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Effects of Fiber Hybridization on Tensile, Flexural, and Impact Strength of Hybrid Natural-Fiber Epoxy Composites

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Abstract

This study investigates the mechanical performance of epoxy composites reinforced with hemp, ramie, and flax fibers and evaluates the effect of fiber hybridization. Single-fiber composites were fabricated using hand lay-up followed by vacuum-bagging consolidation and compared with three hybrid systems: hemp–flax (HF), hemp–ramie (HR), and flax–ramie (FR). Tensile, flexural, and drop-weight impact properties were evaluated using standardized test procedures. Among the single-fiber composites, flax exhibited the highest tensile strength of 88.26 ± 0.28 MPa and flexural strength of 114.97 ± 3.31 MPa, followed by ramie and hemp. Hybridization produced combination-dependent responses. The flax–ramie hybrid achieved the highest tensile strength of 92.32 ± 1.53 MPa, while the hemp–ramie hybrid showed a 69.6% improvement in tensile strength compared with hemp alone. In contrast, the flexural strength of the hybrid systems remained below that of flax, demonstrating that hybridization does not universally improve every mechanical property. SEM fractography revealed fiber pull-out, fiber–matrix debonding, matrix cracking, fiber fracture, fibrillation, crack deflection, localized voids, and resin-rich regions. These observations indicate multiple interacting failure mechanisms and support the role of fiber architecture and interfacial behavior in determining composite performance. Overall, hybridization provides a means of tailoring the balance between tensile, flexural, and impact performance. The developed natural-fiber/epoxy composites show potential for selected structural and semi-structural applications where mechanical performance, low density, and sustainability are required.

Keywords: Natural fiber composites, hybrid composites, flax fiber, hemp fiber, ramie fiber, epoxy, mechanical properties, sustainable material

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INTRODUCTION

Growing environmental concerns, depletion of non-renewable resources, and increasing restrictions on synthetic materials have stimulated research into sustainable composite materials. Natural fiber-reinforced polymer composites (NFRPCs) have attracted considerable attention as potential alternatives to conventional synthetic-fiber composites because of their low density, renewability, biodegradability, cost-effectiveness, and favorable specific mechanical properties [1]. Common natural fibers include jute, flax, hemp, sisal, kenaf, coir, and bamboo, which are primarily composed of cellulose, hemicellulose, and lignin. When incorporated into thermoplastic or thermoset matrices, these fibers can produce lightweight composites with potential applications in structural and semi-structural components [2].

The mechanical performance of natural-fiber composites is influenced by fiber type, fiber content, orientation, surface treatment, fiber–matrix interfacial bonding, and processing conditions [2, 3]. Tensile strength represents load-bearing capability under axial loading, whereas flexural strength indicates resistance to bending. Impact performance represents the ability of a composite to absorb energy under sudden loading and is associated with toughness and damage tolerance [3]. Despite their advantages, natural-fiber composites have limitations, including variability in fiber properties, moisture absorption, interfacial incompatibility, and generally lower absolute mechanical performance than synthetic-fiber composites [4].

Hybridization combines two or more different reinforcement fibers within the same polymer matrix to exploit complementary characteristics and obtain a more balanced combination of mechanical properties [5]. A stronger or stiffer fiber may contribute to tensile and flexural performance, whereas another fiber may provide improved energy absorption or damage tolerance. The mechanical response of hybrid composites is strongly influenced by fiber type, fiber ratio, orientation, stacking sequence, and interfacial characteristics [5, 6]. Appropriate hybridization can modify stress distribution, crack propagation, and failure mechanisms and may, therefore, improve selected mechanical properties.

However, hybridization does not necessarily improve all properties simultaneously. Its effectiveness depends on the compatibility and relative properties of the constituent fibers, their proportions, laminate configuration, and processing conditions [5, 6]. Improvements in one mechanical property may occur at the expense of another, demonstrating that hybrid composites should be designed according to the intended application. In addition, the hydrophilic nature of lignocellulosic fibers makes natural-fiber composites susceptible to moisture absorption, which can cause fiber swelling, interfacial debonding, and deterioration of mechanical properties [4]. Recent studies have continued to demonstrate that processing conditions and hybridization strategies play important roles in determining the mechanical performance of natural-fiber composites [7–9].

Vacuum-assisted processing can improve fiber impregnation and consolidation while reducing void formation, although processing pressure and laminate configuration remain important factors affecting composite quality [10]. Recent reviews have similarly emphasized that hybridization provides opportunities for tailoring the mechanical response of natural-fiber composites, but the resulting performance depends strongly on the selected fiber combination and laminate architecture [5, 8].

Among natural fibers, hemp, flax, and ramie possess different structural and mechanical characteristics and, therefore, provide suitable candidates for comparative hybridization. However, a systematic comparison of hemp, flax, and ramie as individual reinforcements together with their three corresponding binary combinations hemp–flax (HF), hemp–ramie (HR), and flax–ramie (FR)—under comparable fabrication and testing conditions remains limited. Such a comparison is important for determining whether particular fiber combinations improve individual properties or instead provide a more balanced mechanical response.

