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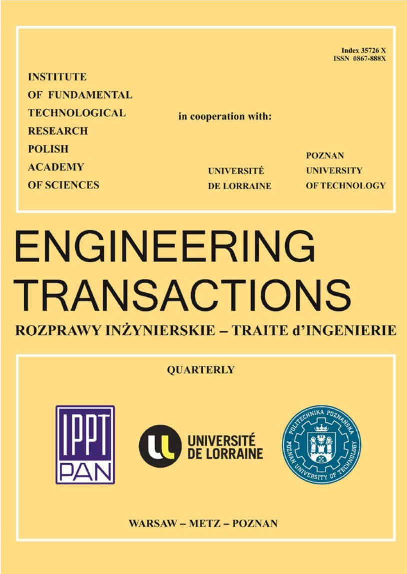

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Sustainable Natural and Synthetic fibers with Epoxy Composites of Mechanical Characterization and One-Way ANOVA Statistical Analysis

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It is now well recognized that the combination of natural and synthetic fibers in synergistic fiber composite materials can greatly broaden their applications in engineering and technology. Natural-fibers are gaining more consciousness because of their biodegradability, easy availability, durability, and resistance to corrosion, positioning them as an eco-friendly substitute 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. Epoxy resin-based hybrid composites were prepared by incorporating glass, hemp and ramie fibers through the hand layup approch. Laminates were characterized for tensile, flexural, impact, and hardness performance using ASTM standard methods. The greatest tensile strength, 73.10 MPa, was achieved in the glass/ramie fiber composite. The hybrid composites comprising glass, ramie, and hemp fibers exhibited enhanced flexural behavior of 18.22 MPa, impact resistance of 142.45 kJ/m². Among the tested configurations, the glass–ramie fiber composite recorded the highest hardness value of 27.73 HV. Overall, the determination highlight that glass-ramie-hemp fiber-mixed epoxy composite materials can serve as prospective eco-friendly substitute to 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 manmade counterparts. Owing to their inherent material characteristics, natural fibers have demonstrated enhanced behavior in key mechanical domains covering tensile strength, flexural performance, and impact resistance prior investigations have systematically evaluated these properties among polymer composites that incorporate both natural and synthetic reinforcements, considering variations in fiber type and content by SADASHIVA K, 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 a reinforcement in epoxy-based composites. This approach not only leveraged the mechanical potential of natural fibers but also promoted relevant 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 outcomes 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. Outcomes demonstrated that 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 but also 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 like flax, jute and hemp, in polymer composites led to a marked decrease in carbon emissions, without compromising mechanical properties relative to traditional man-made fiber–based composite materials. THAPLIYAL et al. [5] found that incorporating natural fibers like 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 Bio-assimilation while simultaneously providing commensurate flexural strength and Endurance. Their results support the use of such composites in practical engineering applications. ISLAM et al. [7] the study revealed that combining sisal with carbon fibers produced composites with lower density and greater toughness, highlighting their potential for lightweight structural uses. By increasing impact resistance and energy-absorbing capacity, natural fibers highlight the viability of bio-based composites as sustainable replacements for synthetic materials. MANJESH et al. [8] the flexural and tensile characteristics of hybrid composites was significantly improved by the incorporation of glass fibers to natural reinforcements like jute or sisal. VENKATESHWARAN et al. [9] Composites made from reinforced with banana and sisal fibers with epoxy were explored, and their water absorption, flexural, tensile characteristics and impact resistance were assessed. Their study 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 Provoked a significant diminish in water uptake and a marked enhancement in mechanical strength, SADASHIVA K, et al. [10] This displays the productiveness 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, treating these fibers with NaOH under saturated conditions revealed to increase their mechanical properties without compromising structural performance RAMESH, M et al. [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 HFRC-based composite materials. The investigated by KOBAYASHI et al. [14] established hemp fiber as a superior fibrous material in textile composites, with its performance markedly improved when integrated using micro-braiding. 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 showed that adding paper layers to unidirectional flax/epoxy and hemp/epoxy composites significantly enhanced tensile strength compared to those without paper reinforcement. ARISTRI M. A. 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 M. et al. [17] Proposed a hybrid composite 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 improves impact performance. This experimental investigation assesses for mechanical characteristics of epoxy based materials combined with hemp, ramie and glass fibers. However specimens, produced through the hand layup approach, were related to mechanical trial to judge their tensile behavior, flexural performance, and surface hardness. The performance shows that the constitution of hemp and ramie fibers significantly enhances the mechanical characteristics of glass fiber related 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 2.1 illustrates the raw fibers used, and Table 2.1 summarizes their key physical and mechanical properties.

2.2 Fabrication Technique

A conventional hand layup method was implemented for composite fabrication. To prevent adhesion to the mold surface, a Teflon-coated sheet was placed at the base. The mold was first cleaned using abrasive paper to remove rust, followed by a wipe-down with thinner and application of Teflon gel. 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 utilized 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 glass-fibers enclosed the outer appearance. Three configurations were prepared hemp-glass, ramie-glass and hemp-ramie-glass composites. All laminates were set through curing under a constant load using a weight press for 12 hours to ensure uniform consolidation and optimal interfacial bonding.

