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Research Paper

Sustainable Natural and Synthetic Fiber/Epoxy Composites: Mechanical Characterization and One-Way ANOVA Statistical Analysis

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It is now well recognized that the combination of natural and synthetic fibers in synergistic fiber-reinforced composite materials can greatly broaden their applications in engineering and technology. Natural fibers are gaining increasing attention because of their biodegradability, easy availability, durability, and resistance to corrosion, positioning them as eco-friendly substitutes for conventional materials. At the same time, fiber-reinforced composites are increasingly replacing metals in multiple sectors owing to their cost-effectiveness and energy efficiency. In this study, epoxy resin-based hybrid composites are prepared by incorporating glass, hemp and ramie fibers through the hand lay-up approach. The laminates are characterized for tensile, flexural, impact, and, hardness performance using ASTM standard methods. The greatest tensile strength, 73.10 MPa, is achieved in the glass/ramie fiber composite. The hybrid composites comprising glass, ramie, and hemp fibers exhibit enhanced flexural behavior of 18.22 MPa and impact resistance of 142.45 kJ/m^2. Among the tested configurations, the glass/ramie fiber composite recorded the highest hardness value of 27.73 HV. Overall, the findings highlight that glass/ramie/hemp fiber-mixed epoxy composite materials can serve as prospective eco-friendly substitutes for conventional synthetic composites in non-structural applications, such as automotive interiors, by offering a balance of good mechanical performance and sustainability.

Keywords: hybrid composite, natural and synthetic fibers, mechanical properties, glass, ramie, hemp, hand lay-up method.

1. Introduction

Recent studies have highlighted the advanced mechanical performance of natural fiber-reinforced composite materials compared to their man-made counterparts. Owing to their inherent material characteristics, natural fibers have demonstrated enhanced behavior in key mechanical domains, including tensile strength, flexural performance, and impact resistance. Prior investigations have systematically evaluated these properties in polymer composites that incorporate both natural and synthetic reinforcements, considering variations in fiber type and content, as reported by Kemparaju *et al.* [1]. Sapuan *et al.* [2] reported notable improvements in mechanical performance through fiber hybridization, alongside reductions in environmental impact. Their study utilized banana fibers, an agricultural byproduct readily available in tropical regions such as South India and Malaysia, as reinforcement in epoxy-based composites. This approach not only leveraged the mechanical potential of natural fibers but also promoted sustainable material sourcing. In contrast to synthetic fibers, natural fibers present distinct advantages including commendable mechanical performance and superior environmental sustainability. Prior investigations have examined maximum stress responses in two principal orientations, together with the corresponding maximum deflection under varying loading conditions. These evaluations were conducted using three different specimen geometries, thereby facilitating a comparative analysis of mechanical behavior as influenced by variations in Young's modulus.

Recent investigation has increasingly emphasized the enhanced mechanical performance and eco-friendly characteristics of natural fiber-reinforced composites over their synthetic counterparts. Aravinth *et al.* [3] assessed the mechanical characteristics of epoxy composites developed with hybrid hemp/glass fiber reinforcement. The outcomes demonstrated that the hybrid laminates achieved notable enhancements in impact resistance and flexural behavior, surpassing the performance of composites relying solely on synthetic fibers. The addition of natural fibers not only improved energy absorption and toughness but also facilitated a more uniform stress distribution, thereby mitigating crack initiation and propagation under mechanical loading. Kandola *et al.* [4] emphasized the dual advantages of bio-based composites, showcasing both their mechanical viability and environmental sustainability. According to their findings, the integration of natural reinforcement such as flax, jute, and hemp into polymer composites led to a marked decrease in carbon emissions, without compromising the mechanical properties relative to traditional man-made fiber-based composite materials. Thapliyal *et al.* [5] found that incorporating natural fibers such as jute into glass fiber composites significantly enhanced tensile and impact strength. This improvement supports their suitability for superior structural applications. Mahakur *et al.* [6] highlighted that incorporating banana fibers into glass fiber composite materials promoted biodegradability while simultaneously providing comparable flexural strength and durability. Their results support the use of such composites in practical engineering applications. Islam *et al.* [7] revealed that combining sisal with carbon fibers produced composites with lower density and greater toughness, highlighting their potential for lightweight structural applications. By increasing impact resistance and energy-absorbing capacity, natural fibers demonstrate the viability of bio-based composites as sustainable replacements for synthetic materials. In [8], the flexural and tensile characteristics of hybrid composites were significantly improved through the incorporation of glass fibers into natural reinforcements such as jute or sisal. In [9], composites reinforced with banana and sisal fibers with epoxy were explored, and their water absorption, flexural behavior, tensile characteristics, and impact resistance were assessed. The findings presented in [9] highlighted the mechanical viability of natural fiber composite materials across multiple performance metrics. Hybridizing ramie and silk fibers in a 1:3 ratio for epoxy composites resulted in a significant reduction in water uptake and a marked enhancement in mechanical strength [10]. This displays the effectiveness of natural fiber combinations in improving composite performance. Due to their biocompatibility, fast-growing natural fibers are gaining attention for use in cost-effective, eco-friendly, and technically demanding applications. Additionally, treatment of these fibers with NaOH under saturated conditions was found to increase their mechanical properties without compromising structural performance [11]. Yuanjian and Isaac [12] conducted fatigue testing to evaluate the performance of hemp-based nonwoven composites fabricated with polyester bonding. Bledzki *et al.* [13] examined how water absorption correlates with toughness, flexural property, specific gravity, and compressive strength, in hemp fiber-reinforced composite (HFRC)-based materials. The investigation by Kobayashi *et al.* [14] established hemp fiber as a superior reinforcement material in textile composites, with its performance markedly improved through micro-braiding techniques. Kabir *et al.* [15] reported that surface functionalization and environmental exposure markedly affect the structural and physical properties of both synthetic and natural fibers. Their study also showed that adding paper layers to unidirectional flax/epoxy and hemp/epoxy composites significantly enhanced tensile strength compared to composites without paper reinforcement. Aristri *et al.* [16] identified the optimal plant fiber blend for jute-reinforced polymer composites intended for automotive applications, considering key factors such as weight, functional performance, and cost efficiency. Torres *et al.* [17] proposed a hybrid composite consisting of ramie and hemp fibers with enhanced impact resistance, suitable for automotive components such as bumper beams. They also noted that optimizing structural parameters or material composition further improved impact performance.