Therefore, the present study investigates the tensile, flexural, and impact performance of hemp-, flax-, and ramie-reinforced epoxy composites and evaluates the influence of their hybridization. Single-fiber composites and three hybrid systems, namely HF, HR, and FR, were fabricated using hand lay-up followed by vacuum-bagging consolidation and comparatively evaluated under standardized mechanical testing conditions. The objective is to determine how different fiber combinations influence mechanical performance and to identify hybrid systems that provide a favorable balance of properties for potential structural and semi-structural applications.

MATERIALS AND METHODS

This section describes the materials, composite fabrication procedure, laminate configurations, specimen preparation, and experimental methods used to evaluate the mechanical performance of the developed natural-fiber/epoxy composites. Hemp, ramie, and flax fibers were investigated individually and in three hybrid combinations; hemp–flax (HF), hemp–ramie (HR), and flax–ramie (FR). A consistent fabrication and laminate configuration were adopted to enable a meaningful comparison among the different composite systems. The tensile, flexural, and impact properties were subsequently evaluated using the respective ASTM standard procedures, and the fractured surfaces were examined using SEM to investigate the associated failure mechanism

Materials

Hemp, ramie, and flax fabrics were selected as natural-fiber reinforcements for the epoxy composites. Hemp and flax fabrics were used in a unidirectional configuration, whereas ramie fabric was bidirectional as shown in Figure 1. LY556 epoxy resin and HY951 hardener were used as the polymer matrix.

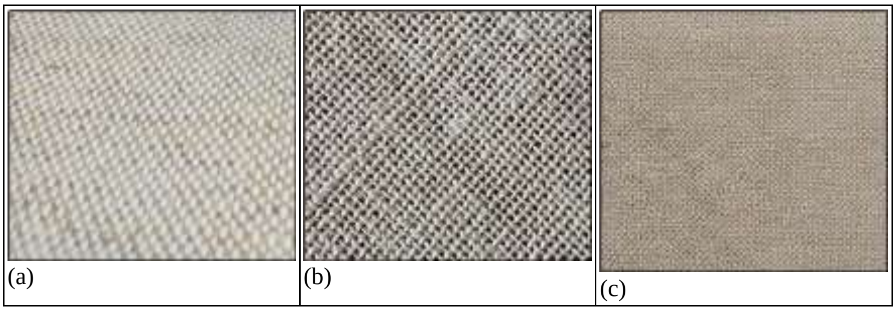

Figure 1. Fiber reinforcements: (a) Hemp, (b) Ramie, and (c) Flax.

Composite Fabrication and Vacuum-Bagging

The composite laminates were fabricated using the hand lay-up technique followed by vacuum-bagging consolidation as represented in Figure 2. For the single-fiber composites, eight reinforcement layers of the corresponding fiber were used. For the hybrid composites, four layers of each constituent fiber were combined, resulting in a total of eight reinforcement layers. The three hybrid configurations investigated were hemp–flax (HF), hemp–ramie (HR), and flax–ramie (FR).

Figure 2. Hand Lay-up and vacuum-bagging fabrication process.

The laminates were arranged using a symmetric stacking configuration alternating 0° and 90° fiber orientations as shown in Table 1. The same overall laminate architecture was maintained among the composite systems to facilitate comparison of the effect of fiber type and hybridization. The present study was designed as a comparative hybridization study rather than an optimization study; alternative fiber ratios, stacking sequences, and orientations were not investigated.

A mold-release agent was applied before lay-up to facilitate demolding. LY556 epoxy resin and HY951 hardener were mixed at a 10:1 ratio and applied uniformly between successive fiber layers. After completion of the lay-up, the laminate was covered with the vacuum-bagging arrangement and sealed. A vacuum pressure of approximately −0.8 bar was applied for about 4–5 h at room temperature to promote resin distribution, fiber wetting, laminate consolidation, and removal of entrapped air [10]. The vacuum-bagged laminates were then allowed to cure at room temperature overnight. No separate post-curing treatment was performed.

Laminate Configuration

The laminate configurations were designed to provide a consistent basis for comparing the mechanical performance of the single-fiber and hybrid composites (Table 1). Symmetric laminate arrangements with alternating 0° and 90° fiber orientations were used for all composite systems. For the hybrid laminates, the constituent fibers were combined within the same laminate while maintaining the same overall layer configuration. This approach enabled the influence of fiber hybridization to be evaluated independently of major changes in laminate architecture.

Table 1. Laminate configurations investigated.

Composite	Fiber configuration	No. of layers	Orientation
Hemp/epoxy	Hemp	8	Symmetric, alternating 0°/90°.
Ramie/epoxy	Ramie	8	Symmetric, alternating 0°/90°.
Flax/epoxy	Flax	8	Symmetric, alternating 0°/90°.
HF	4 Hemp + 4 Flax	8	Symmetric, alternating 0°/90°.
HR	4 Hemp + 4 Ramie	8	Symmetric, alternating 0°/90°.
FR	4 Flax + 4 Ramie	8	Symmetric, alternating 0°/90°.