Table 1: Mechanical characteristics of ramie and hemp fibers

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

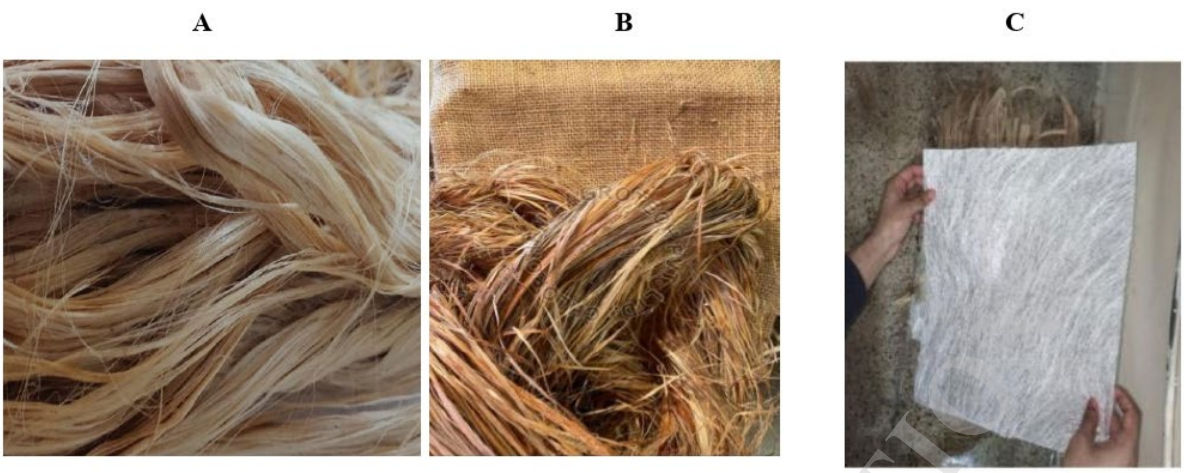


Fig. 1: **A.** Ramie fiber **B**. Hemp fiber **C**. Glass fiber

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.

1.1 Tensile Behavior

Tensile sample were equipped in accordance with ASTM-D638 ASTM [22], standards for evaluating the mechanical behavior of composite laminates. For each laminate configuration, three samples were tested using a Universal Testing Machine (UTM), where load was employed until fracture. The procedure was repeated across all specimens and laminate types to determine the average tensile strength and corresponding stress values for comparative analysis.

1.2 Flexural Behavior

Flexural test sample were exhibited in accordance with ASTM-D790 ASTM [21], which outlines the standard procedure for analyzing the flexural characteristics of polymer composites. For each laminate type combined with glass, hemp and ramie fibers three samples were conducted using a Universal Testing Machine UTM under a three-point bending configuration. During testing, both displacement and flexural strength were recorded to facilitate comparative analysis across different composite systems. Figure 3.1 displays the prepared samples for mechanical testing, involving the tensile, flexural, impact, and hardness evaluations.

