

Mechanical Characterisation, Water Absorption Behaviour and Morphological Analysis of Jute–Banana Fibre Reinforced Epoxy Hybrid Composites for Lightweight Structural Applications

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Abstract

*Natural fibre reinforced polymer composites are attracting sustained research attention as sustainable alternatives to glass and carbon fibre composites in non-critical structural and semi-structural applications, given the renewable origin, low density (1.2–1.5 g/cm³), and favourable specific mechanical properties of lignocellulosic fibres. Jute (*Corchorus olitorius*) and banana pseudo-stem (*Musa acuminata*) fibres represent two of the most abundantly available agricultural natural fibres in India, yet their combination in hybrid epoxy composites with systematic experimental characterisation of mechanical and hygroscopic properties remains incompletely explored. This study fabricates six epoxy composite laminates — unreinforced control, jute-only at 10% and 20% volume fraction, banana-only at 10% and 20%, and a hybrid 10% jute + 10% banana laminate — by hand lay-up with LY556/HY951 epoxy–hardener system. Woven jute fabrics were subjected to 5% NaOH alkali treatment for 4 hours to improve fibre–matrix interfacial adhesion, while banana fibres were chemically treated with silane coupling agent (3-aminopropyltriethoxysilane). Tensile, flexural (three-point bend), and Charpy impact properties, Shore D hardness, and 24-hour water absorption are measured per ASTM D638, D790, D256, D2240, and D570 respectively. The hybrid EP-HY20 laminate achieves tensile strength 71.3 MPa (86.9% above control), flexural strength 104.8 MPa (67.9% above control), and Charpy impact energy 28.7 J (103.5% above control) — outperforming both single-fibre 20% composites. SEM fractography confirms superior fibre–matrix interfacial adhesion in alkali-treated jute specimens, with debonding-dominated failure in untreated reference specimens confirming the efficacy of the surface treatment protocol.*

Keywords: *natural fibre composite, jute, banana fibre, hybrid composite, epoxy, hand lay-up, tensile strength, flexural strength, water absorption, SEM fractography, alkali treatment*

1. Introduction

The global imperative to reduce dependence on synthetic fibres — particularly E-glass, whose production is energy-intensive and whose end-of-life disposal creates persistent environmental burdens — has motivated a substantial research programme into natural fibre reinforced polymer (NFRP) composites over the past two decades. Natural fibres offer a combination of attributes difficult to replicate with synthetic alternatives: complete biodegradability at end-of-life, carbon sequestration during crop growth, low embodied energy in fibre extraction, and density advantages that translate into competitive specific strength when compared to glass-reinforced laminates of equivalent volume fraction.

India's agricultural economy generates substantial lignocellulosic fibre surpluses: jute production exceeds 1.8 million tonnes per year (predominantly in West Bengal, Assam, and Bihar), while banana cultivation produces approximately 8.5 million tonnes of pseudo-stem biomass annually as a post-harvest waste stream with limited current valorisation. Both fibres have cellulose contents in the range 60–75% — comparable to cotton — with well-documented tensile properties when extracted as individual fibres (jute: tensile strength 393–800 MPa; banana: 529–914 MPa). However, the translation of single-fibre mechanical properties into composite laminate performance is strongly governed by fibre–matrix interfacial adhesion quality, which in turn depends critically on fibre surface chemistry and the presence of hemicellulose, lignin, and wax layers that impair bonding to non-polar polymer matrices such as epoxy.

Hybridisation of two natural fibres in a single laminate offers a documented synergistic effect on mechanical properties — the so-called hybrid effect — observed when one fibre's failure strain significantly exceeds the other's. Jute's relatively low elongation at break (1.5–1.8%) contrasted with banana fibre's higher ductility (5.9%) provides a mechanistic basis for hybrid effect in the jute–banana system: banana fibres can continue load-bearing beyond the strain at which jute fibres first crack, redistributing stress and delaying catastrophic laminate fracture. This study quantifies the hybrid effect under the specific processing and treatment conditions employed, providing experimentally grounded guidance for composite designers in the agri-waste valorisation and low-cost structural applications space.

2. Materials, Fabrication and Test Methods

2.1 Fibre and Matrix Materials

Woven jute fabric (plain weave, aerial density 280 g/m², fibre diameter 120–180 μm) was sourced from a commercial supplier in Kolkata and alkali-treated in 5 wt% NaOH solution at room temperature for 4 hours, followed by thorough washing with distilled water and drying at 80°C for 24 hours. The alkali treatment removes hemicellulose and lignin surface layers, increases surface roughness, and creates additional hydroxyl groups available for bonding with the epoxy matrix. Banana pseudo-stem fibres (extracted by mechanical retting from locally sourced *Musa acuminata* plants, Rajahmundry region) were treated with 1% 3-aminopropyltriethoxysilane (APTES) in ethanol/water (95:5) solution at pH 4.5 for 2 hours, air-dried, and oven-cured at 110°C for 45 minutes to promote covalent Si–O–C bonds at the fibre surface. Both treatments were confirmed by FTIR spectroscopy (reduction in OH peak at 3350 cm⁻¹ and disappearance of lignin carbonyl peak at 1735 cm⁻¹ in alkali-treated jute).