Specimen Preparation

After curing, the laminates were removed from the mold and cut into specimens according to the requirements of the respective ASTM test methods. Tensile specimens were prepared with a width of 25 mm and an overall length of 250 mm, with a gauge length of 150 mm. Flexural specimens were prepared according to ASTM D790. For impact testing, specimens of approximately 100 × 150 mm were prepared. Five specimens were tested for tensile and flexural characterization for each composite configuration, and the reported values represent the mean response with the corresponding variation.

MECHANICAL CHARACTERIZATION

The mechanical performance of the fabricated single-fiber and hybrid natural-fiber/epoxy composites was evaluated through tensile, flexural, and impact testing. These tests were selected to assess the load-bearing capacity, bending resistance, and energy absorption characteristics of the developed composite systems, respectively. Standardized ASTM test procedures were followed to ensure consistency and comparability of the experimental results. The obtained mechanical responses were subsequently compared among the different fiber configurations to determine the influence of fiber hybridization on overall composite performance.

Tensile Testing

Tensile testing was performed according to ASTM D3039/D3039M [11], which specifies the determination of in-plane tensile properties of polymer-matrix composite materials. The tensile specimens had a width of 25 mm, an overall length of 250 mm, and a gauge length of 150 mm. The

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tensile strength was determined from the maximum load sustained by the specimen divided by its original cross-sectional area. Five specimens were tested for each composite configuration.

Flexural Testing

Flexural testing was conducted using a three-point bending configuration according to ASTM D790 [12], which covers flexural-property determination for reinforced plastics and high-modulus composites. The distance between the two supports was maintained at 100 mm. Five specimens were tested for each composite configuration. Flexural strength was determined from the maximum load recorded during the test using the applicable ASTM calculation procedure.

Impact Testing

Drop-weight impact testing was performed using an SPRANK Drop Weight Impact Tester according to ASTM D7136/D7136M-15 [13], a standard method for assessing damage resistance of fiber-reinforced polymer-matrix composite laminates subjected to a drop-weight impact event. The test system consisted of a hemispherical steel striker with a diameter of 3.0 cm attached to a 6.73 kg titanium impactor equipped with a force sensor. Impact force and deflection were recorded, and the energy absorbed by the specimens was determined from the recorded response. Tests were conducted at drop heights of 0.1, 0.2, 0.3, 0.4, and 0.5 m to investigate the effect of impact severity on energy absorption. At least five specimens were evaluated for each composite configuration.

RESULTS AND DISCUSSIONS

This section presents and discusses the experimental results obtained from the single-fiber and hybrid natural-fiber/epoxy composites. The tensile, flexural, and impact responses are compared to evaluate the influence of fiber type and hybridization on the mechanical performance of the composites. The observed differences are interpreted in terms of fiber characteristics, load transfer, laminate configuration, and the interaction between the constituent fibers and epoxy matrix. In addition, SEM fractographic observations are presented to relate the macroscopic mechanical behavior to the underlying fiber–matrix interaction and failure mechanisms. The combined results are used to assess the effectiveness of the selected hybrid configurations and their potential for achieving a balanced mechanical performance.

Tensile Strength

The tensile strength results demonstrate clear differences among the single-fiber composites. Flax exhibited the highest tensile strength of 88.26 ± 0.28 MPa, followed by ramie at 62.95 ± 0.49 MPa and hemp at 44.21 ± 0.22 MPa. The higher tensile performance of the flax composite indicates its greater contribution to axial load carrying among the investigated single-fiber systems. The differences among the fibers can be associated with their inherent fiber characteristics, cellulose-rich structure, stiffness, and fiber–matrix load-transfer behavior [1–3].

Hybridization produced different tensile responses depending on the fiber combination. The flax–ramie (FR) composite exhibited the highest tensile strength among the hybrid systems, reaching 92.32 ± 1.53 MPa, which was slightly higher than the tensile strength of the individual flax composite. The hemp–ramie (HR) composite achieved 74.99 ± 3.97 MPa, representing a 69.6% improvement over hemp alone. The hemp–flax (HF) hybrid showed a tensile strength of 69.44 ± 2.16 MPa mentioned in Table 2, corresponding to an improvement of approximately 57.1% compared with hemp.

Table 2. Tensile strength of single-fiber and hybrid composites.

Composite	Tensile strength (MPa)
Hemp	44.21 ± 0.22
Ramie	62.95 ± 0.49
Flax	88.26 ± 0.28
Hemp–Flax (HF)	69.44 ± 2.16
Hemp–Ramie (HR)	74.99 ± 3.97
Flax–Ramie (FR)	92.32 ± 1.53

The improved tensile response of the HR and FR systems can be attributed to complementary load sharing between the constituent fibers. Recent studies on ramie–flax and ramie–hemp hybrid composites, likewise, report that fiber combination, architecture, and interfacial load transfer strongly influence tensile performance [5, 14, 15]. The incorporation of ramie into hemp substantially increased the tensile strength of the hybrid, while the slightly higher tensile strength of FR compared with flax suggests that the combination can promote effective stress redistribution. These results should nevertheless be interpreted as combination-dependent improvements rather than universal synergistic enhancement because hybridization did not improve every measured property.