This experimental investigation assesses the mechanical characteristics of epoxy-based materials reinforced with hemp, ramie and glass fibers. The specimens, produced through the hand lay-up approach, were subjected to mechanical testing to evaluate their tensile behavior, flexural performance, impact resistance and surface hardness. The results shows that the incorporation of hemp and ramie fibers significantly enhances the mechanical characteristics of glass fiber-reinforced composite materials.

2. Materials and methods

2.1. Materials

The composite laminates were fabricated using glass, hemp and ramie fibers as reinforcements within an epoxy resin matrix. Ramie and glass fibers were sourced from Vruksha Composites (Guntur, Andhra Pradesh, India), while hemp fibers, epoxy resin, and hardener HY951 were obtained from UltrananoTech Ltd. (Bengaluru, Karnataka, India). Figure 1 illustrates the raw fibers used, and Table 1 summarizes their key physical and mechanical properties.

a) b) c)

Fig. 1. Fibers used in the study: a) ramie fiber, b) hemp fiber, c) glass fiber.

Table 1. Mechanical characteristics of ramie and hemp fibers.

Properties	Ramie	Hemp
Density [g/cc]	1.52	1.4
Cellulose content [%]	52–57	48–52
Moisture content [%]	1.5–7.5	6-9
Young's modulus [GPa]	86	37

2.2. Fabrication technique

A conventional hand lay-up method was implemented for composite fabrication. To prevent adhesion to the mold surface, a teflon-coated sheet was placed at the base of the mold. The mold was first cleaned using abrasive paper to remove rust, followed by wiping with thinner and the application of teflon gel.

The reinforcement fibers were trimmed to the required dimensions and layered sequentially. Epoxy resin and hardener were mixed in a ratio of 10:1 to initiate curing and applied uniformly over each fiber layer using a roller to ensure proper wetting and adhesion. The hybrid laminates were constructed using three layers of glass fiber and two layers of natural fibers, arranged in an alternating sequence to ensure that glass fibers formed the outer layers. Three configurations were prepared: hemp/glass, ramie/glass, and hemp/ramie/glass composites. All laminates were cured under a constant load using a weighted press for 12 h to ensure uniform consolidation and optimal interfacial bonding.

3. Experimental framework

To design reliable composite structures, it is required to determine key mechanical characteristics such as stiffness and strength through targeted mechanical testing tailored to the specific material system. Adherence to ASTM standards ensures consistent evaluation procedures and facilitates accurate characterization of material behavior and performance.

3.1. Tensile behavior

Tensile samples were prepared in accordance with [22], the standard test method for evaluating the tensile behavior of composite laminates. For each laminate configuration, three samples were tested using a Universal Testing Machine (UTM), where tensile load was applied until fracture occurred. The procedure was repeated for all specimens and laminate configurations to determine the average tensile strength and corresponding stress values for comparative analysis.