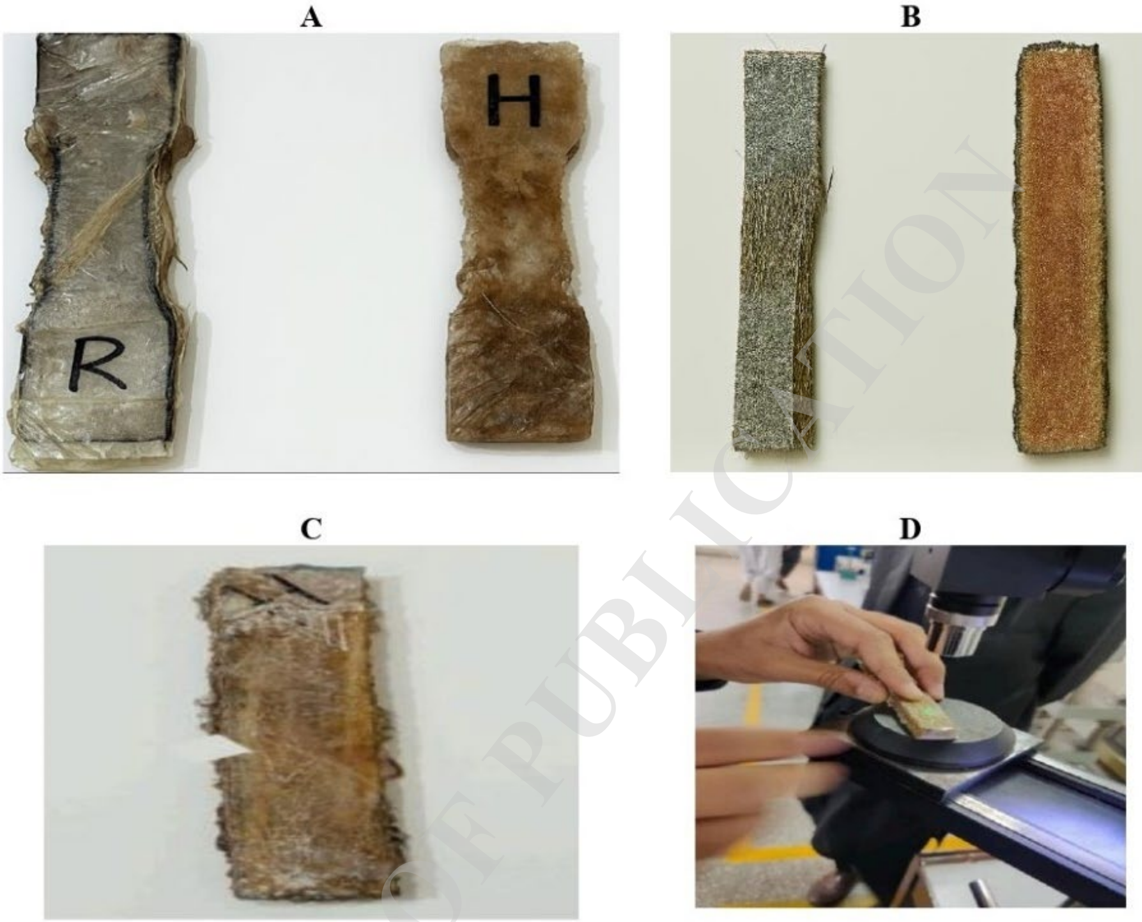


Fig. 3.1: **A**. Tensile specimen **B**. Flexural specimen **C**. Impact specimen **D**. Hardness Specimen

3.3 Impact Strength

To assess how materials respond to sudden or dynamic loading, this study employs the impact behavior was assessed through the Charpy V-notch test. This standardized procedure evaluates the energy absorbed by a specimen during fracture, 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

Micro hardness testing is 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's 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 a micro scale.

4. Results and Discussions

4.1 Tensile Behavior Study

The tensile behavior of the composite samples were tested using a Universal Testing Machine (UTM). During testing, the machine automatically generated a force vs. displacement curve, as illustrated in Fig. 4.1. The tensile behavior results of distinct hybrid laminates are compared in Fig. 4.2. Among the tested samples, the ramie and glass fiber-reinforced composite showed an enhanced performance than the others. The tensile strength values of 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 bar graph. 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 67.23 MPa, which is approximately 62% higher than the Hemp + Glass average (41.58 MPa) and more than double the Hemp + Ramie + Glass average (32.54 MPa). Hemp + Glass laminates exhibited moderate tensile strength values, ranging between 39.40 to 44.30 MPa, accompanied by norm of 41.58 MPa. This performance is about 27% lower than Ramie + Glass, but 28% higher than Hemp + Ramie + Glass. Hemp + Ramie + Glass laminates recorded the lowest tensile strength, varying from 30.02 to 35.70 MPa, with an average of 32.54 MPa. This indicates a reduction of nearly 52% compared to Ramie + Glass laminates. In terms of tensile performance, the Ramie + Glass composite demonstrates superior strength compared to the Ramie + Hemp + Glass hybrid. This enhancement is primarily attributed to the inherently more tensile capacity of glass reinforcement relative to natural reinforcement including ramie/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 in the middle of the matrix and fibers operate a critical function in tensile behavior. Glass fibers exhibit stronger suitability with epoxy resins, facilitating more efficient stress transfer across the interface. In contrast, natural fibers like 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 the hybrid laminate consisting both ramie and jute fibers by YANG, H., et al. [18]. The adoption of hybrid laminate materials has seen notable growth, driven by their environmentally sustainable characteristics including recyclability, biodegradability, and reduced ecological impact SAHARI, I., et al. [19].

Table 4.1. 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

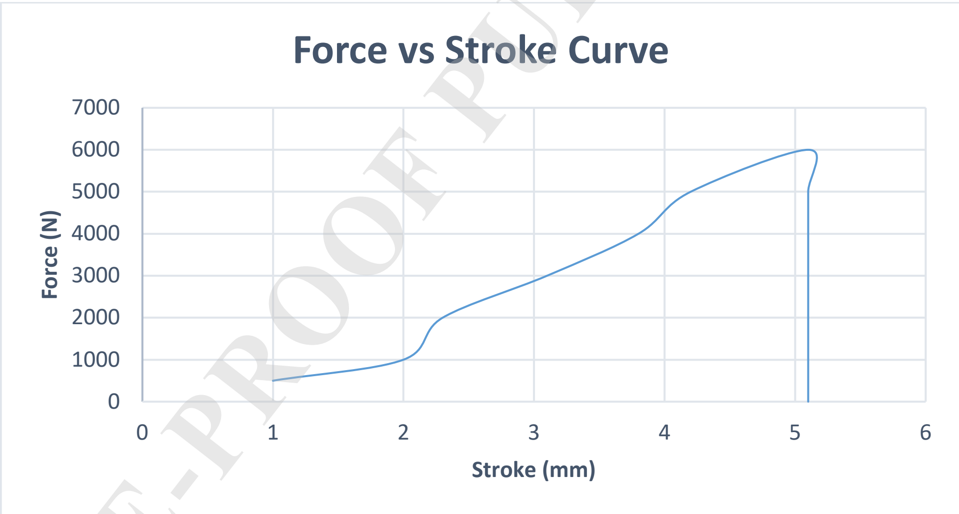


Fig. 4.1. Force vs. stroke curve obtained during tensile testing.