The HF system also demonstrated a substantial improvement over hemp, although its tensile strength remained below that of the individual flax composite as represented in Figure 3. Thus, the properties of the constituent fibers are not simply transferred directly to the hybrid composite; the final response depends on fiber interaction, load transfer, fiber architecture, and matrix impregnation [5, 6].

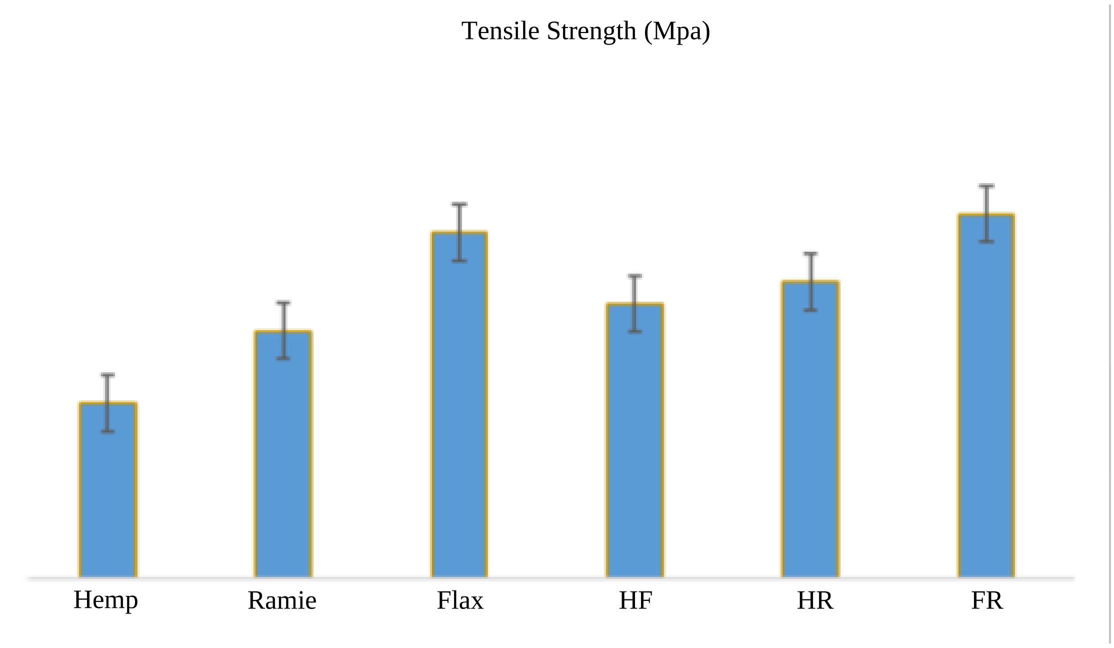

Figure 3. Comparative tensile strength of the single-fiber and hybrid composites.

Flexural Strength

The flexural results show a different trend from the tensile results. The flax composite exhibited the highest flexural strength of 114.97 ± 3.31 MPa, indicating superior resistance to bending among the single-fiber systems. Hemp exhibited a flexural strength of 78.24 ± 13.31 MPa, while ramie showed the lowest single-fiber flexural strength at 43.83 ± 2.20 MPa mentioned in Table 3.

Table 3. Flexural strength of single-fiber and hybrid composites.

Composite	**Flexural strength (MPa)**
Hemp	78.24 ± 13.31
Ramie	43.83 ± 2.20
Flax	114.97 ± 3.31
Hemp–Flax (HF)	53.08 ± 6.49
Hemp–Ramie (HR)	57.85 ± 2.95
Flax–Ramie (FR)	61.50 ± 4.51

The hybrid systems did not produce a universal improvement in flexural strength. The FR composite exhibited a flexural strength of 61.50 ± 4.51 MPa, approximately 40.3% higher than ramie alone but approximately 46.5% lower than flax alone as depicted in Figure 4. Therefore, FR should not be described as providing enhanced flexural performance compared with flax. Instead, the result indicates a trade-off between the high flexural performance of flax and the characteristics contributed by ramie. The HR hybrid exhibited 57.85 ± 2.95 MPa, approximately 32.0% higher than ramie alone, while the HF hybrid showed 53.08 ± 6.49 MPa.