3.2. Flexural behavior

Flexural test samples were prepared in accordance with [21], which outlines the standard procedure for analyzing the flexural characteristics of polymer composites. For each laminate type incorporating glass, hemp, and ramie fibers, three samples were tested using the UTM under a three-point bending configuration. During testing, both displacement and flexural strength were recorded to facilitate comparative analysis across the different composite systems. Figure 2 displays the prepared samples for mechanical testing, involving tensile, flexural, impact, and hardness evaluations.

3.3. Impact strength

To assess how the materials respond to sudden or dynamic loading, this study employs the impact behavior assessed using the Charpy V-notch test.

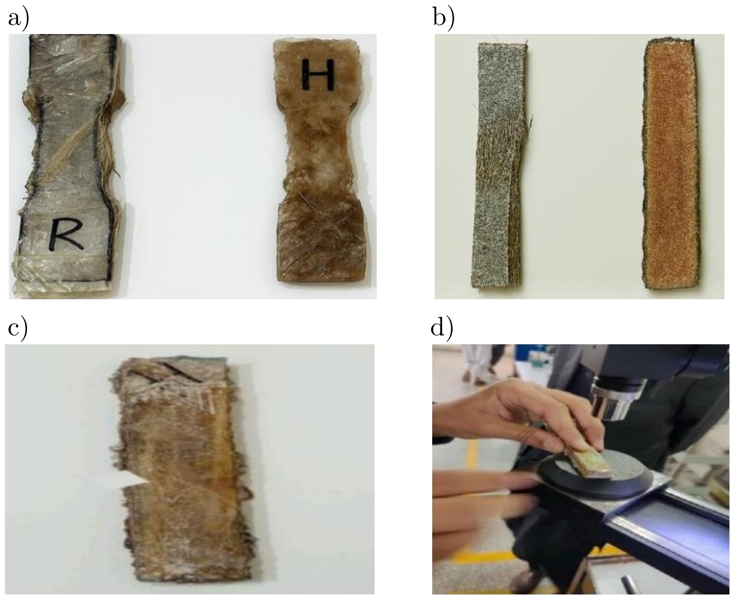

Fig. 2. Mechanical test specimens: a) tensile specimen, b) flexural specimen, c) impact specimen, d) hardness evaluation specimen.

This standardized procedure measures the energy absorbed by a specimen during fracture, thereby offering insight into its toughness under high strain-rate conditions. All specimens were prepared and tested in accordance with ASTM D6110 specifications.

3.4. Hardness test

Microhardness testing is commonly applied to materials such as metals, ceramics, and composites when conventional macro-scale hardness methods are unsuitable. This technique is particularly effective for examining hardness variations across a specimen cross-section, analyzing thin sheet-like materials, and evaluating localized microstructural features within a broader matrix. Typically, static loads of 1 kg or less are used to create small indentations, allowing precise measurement of surface hardness at the microscale.

4. Results and discussions

4.1. Tensile behavior study

The tensile behavior of the composite samples were tested using the UTM. During testing, the machine automatically generated a force-displacement curve, as illustrated in Fig. 3. The tensile behavior results of the different hybrid laminates are compared in Fig. 4. Among the tested samples, the ramie and glass

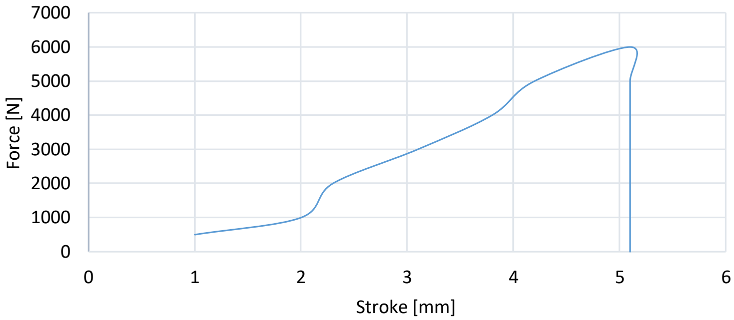

FIG. 3. Force-stroke curve obtained during tensile testing.

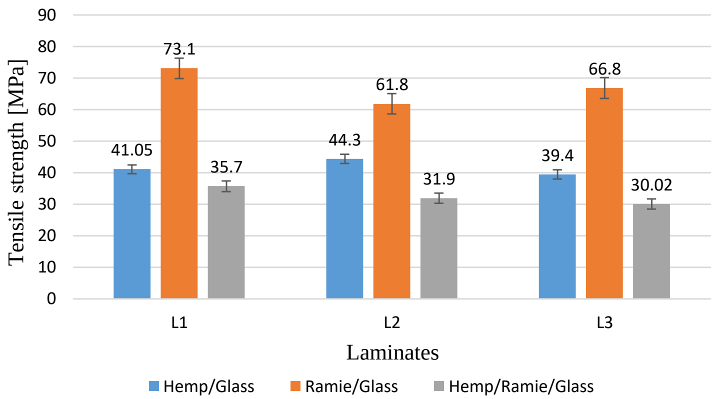

FIG. 4. Tensile strength performance of different hybrid fiber laminates.