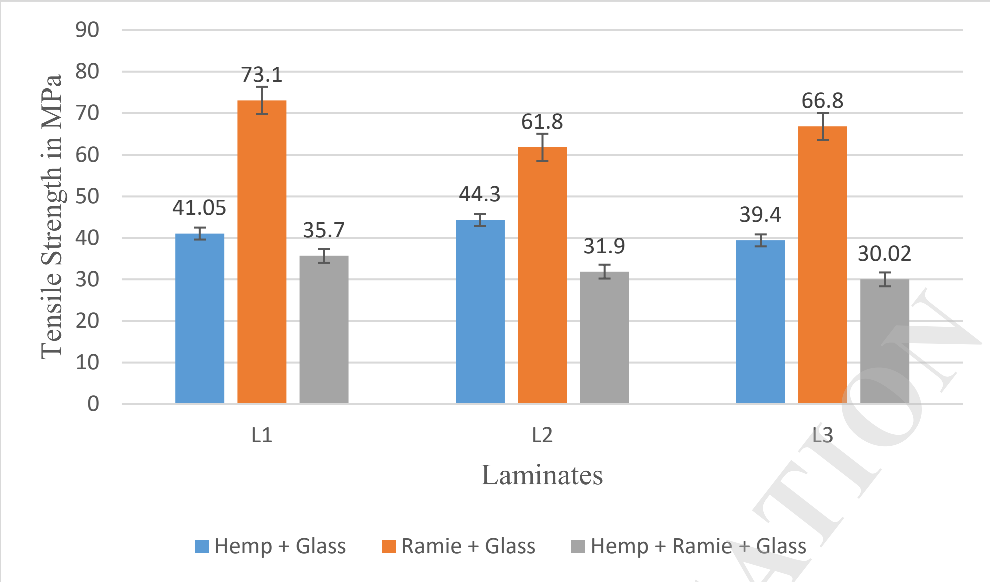


Fig. 4.2. Tensile strength performance of different hybrid fiber laminates.

4.2 Flexural Behavior Study

The flexural performance of synergistic composite specimens was systematically evaluated, as presented in Table 4.2. During mechanical testing, the force–stroke response was recorded in real time, with representative curves illustrated in Fig. 4.3. A comparative analysis of flexural strength across various hybrid configurations is illustrated in Fig. 4.4. 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 achieved 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, contributing about 54.7% of the maximum strength, while the Hemp + Glass laminate had the lowest value with an average of 8.49 MPa, equal to 47.7% of the maximum strength. The higher strength in the Hemp + Ramie + Glass laminate is due to the synergistic effect of 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 minimum strength because hemp has relatively low stiffness, which limits its reinforcement capability. The Ramie + Glass laminate showed moderate strength, as ramie has superior mechanical properties compared to hemp, but the absence of a third fiber restricted its ability to distribute stress as effectively as the three-fiber hybrid. The enhanced flexural and impact performance of Ramie-Hemp-Glass hybrid composites can be attributed to the synergistic interaction among the constituent fibers. Each fiber type contributes distinct mechanical advantages, glass fibers impart high resistance to stiffness to impact, while natural reinforcement like hemp and ramie improve energy absorption and toughness.

Table 4.2. 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

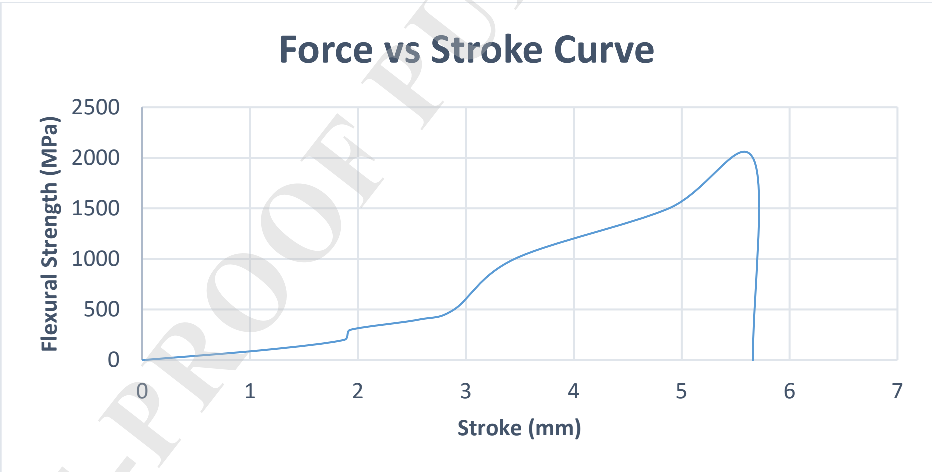


Fig. 4.3. Force vs. stroke curve obtained during flexural testing.

These results exceed those reported by SAPUAN et al. [2], Flexural strength values ranging from 0.3 to 0.4 kN/m² were achieved in epoxy composites reinforced with woven banana fibers. (approximately 0.3 to 0.4 MPa). The superior performance observed in the current study highlights effectiveness of mixer 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 micro-cracks and inhibiting their propagation, thereby Advancing the composite's competence to resist deformation and absorb dynamic loads SAVASTANO J., et al. [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 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 reduced risk of failure.