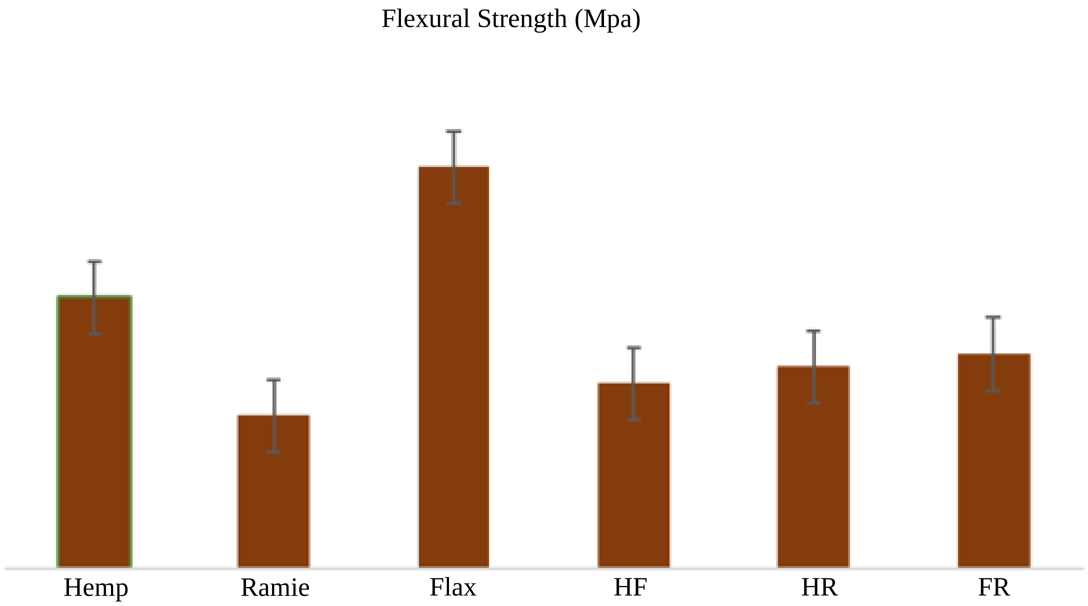

Figure 4. Comparative flexural strength of the single-fiber and hybrid composites.

These results demonstrate that hybridization should not be considered a universal method for increasing all mechanical properties simultaneously. Tensile loading emphasizes axial load transfer through the fibers, whereas flexural loading involves tensile, compressive, shear, matrix, and interfacial stresses. Consequently, a fiber combination that performs well in tension may not provide the same advantage under bending. The relatively high variation observed for the hemp flexural specimens may also be associated with local variations in fiber distribution and resin impregnation. Vacuum-bagging promotes consolidation and impregnation, but local laminate architecture can still influence flexural response [10].

Impact Energy Absorption

The drop-weight impact results demonstrate that energy absorption was strongly dependent on both fiber combination and impact height. At 0.1 m, flax exhibited the highest energy absorption (30 J), followed by HR (23 J), ramie (20 J), and hemp, HF, and FR (18 J each). At 0.2 m, flax again exhibited the highest value (26 J), while HF absorbed 24 J and ramie absorbed 18 J represented in Figure 5. At higher drop heights, the response became more variable. At 0.3 m, HF exhibited the highest energy absorption (23 J), whereas FR showed the lowest value (6 J). At 0.4 m, hemp exhibited the highest value (24 J), while flax showed 11 J. At 0.5 m, hemp again exhibited the highest energy absorption (24 J), followed by ramie and FR (18 J each), while flax exhibited the lowest value (6 J) as listed in Table 4. The results indicate that the composite with the highest tensile or flexural strength does not necessarily provide the highest impact energy absorption at every impact condition. Recent reviews of natural-fiber/epoxy impact behavior emphasize that impact response is sensitive to fiber type, stacking sequence, interfacial characteristics, manufacturing conditions, and impact severity [9, 16]. The relatively high impact energy absorption of hemp at the higher drop heights suggests greater tolerance to damage under the investigated conditions, whereas the lower values observed for flax at 0.4–0.5 m indicate a greater tendency toward localized damage or fracture at these impact energies. The hybrid systems showed different responses depending on fiber combination, demonstrating that hybridization can alter the balance between strength and energy absorption.

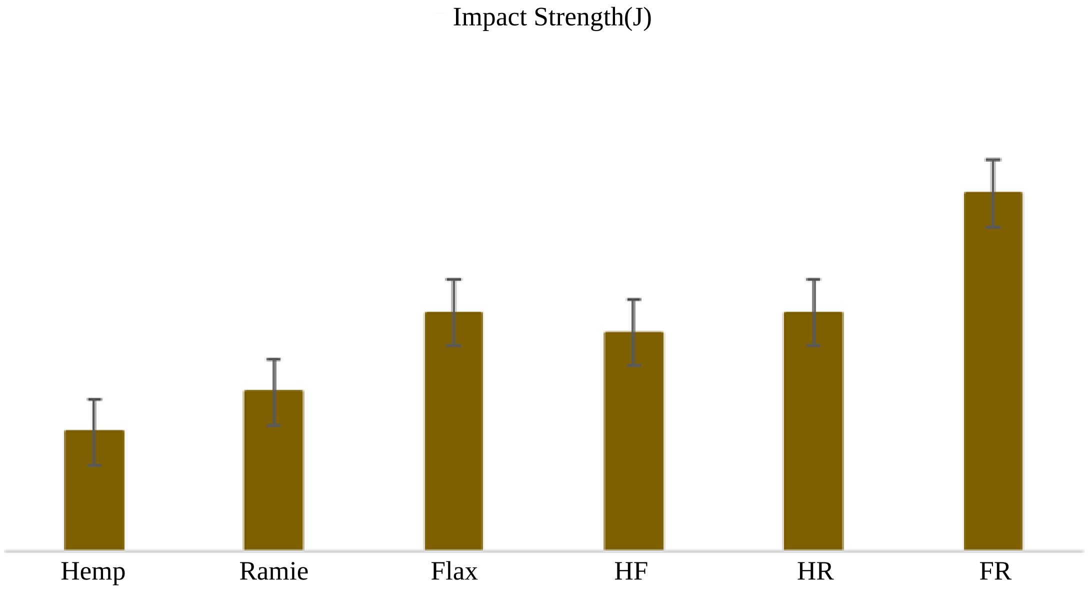

Figure 5. Comparative impact energy absorption of the single-fiber and hybrid composites.