fiber-reinforced composite showed an enhanced performance compared to the other laminate configurations. The tensile strength values of the three different laminate configurations: hemp/glass, ramie/glass, and hemp/ramie/glass were evaluated for three specimens (L1, L2, and L3). The results are summarized in the corresponding bar graph. The ramie/glass laminates consistently showed the highest tensile strength across all specimens, with 73.10 MPa for L1, 61.80 MPa for L2, and 66.80 MPa for L3. On average, this laminate achieved a tensile strength of 67.23 MPa, which is approximately 62 % higher than the average value of hemp/glass laminate (41.58 MPa) and more than double that of the hemp/ramie/glass laminate (32.54 MPa).

The hemp/glass laminates exhibited moderate tensile strength values ranging from 39.40 MPa to 44.30 MPa, with an average value of 41.58 MPa. This performance is about 27 % lower than that of ramie/glass laminate but 28 % higher than that of the hemp/ramie/glass laminate. The hemp/ramie/glass laminates recorded the lowest tensile strength, varying from 30.02 MPa to 35.70 MPa, with an average of 32.54 MPa. This indicates a reduction of nearly 52 % compared to the ramie/glass laminates. In terms of tensile performance, the ramie/glass composite demonstrates superior strength compared to the ramie/hemp/glass hybrid laminate. This enhancement is primarily attributed to the inherently more tensile capacity of glass fiber reinforcement relative to natural reinforcement including ramie and hemp. Since the tensile characteristics of a laminate is predominantly governed by the mechanical characteristics of its reinforcing constituents, a greater proportion of glass fibers contributes to improved load-bearing capability. Furthermore, the interfacial bonding between the matrix and the fibers plays a critical role in tensile behavior. Glass fibers exhibit stronger suitability with epoxy resins, facilitating more efficient stress transfer across the interface. In contrast, natural fibers such as hemp and ramie tend to have weaker adhesion with the matrix, making them more susceptible to fiber pull-out under tensile loading. This interfacial limitation reduces the overall tensile capacity of hybrid laminates consisting of both ramie and jute fibers, as reported by YANG *et al.* [18]. The adoption of hybrid laminate materials has experienced notable growth, driven by their environmentally sustainable characteristics, including recyclability, biodegradability, and reduced ecological impact [19].

TABLE 2. Tensile strength values of various composites.

Laminates	Hemp/glass [MPa]	Ramie/glass [MPa]	Hemp/ramie/glass [MPa]
L1	41.05	73.10	35.70
L2	44.30	61.80	31.90
L3	39.40	66.80	30.02
Average	41.58	67.23	32.54
Standard deviation	2.49	5.68	2.91

4.2. FLEXURAL BEHAVIOR STUDY

The flexural performance of the hybrid composite specimens was systematically evaluated, as presented in Table 3. During mechanical testing, the force–stroke response was recorded in real time, with representative curves illustrated in Fig. 5. A comparative analysis of the flexural strength across the various hybrid configurations is illustrated in Fig. 6. The outcomes indicate that composites reinforced with a combination of ramie, hemp, and glass fibers exhibit enhanced flexural resistance compared to those reinforced solely with hemp/glass or ramie/glass fiber systems. The flexural strength results show that the hemp/ramie/glass laminate achieve the highest strength with an average of 17.79 MPa, which is considered 100 % performance. In comparison, the ramie/glass laminate recorded an average of 9.74 MPa, corresponding to about 54.7 % of the maximum strength, while the hemp/glass laminate had the lowest avarage value of 8.49 MPa, equivalent to 47.7 % of the maximum strength.

Table 3. Flexural strength values of various composites.

Laminates	Hemp/glass [MPa]	Ramie/glass [MPa]	Hemp/ramie/glass [MPa]
L1	8.52	10.25	18.22
L2	8.88	8.89	17.74
L3	8.06	10.07	17.42
Average	8.49	9.74	17.79
Standard deviation	0.42	0.74	0.41

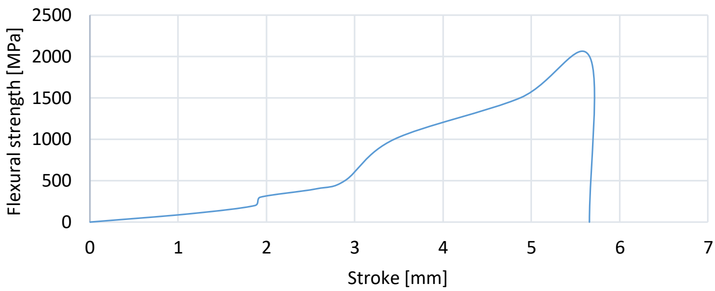

Fig. 5. Force-stroke curve obtained during flexural testing.