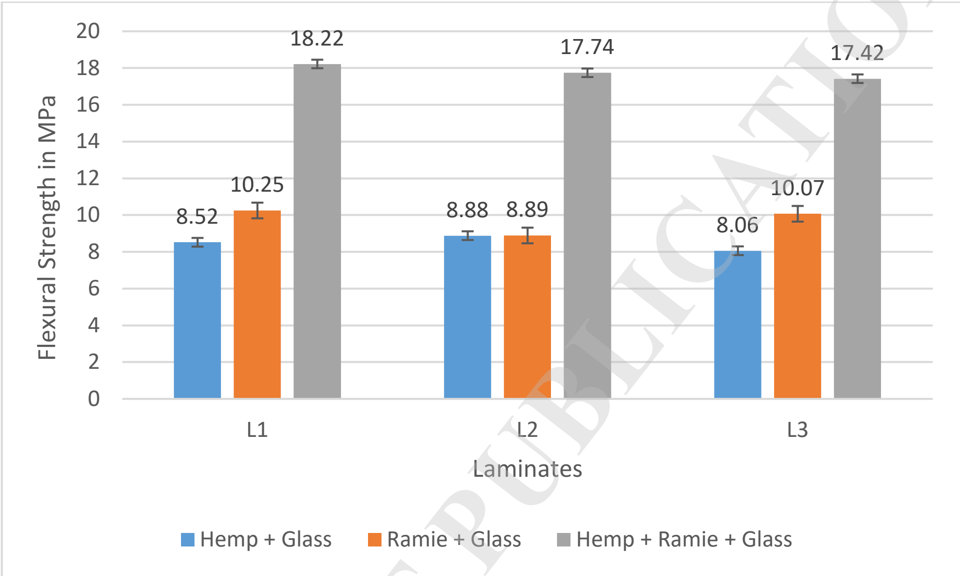


Fig. 4.4. Flexural strength performance of different hybrid fiber laminates.

4.3 Impact Strength Analysis of Hybrid Composites

This study incorporates impact testing to using the Charpy technique, the load-bearing behavior and impact energy of several hybrid composite specimens were assessed. Energy absorption was determined based on data recorded by the testing apparatus. Fig. 4.5 illustrates the comparative impact strength across the different laminate configurations. Among them, the composite made of hemp, ramie and glass fibers demonstrated the superior impact resistance, reaching up to 142.45 kJ/m². Composites made with glass fiber and ramie showed comparable performance levels, as detailed in Table 4.3. Among the configurations, the Hemp + Ramie + Glass composite demonstrated the highest impact resistance, with values ranging from 135.73 to 142.45 kJ/m² approximately 45 to 50% greater than Hemp + Glass and 40 to 46% higher than Ramie + Hemp. This enhanced performance is likely due to the combined effect of natural and synthetic fibers, which promote better interfacial adhesion and improve the materials ability to absorb energy during sudden loading. Conversely, the Hemp + Glass laminate recorded the lowest impact strength, between 90.45 and 95.91 kJ/m², 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 + Hemp laminate exhibited intermediate values, ranging from 92.27 to 99.55 kJ/m² roughly 30 to 33% lower than the top-performing hybrid. Its moderate behavior can be attributed to the predominance of natural fibers, which, while sustainable, offer less resistance to crack propagation under impact. These findings underscore the effectiveness of integrating ramie fibers with hemp and glass in enhancing the impact durability of epoxy-based hybrid laminates, making them promising candidates for implementation requiring high toughness and energy absorption. Natural fibers are increasingly integrated into hybrid composite systems, offering a sustainable alternative to conventional materials. A growing body of research is focused on optimizing fiber hybridization to replace conventional metals and alloys in engineering advancement, while maintaining structural integrity and cost-efficiency. The present study, composite laminates were fabricated by combining glass fibers with natural-fibers such as ramie and hemp. Test samples were eventually prepared from these composites in correspondence with ASTM standards ensuring consistency and reliability in mechanical evaluation. The hemp/ramie/glass fiber reinforced composites invented in this study exhibited an impact strength of 142.45 kJ/m², closely aligning with the 157.64 kJ/m² established by BHOOPATHI, R., et al, [23] and VENKATESHWARAN, N., 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.

Table 4.3 Measured Impact Resistance across Composite Configurations

Laminates	Hemp + Glass (kJ/m²)	Ramie + Glass (kJ/m²)	Hemp + Ramie + Glass (kJ/m²)
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

Laminates	Hemp + Glass (kJ/m²)	Ramie + Glass (kJ/m²)	Hemp + Ramie + Glass (kJ/m²)
Standard Deviation	2.79	3.73	3.80