Table 4. Impact energy absorption at different drop heights.

Drop height (m)	Hemp (J)	Ramie (J)	Flax (J)	HF (J)	HR (J)	FR (J)
0.1	18	20	30	18	23	18
0.2	12	18	26	24	12	12
0.3	18	16	12	23	18	6
0.4	24	12	11	18	18	12
0.5	24	8	6	12	12	18

Scanning Electron Microscopy Analysis

SEM analysis was performed on fractured surfaces of the hybrid composites to examine fiber–matrix interaction and the mechanisms associated with tensile fracture. The micrographs shown in Figure 6 indicate fiber pull-out, fiber–matrix debonding, matrix cracking, fiber fracture, fibrillation, localized voids, and resin-rich regions. These are established indicators used to assess interfacial adhesion and fracture behavior in natural-fiber/epoxy composites [17]. In several regions, fibers remain partially embedded within the epoxy matrix, indicating mechanical interlocking and load transfer between the reinforcement and matrix. At the same time, pulled-out fibers and interfacial gaps indicate localized fiber–matrix debonding. Fiber pull-out can contribute to fracture-energy dissipation because additional energy is required to separate and extract fibers from the surrounding matrix. The simultaneous occurrence of fiber fracture and pull-out, therefore, indicates that failure was governed by multiple mechanisms rather than by a single brittle fracture process. Longitudinal splitting and fibrillation are also visible on some fractured fibers. These features indicate progressive fiber damage before final fracture and suggest that part of the applied load was transferred to the reinforcement before catastrophic failure. The rough fracture surfaces further suggest that fibers interrupted and deflected crack propagation, increasing the effective fracture path and contributing to energy dissipation. Localized voids and resin-rich regions are also visible. Such regions may originate from incomplete local impregnation or localized fiber–matrix separation during fabrication and can act as stress-concentration sites for crack initiation. Conversely, areas showing intimate contact between the fibers and epoxy indicate adequate matrix impregnation and interfacial bonding. The coexistence of good interfacial contact, fiber fracture, and fiber pull-out suggests a balance between load transfer and energy-dissipating interfacial failure. The hybrid systems provide opportunities for heterogeneous crack propagation and progressive load sharing because the constituent fibers possess different mechanical characteristics. Fibers with different stiffness and strength can contribute to sequential failure and reinforcement utilization. Recent work on natural-fiber/epoxy interfaces indicates that interfacial characteristics strongly affect stress transfer and fracture behavior [17, 18]. This provides a plausible microstructural explanation for the improved tensile performance observed for the HR and FR composites. The SEM observations are interpreted as qualitative evidence of the proposed failure mechanisms and should not be considered direct quantitative proof of synergistic behavior.