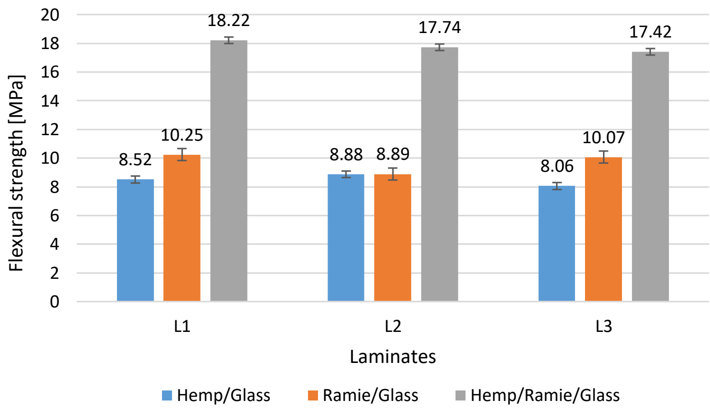

Fig. 6. Flexural strength performance of different hybrid fiber laminates.

The higher strength in the hemp/ramie/glass laminate is due to the synergistic effect of the three different fibers, where ramie adds stiffness, glass provides strength, and hemp improves flexibility, resulting in better stress distribution under bending loads. On the other hand, the hemp/glass laminate showed the lowest flexural strength because hemp fibers have relatively low stiffness, which limits their reinforcement capability. The ramie/glass laminate showed moderate strength, as ramie fibers have superior mechanical properties compared to hemp fibers; however, the absence of a third reinforcing fiber restricted its ability to distribute stress as effectively as the three-fiber hybrid laminate. The enhanced flexural and impact performance of the ramie/hemp/glass hybrid composites can further be attributed to the synergistic interaction among the constituent fibers. Each fiber type contributes distinct mechanical advantages: glass fibers impart high stiffness and impact resistance, while natural reinforcement such as hemp and ramie improve energy absorption and toughness.

These results exceed those reported by SAPUAN *et al.* [2], where flexural strength values ranging from $0.3\,\mathrm{kN/m^2}$ to $0.4\,\mathrm{kN/m^2}$ were achieved in epoxy composites reinforced with woven banana fibers. The superior performance observed in the current study highlights the effectiveness of mixed-fiber configurations in enhancing flexural behavior. This multi-fiber architecture facilitates more uniform stress distribution under flexural and impact loading conditions. Additionally, the natural fibers play a critical role in bridging microcracks and inhibiting their propagation, thereby improving the composite's ability to resist deformation and absorb dynamic loads [20]. Moreover, the strategic layering of hemp, ramie, and glass fibers within the hybrid composite enhances load-transfer efficiency. This architecture proves especially advantageous under flexural stress, as the outer glass fiber layers deliver structural rigidity, while the inner natural fibers, namely ramie and hemp, offer improved toughness and ductility. The complementary roles of these fibers contribute to a more resilient and adaptable composite structure capable of withstanding bending forces with a reduced risk of failure.

4.3. IMPACT STRENGTH ANALYSIS OF HYBRID COMPOSITES

This study incorporates impact testing using the Charpy technique to evaluate the load-bearing behavior and impact energy of several hybrid composite specimens. The absorbed energy was determined based on data recorded by the testing apparatus. Figure 7 illustrates the comparative impact strength across

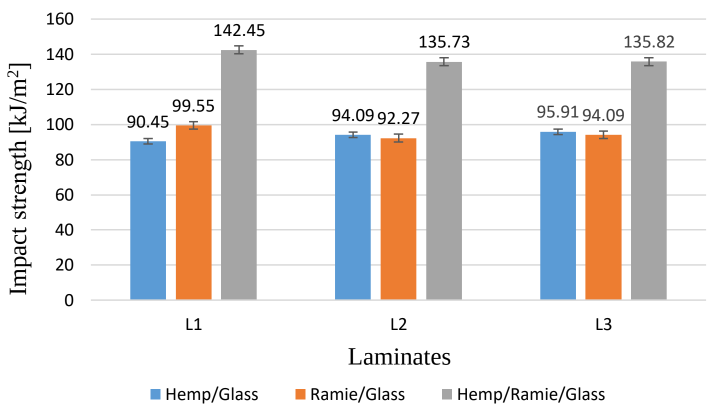

FIG. 7. Impact strength distribution among different hybrid laminate systems.