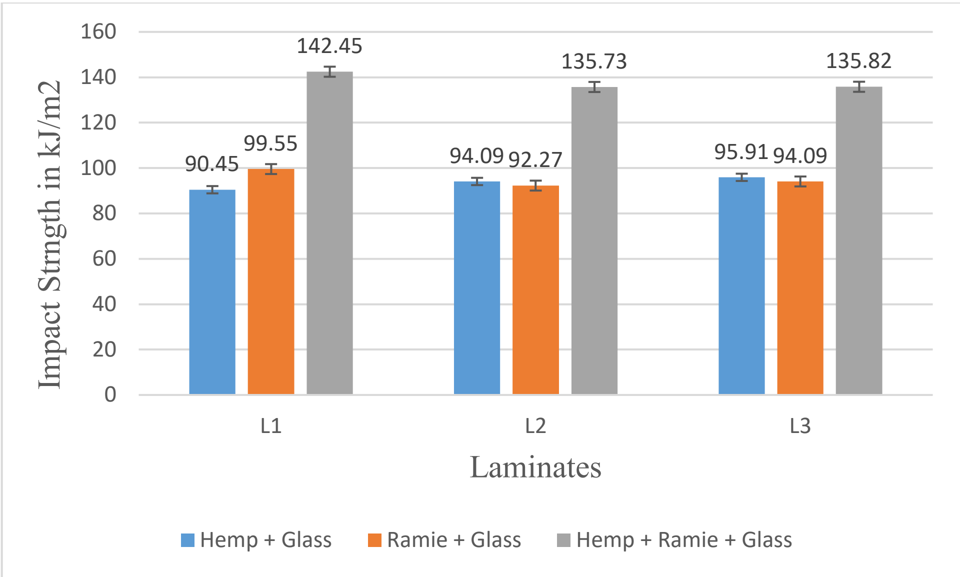


Fig. 4.5. Impact strength distribution among different hybrid laminate systems

4.4 Hardness Value Analysis

Fig. 4.6 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 HV 27.73. This performance notably surpasses that of the other laminates, as detailed in Table 3.4, 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 to 27.73 HV approximately 35 to 40% greater than the Hemp + Glass configuration and around 30% higher than 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 deformation under load. The Hemp + Ramie + Glass laminate demonstrated intermediate hardness values, measured between 19.90 and 20.61 HV. While these values are 25 to 28% lower than those of Ramie + Glass, they remain 10 to 15% higher than Hemp + Glass. The moderate performance reflects the composite's balanced fiber architecture, where the reinforcing effect of ramie and glass is partially offset by the relatively lower stiffness of hemp. Among the tested laminates, Hemp + Glass recorded the lowest hardness, with values ranging from 17.38 to 18.12 HV approximately 36% below Ramie + Glass and 10% below 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 Ramie + Glass composites are particularly well-suited for applications demanding high surface durability and resistance to concentrated mechanical stresses.

Table 4.4. 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

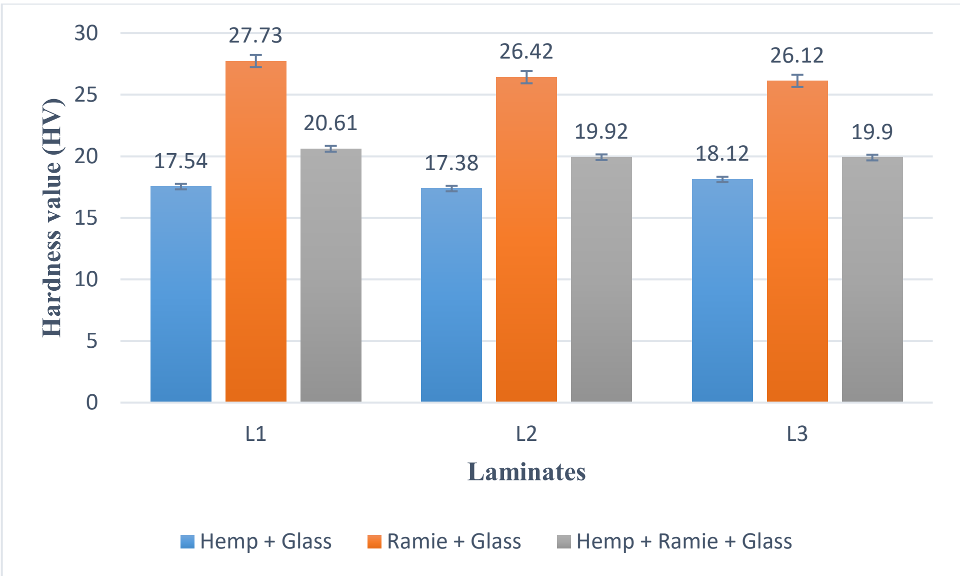


Fig. 4.6. Hardness performance of various hybrid composites.

Table 4.5: 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/m²)	Micro-Hardness (HV)
Glass–Ramie Fibre	73.10	10.25	99.55	27.73
Glass–Hemp Fibre	44.30	8.88	95.91	18.12
Glass–Hemp–Ramie Fibre	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 micro hardness across the trio of composites are statistically meaningful, a one-way ANOVA was conducted. A comprehensive overview of the findings is provided in Table 4.6.

Table 4.6: One-way ANOVA was applied, and corresponding F-statistics and p-values were computed to evaluate the significance of observed differences.

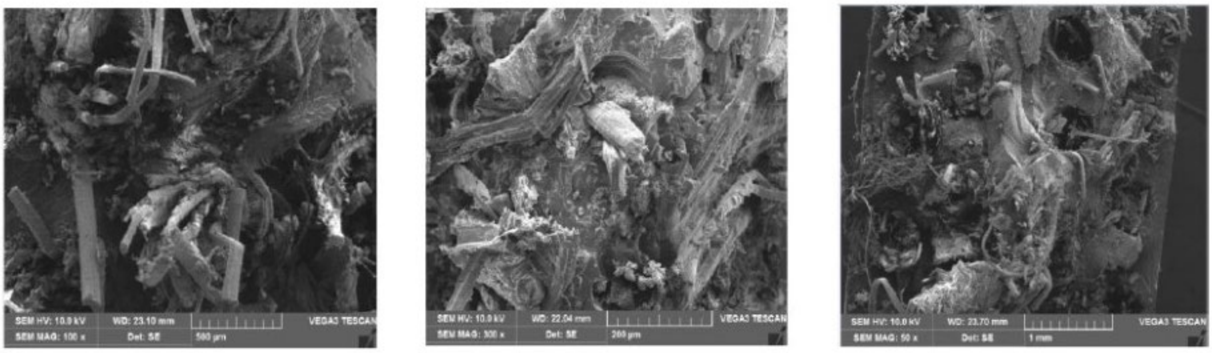
Property	Count value	Mean value	Standard Deviation value (SD)	Minimum value	25th Percentile value (Q1)	Median value	75th Percentile value (Q3)	Maximum value
Tensile behavior (MPa)	3	51.47	22.00	29.00	40.24	51.47	62.70	73.10
Flexural behavior (MPa)	3	12.15	6.00	6.00	9.08	12.15	15.22	18.22
Impact resistance (kJ/m²)	3	95.30	47.15	47.15	71.23	95.30	119.37	142.45