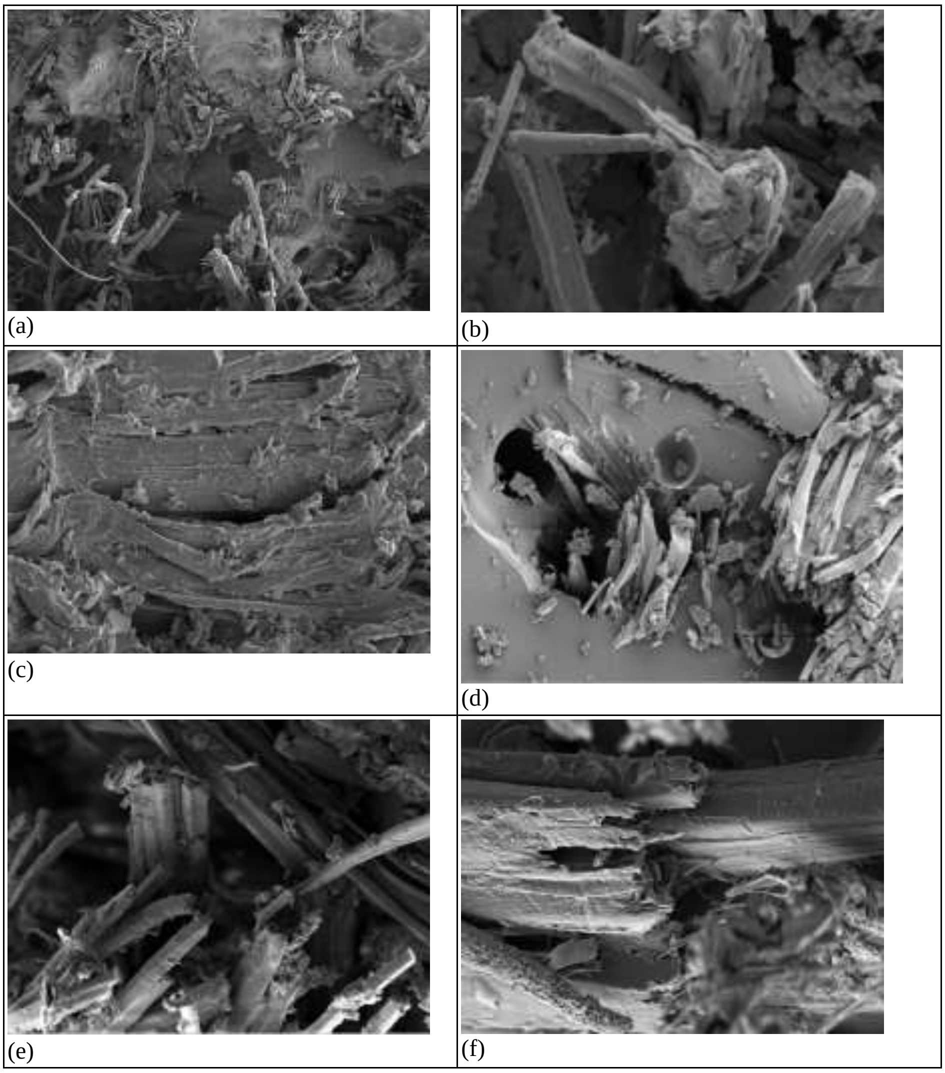

Figure 6. SEM Micrographs of fractured hybrid natural-fiber/epoxy composites: (a, b) hemp–flax, (c, d) hemp–ramie, and (e, f) flax–ramie, showing fiber pull-out, fiber–matrix debonding, matrix cracking, fiber fracture, fibrillation, crack deflection, localized voids, and resin-rich regions.

Overall Effect of Fiber Hybridization

The combined tensile, flexural, impact, and SEM results demonstrate that the effect of hybridization is fiber- and property-dependent. Flax provided the highest tensile and flexural performance among the single-fiber composites, whereas hemp and ramie exhibited different levels of tensile and impact performance. Hybridization particularly improved tensile performance in the HR and FR systems, with

HR showing a 69.6% increase over hemp and FR achieving 92.32 ± 1.53 MPa, slightly higher than the flax single-fiber composite. In contrast, the flexural results demonstrate that hybridization does not necessarily improve bending strength. The highest flexural strength remained that of the flax composite (114.97 ± 3.31 MPa), while the FR, HR, and HF systems exhibited lower values. Therefore, the principal benefit of hybridization in the present investigation is better described as tailoring and balancing mechanical performance rather than simultaneous enhancement of tensile, flexural, and impact properties [19–21]. Overall, the results demonstrate that there is no single fiber or hybrid combination that provides the highest performance in all mechanical properties. Selection of a hybrid system should, therefore, depend on the dominant loading condition and the desired balance between strength, damage tolerance, and sustainability. This finding is relevant to the development of natural-fiber composites for applications in which balanced mechanical performance is more important than optimization of a single property [22, 23].

CONCLUSIONS

In this study, the tensile, flexural, and impact performance of single and hybrid natural-fiber-reinforced epoxy composites was systematically evaluated. Among the single-fiber composites, flax exhibited the highest tensile strength (88.26 ± 0.28 MPa) and flexural strength (114.97 ± 3.31 MPa), demonstrating its strong potential as a reinforcement for load-bearing applications.

Hybridization produced combination-dependent effects, with the flax–ramie hybrid achieving the highest tensile strength of 92.32 ± 1.53 MPa, while the hemp–ramie hybrid showed a 69.6% improvement in tensile strength compared with hemp alone. However, hybridization did not improve all mechanical properties simultaneously; for example, the flexural strength of the flax–ramie hybrid (61.50 ± 4.51 MPa) was lower than that of the individual flax composite. Therefore, the main advantage of hybridization in the present study is its ability to tailor and balance mechanical performance through appropriate fiber combinations rather than universally enhancing all properties.

SEM fractographic observations revealed fiber pull-out, fiber–matrix debonding, matrix cracking, fiber fracture, fibrillation, and crack deflection, indicating multiple interacting failure mechanisms and providing microstructural support for the observed mechanical behavior. Localized voids and resin-rich regions were also observed, indicating that local processing and interfacial conditions can influence fracture behavior. Overall, the developed hybrid natural-fiber/epoxy composites show potential for selected structural and semi-structural applications where a balance of mechanical performance, low density, and sustainability is required. Future work should investigate moisture absorption, thermal aging, UV exposure, fatigue/cyclic loading, and optimization of fiber ratio, orientation, and stacking sequence to establish long-term durability and further optimize composite performance.