the different laminate configurations. Among them, the composite reinforced with hemp, ramie and glass fibers demonstrated superior impact resistance, reaching up to 142.45 kJ/m^2. Composites reinforced with glass and ramie fibers also showed comparable performance levels, as detailed in Table 4. Among the configurations, the hemp/ramie/glass composite demonstrated the highest impact resistance, with values ranging from 135.73 kJ/m^2 to 142.45 kJ/m^2, approximately 45 % to 50 % greater than the hemp/glass laminate and 40 % to 46 % higher than the ramie/hemp laminate. This enhanced performance is likely due to the combined effect of natural and synthetic fibers, which promotes better interfacial adhesion and improves the material's ability to absorb energy during sudden loading. Conversely, the hemp/glass laminate recorded the lowest impact strength, between 90.45 kJ/m^2 and 95.91 kJ/m^2, reflecting a reduction of about 36 % compared to the hemp/ramie/glass composite. This lower toughness may stem from the limited energy-dissipation capacity inherent to the dual-fiber system. The ramie/glass laminate exhibited intermediate values, ranging from 92.27 kJ/m^2 to 99.55 kJ/m^2, roughly 30 % to 33 % lower than those of the top-performing hybrid laminate. Its moderate behavior can be attributed to the predominance of natural fibers, which, although sustainable, offer lower resistance to crack propagation under impact loading. These findings underscore the effectiveness of integrating ramie fibers with hemp and glass fibers in enhancing the impact durability of epoxy-based hybrid laminates, making them promising candidates for implementations requiring high toughness and energy absorption. Natural fibers are increasingly being integrated into hybrid composite systems, offering a sustainable alternative to conventional materials. A growing body of research focuses on optimizing fiber hybridization to replace conventional metals and alloys in engineering advancements while maintaining structural integrity and cost efficiency. In the present study, composite laminates were fabricated by combining glass fibers with natural fibers such as ramie and hemp fibers. Test samples were subsequently prepared from these composites in accordance with ASTM standards to ensure consistency and reliability in mechanical evaluation. The hemp/ramie/glass fiber-reinforced composites developed in this study exhibited an impact strength of 142.45 kJ/m^2, closely aligning with the value

TABLE 4. Measured impact resistance across composite configurations.

Laminates	Hemp/glass [kJ/m^2]	Ramie/glass [kJ/m^2]	Hemp/ramie/glass [kJ/m^2]
L1	90.45	99.55	142.45
L2	94.09	92.27	135.73
L3	95.91	94.09	135.82
Average	93.48	95.30	138.00
Standard deviation	2.79	3.73	3.80

of 157.64 kJ/m^2 reported by BHOOPATHI *et al.* [23] and VENKATESHWARAN *et al.* [9] for banana-hemp-glass fiber laminates. This comparative performance underscores the mechanical robustness of the present hybrid configuration and reinforces its viability as a competitive alternative to previously investigated systems.

4.4. HARDNESS VALUE ANALYSIS

Figure 8 illustrates the Vickers hardness test results for composite specimens featuring various fiber combinations. Among the tested configurations, the ramie fiber-reinforced polymer composite exhibited the highest hardness value, reaching 27.73 HV. This performance notably surpasses that of the other laminates, as detailed in Table 5, thereby highlighting the effectiveness of ramie fibers in enhancing surface resistance. The hardness assessment revealed that the ramie/glass laminate exhibited the highest values, ranging from 26.12 HV to 27.73 HV, approximately 35 % to 40 % greater than that of the hemp/glass configuration and around 30 % higher than that the hemp/ramie/glass variant. This enhanced surface resistance is likely attributed to the robust interfacial bonding between ramie and glass fibers, which effectively limits localized defor-

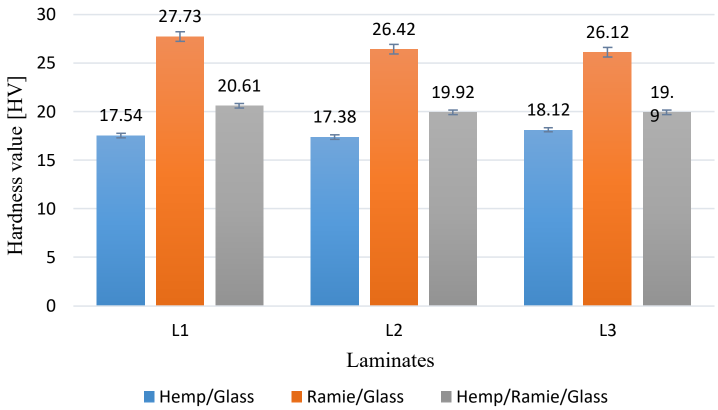

FIG. 8. Hardness performance of various hybrid composites.

TABLE 5. Hardness performance of hybrid composites.