Property	Count value	Mean value	Standard Deviation value (SD)	Minimum value	25th Percentile value (Q1)	Median value	75th Percentile value (Q3)	Maximum value
Micro-Hardness (HV)	3	18.61	9.12	9.12	13.86	18.61	23.47	27.73

Hypotheses.

- Null Hypothesis (H_0): The mean values of the mechanical properties like tensile behavior, flexural behavior, impact resistance, and micro hardness were found 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 Aspects, suggesting that composite type influences the consequence.

4.6 Microstructure of hybrid fiber reinforced composites



a) Hemp+Glass b) Ramie+Glass c) Hemp+Ramie+Glass

Fig 4.7. SEM images of various hybrid composites

Hemp fibers are extracted from the matrix, leaving holes or cavities on the fracture surface, glass fibers may remain partially bonded or protruding. The softer epoxy matrix surrounding hemp fibers cracks more easily, 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 4.7 (a).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, with visible layering and fiber alignment dependent on the stacking sequence as depicts in Fig 4.7(b). Fig 4.7(c) shows fiber pull-out, matrix crazing, rough texture, multiple micro-cracks radiating from hemp fiber breaks. Sharp, brittle transverse fracture, minimal pull-out, clean glass fiber ends, little to no matrix deformation around glass fibers. Ramie and glass show good adhesion (resin stuck to fiber), hemp shows weaker adhesion SADASHIVA K, et al. [24] and PRASAD, L., et al, [25].

Results.

[P-value]: 0.0025

The calculated (p-value) is 0.0025 which is less than the established level of significance (0.05), the findings reject null hypothesis. This means that differences observed in mechanical characteristics like tensile behavior, flexural behavior, impact resistance and hardness between the various composite types are statistically significant. This result gives confidence in the experimental results, that these deviations may be due to fibre types rather than random.

5. Overall Summary and Interpretations

The study compared the mechanical characteristics tensile behavior, flexural behavior, impact resistance, and micro-hardness of different hybrid composites made of Glass-Ramie, Glass-Hemp, and Glass-Hemp-Ramie fibres. Tensile strength was highest in the Glass/Ramie composite (73.10 MPa), followed by Glass-Hemp (44.30 MPa), with the Glass-Hemp-Ramie hybrid showing 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 pattern, with the Glass-Hemp-Ramie composite achieving a significantly higher value (142.45 kJ/m^2) compared to Glass-Ramie (99.55 kJ/m^2) and Glass-Hemp (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 along with highlight the potential of multi-fiber composites in tailoring properties for specific engineering applications.

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References

1. Sadashiva K., Shashanka G., Rakshitha K., Shreya V., and Santhosh Y., "Experimental and Validation of the Mechanical Characteristics of Bio Based Hybrid Composites," *Environmental Engineering & Management Journal*, vol. **23**, pp. 59–67, 2024. DOI: 10.30638/eemj.2024.006

2. Sapuan S., Leenie A., Harimi M., and Beng Y.K., "Mechanical properties of woven banana fiber reinforced epoxy composites," *Materials & Design*, vol. **27**, pp. 689–693, 2006. DOI: 10.1016/j.matdes.2005.01.014

3. Aravinth K., Sathish K., Ramakrishnan T., and Mohamed Asif A., "Mechanical and thermal behavior of aligned coir fiber reinforced epoxy composites based on fiber orientation, fiber length, and fiber volume fraction," *Materials Today: Proceedings*, 2023. DOI: 10.1016/j.matpr.2023.05.436

4. Kandola B.K., Bingham N., Velusamy S., Wedlock B., and Ebdon J.R., "Fully bio-based flax/furan versus carbon/glass epoxy composites: Scope and limitations in terms of fire, mechanical and thermal performances," *Polymer Composites*, vol. **45**, pp. 11004–11021, 2021. DOI: 10.1002/pc.26131

5. Thapiyal D., Verma S., Sen P., Kumar R., Thakur A., Tiwari A.K., et al., "Natural fibers composites: Science, manufacturing, pattern and challenges," *J. Compos. Sci.*, vol. **7**, p. 506, 2023. DOI: 10.3390/jcs7120506

6. Mahakur V.K., Bhowmik S., and Patowari P.K., "Mechanical property study on the natural fiber reinforced epoxy composite," *Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci.*, vol. **236**, pp. 6322–6349, 2022. DOI: 10.1177/09544062221075797