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REFERENCES

1. Pickering KL, Efendy MGA, Le TM. A review of recent developments in natural fibre composites and their mechanical performance. Compos Part A Appl Sci Manuf. 2016;83:98–112. doi: 10.1016/j.compositesa.2015.08.038.
2. Faruk O, Bledzki AK, Fink HP, Sain M. Biocomposites reinforced with natural fibers: 2000–2010. Prog Polym Sci. 2012;37(11):1552–1596. doi: 10.1016/j.progpolymsci.2012.04.003.
3. Thakur VK, Thakur MK, Gupta RK. Raw natural fiber-based polymer composites: a review. Carbohydr Polym. 2014;109:102–117. doi: 10.1016/j.carbpol.2014.04.009.
4. Dhakal HN, Zhang ZY, Richardson MOW. Effect of water absorption on the mechanical properties of hemp fibre reinforced polyester composites. Compos Sci Technol. 2007;67(7–8):1674–1683.

5. Nurazzi NM, Asyraf MRM, Fatimah Athiyah S, Shazleen SS, Rafiqah SA, Harussani MM, et al. A review on mechanical performance of hybrid natural fiber polymer composites for structural applications. Polymers (Basel). 2021;13(13):2170.
6. Prem Kumar R, Muthukrishnan M, Felix Sahayaraj A. Effect of hybridization on natural fiber reinforced polymer composite materials: A review. Polym Compos. 2023;44(8):4459–4479.
7. Kumlu U, Karaçor B, Özcanlı M. Effects of different production methods and hybridization on mechanical characteristics of basalt, flax, and jute fiber-reinforced composites. Mater Test. 2025;67(1):111–124.
8. Thimmegowda DY, Hindi J, Markunti GB, Kakunje M. Enhancement of mechanical properties of natural fiber reinforced polymer composites using different approaches: A review. J Compos Sci. 2025;9(5):220. doi: 10.3390/jcs9050220.
9. Pingulkar H, Mache A, Munde Y, Siva I. A comprehensive review on drop weight impact characteristics of bast natural fiber reinforced polymer composites. Mater Today Proc. 2021;44:3872–3880. doi: 10.1016/j.matpr.2020.12.925.
10. Francucci G, Palmer S, Hall W. External compaction pressure over vacuum-bagged composite parts: Effect on the quality of flax fiber/epoxy laminates. J Compos Mater. 2018;52(1):3–15. doi: 10.1177/0021998317701998.
11. ASTM International. ASTM D3039/D3039M: Standard test method for tensile properties of polymer matrix composite materials. West Conshohocken (PA): ASTM International.
12. ASTM International. ASTM D790: Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. West Conshohocken (PA): ASTM International.
13. ASTM International. ASTM D7136/D7136M-15: Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop-weight impact event. West Conshohocken (PA): ASTM International.
14. Sumesh KR, Ajithram A, Palanisamy S, Kavimani V. Mechanical properties of ramie/flax hybrid natural fiber composites under different conditions. Biomass Convers Biorefin. 2023;14:29579–29590. doi: 10.1007/s13399-023-04628-5.
15. Mohanavel V, Diwakar G, Govindasamy M, Singh V, Rajakumar IPT, Soudagar MEM, et al. Fabrication of ramie/hemp fibers-reinforced hybrid polymer composite: A comprehensive study on biological and structural application. AIP Adv. 2024;14(8):085325. doi: 10.1063/5.0223604.
16. Seid AM, Adimass SA. Review on the impact behavior of natural fiber epoxy based composites. Heliyon. 2024;10(20):e39116. doi: 10.1016/j.heliyon.2024.e39116.
17. Le Duigou A, Kervoelen A, Le Grand A, Nardin M, Baley C. Interfacial properties of flax fibre-epoxy resin systems: Existence of a complex interphase. Compos Sci Technol. 2014;100:152–157. doi: 10.1016/j.compscitech.2014.06.009.
18. Fegade R, Chaudhari R, Nehete R, Tale V, Mate D, Chopade P, et al. Comprehensive review of composite materials: Classification, manufacturing methods, mechanical behavior, failure modes, and emerging applications. J Polym Compos. 2026;14(1):923–939.
19. Fegade R, Chaudhari R, Nehete R, Tale V, Mate D, Yadav S, et al. Development and mechanical characterization of hybrid natural fiber-reinforced polymer matrix composites for structural applications. J Polym Compos. 2026;14(1):1181–1189.
20. Yadav S, Pawar RS, Tale V, Sambare A, Fegade R, Kolgiri S. Evaluating fiber volume fraction and defects in fiber reinforced polymer composites for T-joint applications. J Polym Compos. 2026;14(1):1222–1235.
21. Wadate PR, Fegade RS, Gaikwad MN, Sawalkar YM, Shevale RA. Design and mathematical quantification of a compressed-air vehicle. J Polym Compos. 2026;14(1):1026–1035.
22. Tike RH, Gautam NK, Kattimani PC, Bhople N, Fegade R, Nehete R, et al. Design and computational analysis of hybrid carbon fiber-enhanced metal matrix composite spur gears. J Polym Compos. 2026;14(1):158–172.
23. Tike RH, Gautam NK, Yadav TK, Deokar S, Fegade R, Nehete R, et al. A systematic review of advanced composite materials for high-performance spur gear applications. J Polym Compos. 2026;14(1):209–220.