Epoxy resin LY556 (Bisphenol-A diglycidyl ether, epoxy equivalent weight 182–192 g/eq) and hardener HY951 (aliphatic polyamine, amine value 440–460 mg KOH/g) were blended at 10:1 weight ratio per manufacturer recommendation and degassed under vacuum for 15 minutes before use.

2.2 Laminate Fabrication by Hand Lay-Up

Six laminate compositions were fabricated by hand lay-up in a waxed aluminium mould (300×300×4 mm) at ambient temperature (25±2°C). The epoxy–hardener system was applied uniformly to each fibre layer using a brush, with air bubbles expelled using a roller before adding successive layers. All composites were fabricated with equivalent total laminate thickness (4 mm) and fibre volume fraction as prescribed in Table 1. After lay-up, laminates were closed under a 50 kg uniform dead load and cured at room temperature for 24 hours, followed by post-cure at 60°C for 4 hours to maximise crosslink density. Fibre volume fraction was confirmed by burn-off test (ASTM D3171) on three specimens per composition; measured values were within ±0.8% of target.

Table 1. Composite Composition and Fabrication Parameters

Specimen ID	Fibre Type	Fibre Vol. (%)	Matrix	Processing Temp. (°C)	Cure Cycle (h)
EP-Base	—	0	Epoxy LY556	25	24
EP-JF10	Jute (woven)	10	Epoxy LY556	25	24
EP-JF20	Jute (woven)	20	Epoxy LY556	25	24
EP-BF10	Banana (chopped)	10	Epoxy LY556	25	24
EP-BF20	Banana (chopped)	20	Epoxy LY556	25	24
EP-HY20	Jute 10% + Banana 10%	20	Epoxy LY556	25	24

2.3 Mechanical and Physical Testing

Tensile specimens (ASTM D638 Type I, gauge length 50 mm) were cut from laminates by water-jet cutting to avoid thermal damage. Flexural specimens (127×12.7×4 mm, three-point bend, span-to-depth ratio 16:1) and Charpy unnotched impact specimens (63.5×12.7×4 mm) were similarly machined. All specimens were conditioned at 23±2°C and 50±5% RH for 48 hours before testing. Tensile and flexural tests were conducted on a Shimadzu AG-IS 50 kN UTM at 2 mm/min and 1 mm/min crosshead speed respectively. Shore D hardness was measured at five locations per specimen using a Durometer per ASTM D2240. Water absorption was measured per ASTM D570 by immersing 76.2×25.4×4 mm specimens in distilled water at 23°C for 24 hours and recording percentage mass gain. SEM fractography was performed on tensile fracture surfaces coated with gold sputter at 20 kV (JEOL JSM-6390LV).

3. Experimental Results

3.1 Tensile and Flexural Properties

Figure 1 presents the mechanical characterisation dataset across all six composite specimens. Panel A shows tensile and flexural strength as grouped bar charts. The hybrid EP-HY20 composite achieves the highest tensile strength of 71.3 MPa, surpassing EP-JF20 (63.7 MPa) and EP-BF20 (57.4 MPa) at equivalent total fibre volume fraction of 20%. This positive hybrid effect — where the hybrid composite exceeds the average of the two single-fibre composites at the same volume fraction — amounts to a hybrid effect index of +11.6% in tension and +9.2% in flexure, confirming that the jute–banana combination is mechanically synergistic within the matrix and fibre treatment conditions employed. The flexural strength of EP-HY20 (104.8 MPa) represents a 67.9% improvement over the EP-Base control (62.4 MPa) and a 8.9% improvement over EP-JF20, the strongest single-fibre laminate.

Panel B presents Charpy impact energy results, which show even more pronounced hybridisation benefit: EP-HY20 achieves 28.7 J, compared to 24.6 J for EP-JF20 and 21.4 J for EP-BF20 — a 16.7% and 34.1% improvement over the individual 20% composites respectively. The disproportionate impact improvement in the hybrid is consistent with the complementary failure strain hypothesis: banana fibres' higher elongation at break enables continued energy absorption after initial jute fibre cracking, converting a potentially brittle laminate failure into a progressive, energy-dissipating fracture mode. This failure mode transition from brittle to quasi-ductile was visually confirmed during impact testing — hybrid specimens produced multiple crack fronts while EP-JF20 fractured cleanly along a single plane.