7. Islam M.Z., Sabir E.C., and Syduzzaman M., "Experimental investigation of mechanical properties of jute/hemp fibers reinforced hybrid polyester composites," *SPE Polymers*, vol. **5**, pp. 192–205, 2023. DOI: 10.1002/pls2.10104

8. Manjesh M., Palanikumar K., and Reddy K.H., “Comparative evaluation on properties of hybrid glass fiber-sisal-jute reinforced epoxy composites,” *Materials Today: Proceedings*, vol. **72**, pp. 1053–1057, 2023. DOI: 10.1016/j.matpr.2023.05.438

9. Venkateshwaran N., ElayaPerumal A., Alavudeen A., and Thiruchitrambalam M., “Mechanical and thermal behavior evaluation of banana/sisal reinforced hybrid composites,” *Materials & Design*, vol. **32**, pp. 4017–4021, 2011. DOI: 10.1016/j.matdes.2011.03.002

10. Sadashiva K. and Purushothama K.M., “Physical and Mechanical Properties of Bio Based Natural Hybrid Composites,” *J. Mater. Environ. Sci.*, vol. 14, no. **01**, pp. 131–140, 2023. DOI: 10.26872/jmes.2023.14.1.12

11. Ramesh M., Palanikumar K., and Reddy K.H., “Influence of fiber treatment on mechanical properties of sisal–jute–glass fiber reinforced polyester composites,” *J. Reinforced Plastics and Composites*, vol. **34**, no. 6, pp. 488–502, 2015. DOI: 10.1177/0731684414567881

12. Yuanjian T. and Isaac D., “Impact and fatigue behaviour of hemp fibre composites,” *Composites Science and Technology*, vol. 67, pp. 3300–3307, 2007. DOI: 10.1016/j.compscitech.2007.03.039

13. Bledzki A., Mamun A., and Faruk O., “Abaca fibre reinforced PP composites and comparison with jute and flax fibre PP composites,” *Express Polymer Letters*, vol. **1**, pp. 755–762, 2007. DOI: 10.3144/expresspolymlett.2007.104

14. Kobayashi S., Takada K., and Nakamura R., “Processing and characterization of hemp fiber textile composites with micro-braiding technique,” *Composites Part A: Applied Science and Manufacturing*, vol. **59**, pp. 1–8, 2014. DOI: 10.1016/j.compositesa.2014.01.001

15. Kabir M., Wang H., Latu K., and Cardona F., “Tensile properties of chemically treated hemp fibres as reinforcement for composites,” *Composites Part B: Engineering*, vol. **53**, pp. 362–368, 2013. DOI: 10.1016/j.compositesb.2013.04.087

16. Aristri M.A., Lubis M.A.R., Laksana R.P.B., Sari R.K., Iswanto A.H., Kristak L., Antov P., and Pizzi A., “Thermal and Mechanical Performance of Ramie Fibers Modified with Polyurethane Resins Derived from Acacia Mangium Bark Tannin,” *J. Mater. Res. Technol.*, vol. **18**, pp. 2413–2427, 2022.

17. Torres-Arellano M., Renteria-Rodríguez V., and Franco-Urquiza E., "Mechanical Properties of Natural-Fibre-Reinforced Bio-based Epoxy Resins Manufactured by Resin Infusion Process," *Polymers*, vol. **12**, p. 2841, 2020. DOI: 10.3390/polym12122841

18. Yang H., Zhang H., Li X., Yin L., Guo X., Fan H., et al., "Load-bearing capacity and failure mechanism of integrated fluted-core composite sandwich cylinders," *Composites Science and Technology*, vol. **221**, p. 109344, 2022. DOI: 10.1016/j.compscitech.2022.109344

19. Sahari I. and Sapuan S., "Natural fibre reinforced biodegradable polymer composites," *Rev. Adv. Mater. Sci.*, vol. **30**, pp. 166–174, 2011. DOI: 10.1515/rams-2011-0009

20. Savastano J. Jr., Santos S.F., Radonjic M., and Soboyejo W., "Fracture and fatigue of natural fiber-reinforced cementitious composites," *Cement and Concrete Composites*, vol. **31**, pp. 232–243, 2009. DOI: 10.1016/j.cemconcomp.2009.02.006

21. ASTM, *ASTM D790: Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*, Annual Book of ASTM Standards, 1997.

22. ASTM, *ASTM D638-14: Standard Test Method for Tensile Properties of Plastics*, ASTM International, 2014.

23. Bhoopathi R., Ramesh M., and Deepa C., "Fabrication and property evaluation of banana–hemp–glass fiber reinforced composites," *Procedia Engineering*, vol. **97**, pp. 2032–2041, 2014. DOI: 10.1016/j.proeng.2014.12.448

24. Sadashiva, K., Sarvamangala, S. P., Shanshanka, G., Tarakeshwar, J., & Pradeep Kumar, P. "Mechanical, tribological and morphological characteristics of glass and jute reinforced epoxy hybrid composite;" *Journal of Materials and Environmental Science*, vol.**15** (5), pp.700–711, 2024.

Prasad, L., Kapri, P., Patel, R. V., Yadav, A., & Winczek, J. Physical and mechanical behavior of ramie and glass fiber reinforced epoxy resin-based hybrid composites. *Journal of Natural Fibers,* **20**(2), 2234080, 2023. https://doi.org/10.1080/15440478.2023.2234080**.**