Laminates	Hemp/glass [HV]	Ramie/glass [HV]	Hemp/ramie/glass [HV]
L1	17.54	27.73	20.61
L2	17.38	26.42	19.92
L3	18.12	26.12	19.90
Average	17.68	26.76	20.14
Standard deviation	0.39	0.83	0.40

mation under load. The hemp/ramie/glass laminate demonstrated intermediate hardness values, measured between 19.90 HV and 20.61 HV. While these values are 25 % to 28 % lower than those of the ramie/glass laminate, they remain 10 % to 15 % higher than those of the hemp/glass laminate. This moderate performance reflects the composite's balanced fiber architecture, where the reinforcing effect of ramie and glass fibers is partially offset by the relatively lower stiffness of hemp fibers. Among the tested laminates, the hemp/glass laminate recorded the lowest hardness, with values ranging from 17.38 HV to 18.12 HV approximately 36 % lower than those of the ramie/glass laminates and 10 % lower than the hybrid containing all three fibers. The reduced hardness is primarily due to the limited interfacial bonding and lower mechanical rigidity of hemp fibers, which restrict the material's resistance to indentation and surface wear. These findings suggest that the ramie/glass composites are particularly well suited for applications demanding high surface durability and resistance to concentrated mechanical stresses (see Table 6).

Table 6. Comparative values of tensile strength, flexural strength, impact resistance, and hardness for selected composites.

Composite type	Tensile behavior [MPa]	Flexural behavior [MPa]	Impact resistance [kJ/m^2]	Micro-hardness [HV]
Glass/ramie fiber-reinforced composite	73.10	10.25	99.55	27.73
Glass/hemp fiber-reinforced composite	44.30	8.88	95.91	18.12
Glass/hemp/ramie fiber-reinforced composite	35.70	18.22	142.45	20.61

4.5. Statistical analysis using one-way ANOVA

To evaluate whether the observed differences in tensile behavior, flexural behavior, impact resistance, and microhardness across the three composites are statistically significant one-way ANOVA was applied, and the corresponding F-statistics and p-values were computed to evaluate the significance of observed differences. A comprehensive overview of the statistical parameters is provided in Table 7.

4.5.1. Hypotheses

Null hypothesis (H_0): the mean values of mechanical properties such as tensile behavior, flexural behavior, impact resistance, and microhardness were found

TABLE 7. One-way ANOVA descriptive statistics for mechanical properties.

Property	Count	Mean value	Standard deviation (SD)	Minimum	25th percentile (Q1)	Median	75th percentile (Q3)	Maximum
Tensile behavior [MPa]	3	51.47	22.00	29.00	40.24	51.47	62.70	73.10
Flexural behavior [MPa]	3	12.15	6.00	6.00	9.08	12.15	15.22	18.22
Impact resistance [kJ/m^2]	3	95.30	47.15	47.15	71.23	95.30	119.37	142.45
Micro-hardness [HV]	3	18.61	9.12	9.12	13.86	18.61	23.47	27.73

to be similar across all composite types, indicating that the type of composite had no significant effect.

Alternative hypothesis (H_1): at least one composite type shows a statistically pronounced disparity in the mean values of the mechanical properties, suggesting that composite type influences the mechanical response.

4.6. MICROSTRUCTURE OF HYBRID FIBER-REINFORCED COMPOSITES

Hemp fibers are extracted from the matrix, leaving holes or cavities on the fracture surface, and glass fibers may remain partially bonded or protruding. The softer epoxy matrix surrounding hemp fibers cracks more easily, and gaps appear between fiber and matrix where debonding has occurred. The fracture is usually non-planar, hemp-rich regions show shear failure (diagonal cracking) while glass-rich regions show more brittle fracture with fiber breakage, as shown in Fig. 9a. Some ramie and glass fibers show clean breaks (transverse cracks), while others exhibit partial pull-out with attached matrix resin on the fiber surface, indicating strong fiber–matrix bonding. Fine cracks in the matrix radiate from broken fiber ends; voids or stress concentrations appear where fibers have debonded. Ramie/glass composites typically show flatter fracture surfaces than hemp/glass composites, with visible layering and fiber alignment dependent on the stacking sequence, as depicted in Fig. 9b. Figure 9c shows fiber pull-out, matrix crazing, rough texture, multiple microcracks radiating from hemp fiber breaks. A sharp, brittle transverse fracture is observed, with minimal pull-out, clean glass fiber ends, and little to no matrix deformation around glass fibers. Ramie and glass show good adhesion (resin attached to fiber), while hemp shows weaker adhesion [24, 25].

