characteristics," *Mechanics of Composite Materials*, vol. 61, no. 1, pp. 53–66, Feb. 2025, doi: 10.1007/s11029-025-10261-2.

[31] P. Ghabezi and N. M. Harrison, "Hygrothermal deterioration in carbon/epoxy and glass/epoxy composite laminates aged in marine-based environment (degradation mechanism, mechanical and physicochemical properties)," *Journal of Materials Science*, vol. 57, no. 6, pp. 4239–4254, Jan. 2022, doi: 10.1007/s10853-022-06917-2.

[32] B. A. Praveena *et al.*, "Investigation of moisture absorption and mechanical properties of natural fibre reinforced polymer hybrid composite," *Materials Today Proceedings*, vol. 45, pp. 8219–8223, Jan. 2021, doi: 10.1016/j.matpr.2021.04.254.

[33] Y. K. Yadav, G. Dixit, and S. Dixit, "Natural fiber reinforced rPET/polyester composites: a review on development, mechanical performance, and sustainable management," *Polymer-Plastics Technology and Materials*, vol. 62, no. 14, pp. 1823–1843, Jul. 2023, doi: 10.1080/25740881.2023.2237100.

[34] P. S. Khoo *et al.*, "Sustainable chemically treated lignocellulosic pineapple leaf fibre-reinforced polymer composites: mechanical properties, environmental aspects and applications," *Cellulose*, vol. 32, no. 7, pp. 4101–4142, Apr. 2025, doi: 10.1007/s10570-025-06519-6.

[35] Â. Pinto, D. Esteves, L. Nobre, J. Bessa, F. Cunha, and R. Fangueiro, "Mechanical performance enhancement in natural Fibre-Reinforced thermoplastic composites through surface treatment and matrix functionalisation," *Polymers*, vol. 17, no. 4, p. 532, Feb. 2025, doi: 10.3390/polym17040532.

[36] S. O. Amiandamhen, M. Meincken, and L. Tyhoda, "Natural fibre modification and its influence on fibre-matrix interfacial properties in biocomposite materials," *Fibers and Polymers*, vol. 21, no. 4, pp. 677–689, Apr. 2020, doi: 10.1007/s12221-020-9362-5.

[37] R. Várdai *et al.*, "Reinforcement of PP with polymer fibers: Effect of matrix characteristics, fiber type and interfacial adhesion," *Polymer*, vol. 190, p. 122203, Jan. 2020, doi: 10.1016/j.polymer.2020.122203.

[38] J. Yang, Y. Guo, L. Yao, and Y. Qiu, "Micromechanical modeling of water-induced interfacial failure of ramie fiber reinforced thermoplastic composites," *Composite Structures*, vol. 203, pp. 259–266, Jul. 2018, doi: 10.1016/j.compstruct.2018.07.011.

[39] J. Beter, B. Schrittesser, B. Maroh, E. Sarlin, P. F. Fuchs, and G. Pinter, "Comparison and impact of different fiber debond techniques on fiber reinforced flexible composites," *Polymers*, vol. 12, no. 2, p. 472, Feb. 2020, doi: 10.3390/polym12020472.

[40] M. Arulmurugan, A. S. Selvakumar, K. Prabu, and G. Rajamurugan, "Effect of barium sulphate on mechanical, DMA and thermal behaviour of woven aloevera/flax hybrid composites," *Bulletin of Materials Science*, vol. 43, no. 1, Jan. 2020, doi: 10.1007/s12034-019-2018-7.