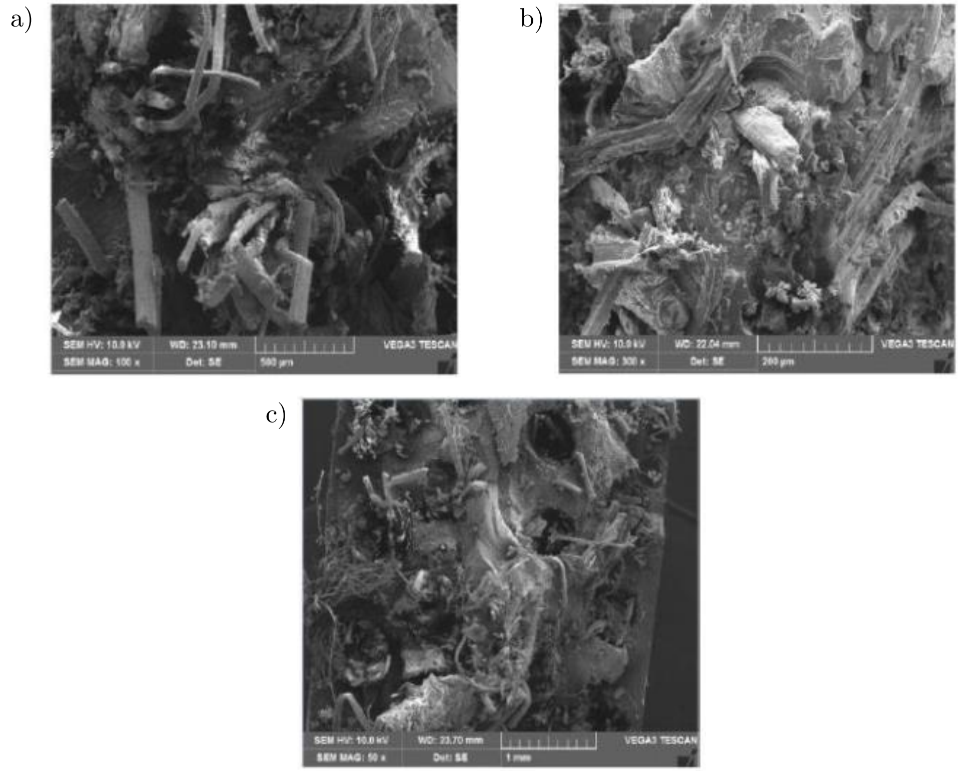

Fig. 9. SEM images of various hybrid composites:
a) hemp/glass, b) ramie/glass, c) hemp/ramie/glass.

5. Results

The calculated p-value is 0.0025, which is less than the established level of significance (0.05); therefore, the findings reject null hypothesis. This means that differences observed in mechanical characteristics, such as tensile behavior, flexural behavior, impact resistance, and hardness, among the various composite types are statistically significant. This result gives confidence that these variations may be due to fiber types rather than random variation.

6. Overall summary and interpretations

This study compared the mechanical characteristics: tensile behavior, flexural behavior, impact resistance, and microhardness of different hybrid composites made from glass/ramie, glass/hemp, and glass/hemp/ramie fibers. The tensile strength was highest in the glass/ramie composite (73.10 MPa), followed by glass/hemp (44.30 MPa), while the glass/hemp/ramie hybrid showed the lowest value (35.70 MPa). In contrast, flexural strength peaked in the glass/hemp/ramie hybrid (18.22 MPa), outperforming both glass/ramie and glass/hemp variants (10.25 MPa and 8.88 MPa, respectively). Impact strength exhibited a similar trend, with the glass/hemp/ramie composite achieving a significantly higher value (142.45 kJ/m^2) compared to glass/ramie composite (99.55 kJ/m^2) and glass/hemp composite (95.91 kJ/m^2). Hardness was greatest in the glass/ramie composite (27.73 HV), moderate in the hybrid (20.61 HV), and lowest in the glass/hemp configuration (18.12 HV). Statistical analysis using one-way ANOVA confirmed that the differences in flexural behavior, impact behavior, and microhardness across the composite types were statistically significant ($p < 0.05$), while variations in tensile strength were less pronounced. The outcomes emphasize the impact of fiber hybridization on mechanical performance and highlight the potential of multi-fiber composites for tailoring properties for specific engineering applications.

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Conflict of interest

The authors declare that there are no known competing financial interests or personal relationships that could have influenced the work described in this paper.

Authors' contributions

Sadashiva Kemparaju: conceptualization, methodology, and writing – original draft preparation. Bhanu Prathap Rangaswamy: methodology and writing – review and editing. Balaji Javaraiah: validation, resources, and writing – review and editing. Shwetha Mahadev, Rathika Murugan, Tarakeshwar Jane: resources and literature survey. All authors reviewed and approved the final manuscript.

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