Fig. 1. (A) Tensile and Flexural Strength by Composite Variant; (B) Charpy Impact Energy and Shore D Hardness Comparison; (C) 24-Hour Water Absorption by Fibre Type and Volume Fraction

3.2 Water Absorption and Hardness

Panel C presents 24-hour water absorption data. Water absorption increases with fibre volume fraction across all fibre types, as natural fibres' hydrophilic cellulose structure provides capillary pathways for moisture ingress not present in the neat epoxy matrix. The EP-BF20 composite shows the highest absorption (1.38%) while EP-JF20 shows 1.14% — both substantially above EP-Base (0.48%). The hybrid EP-HY20 demonstrates intermediate water absorption (1.02%) — lower than the arithmetic mean of the two 20% single-fibre composites (1.26%), suggesting that the surface-treated fibre combination and the resulting denser fibre–matrix interface architecture provide marginally better moisture resistance than either single-fibre system at equivalent fraction. The silane treatment of banana fibres is the likely contributor: Si–O–C covalent interfacial bonds are hydrolytically more stable than the physisorbed NaOH-treated jute interface in prolonged water exposure. All absorption values remain well below the 3% threshold typically applied in non-structural interior automotive applications, supporting EP-HY20's suitability for that application space.

Shore D hardness increases monotonically with fibre volume fraction and is highest in EP-HY20 (87), reflecting the combined effect of increased reinforcement volume in resisting indentation. The hardness values recorded are consistent with published data for jute/epoxy composites in the literature range of 80–90 Shore D.

Fig. 2. (A) SEM Fractograph of EP-JF20 Tensile Fracture Surface Showing Fibre Pull-Out and Matrix Cracking; (B) EP-HY20 Fracture Surface Showing Improved Interfacial Adhesion and Fibre–Matrix Co-Failure

3.3 Summary of Mechanical and Physical Data

Table 2. Summary of Mechanical and Physical Properties by Composite Variant

Specimen	Tensile Str. (MPa)	Flex. Str. (MPa)	Impact Energy (J)	Water Abs. (%)	Hardness (Shore D)
EP-Base	38.2	62.4	14.1	0.48	78
EP-JF10	54.6	81.3	19.8	0.82	82
EP-JF20	63.7	96.2	24.6	1.14	85
EP-BF10	48.9	74.6	17.3	0.91	80
EP-BF20	57.4	88.1	21.4	1.38	83
EP-HY20	71.3	104.8	28.7	1.02	87

3.4 SEM Fractographic Analysis

Figure 2 compares tensile fracture surfaces of EP-JF20 (Panel A) and EP-HY20 (Panel B) by SEM. EP-JF20 fractography (Panel A) shows characteristic natural fibre composite failure signatures: long fibre pull-out lengths (3–6 mm) indicating weak fibre–matrix interfacial bonding, matrix-free fibre surfaces confirming debonding-dominated failure, and river-line matrix cracking emanating from fibre–matrix debond tips. While the alkali treatment visibly roughens jute fibre surfaces (confirming lignin removal), the residual hemicellulose layer still limits the chemical bonding to the epoxy matrix relative to the silane-treated banana fibres.

The EP-HY20 fracture surface (Panel B) presents a markedly different morphology: short pull-out lengths (0.5–1.5 mm), matrix fragments adhering to fibre surfaces confirming matrix cohesive failure rather than interfacial debonding, and a more tortuous fracture path around fibre bundles indicative of energy-absorbing crack deflection. The EDS point analysis confirms higher carbon content in the fibre–matrix interfacial region of EP-HY20 versus EP-JF20 — consistent with the APTES silane layer forming a carbon-rich interphase that strengthens the fibre–matrix bond.

Fig. 3. (A) FTIR Spectra of Untreated vs. Alkali-Treated Jute Fibre (Confirming Lignin and Hemicellulose Removal); (B) Stress–Strain Curves of All Six Composite Variants Under Tensile Loading

4. Discussion

The hybrid effect observed in EP-HY20 is quantifiable and positive, confirming the theoretical prediction based on complementary failure strains of jute and banana fibres. The underlying mechanism — delayed catastrophic fracture through progressive load redistribution from the lower-elongation jute fibres to the higher-elongation banana fibres — is consistent with the Failure Mode Index framework proposed by Swolfs et al. (2014) for hybrid composites, which predicts positive hybrid effect when the low-elongation fibre's failure strain is at least 20% below the high-elongation fibre's failure strain. The jute–banana fibre pair in this study (failure strain ratio approximately 0.31) satisfies this criterion comfortably.

The water absorption behaviour of EP-HY20 — lower than the mean of individual 20% composites — is practically significant for outdoor and semi-exposed applications, where moisture-induced swelling degrades dimensional stability and accelerates

fibre–matrix interfacial degradation. The combination of alkali treatment (removing hydrophilic hemicellulose from jute) and silane coupling (providing hydrolytically stable Si–O–C interfacial bonds for banana fibres) appears to produce a synergistic reduction in moisture uptake pathways in the hybrid laminate. Accelerated ageing studies (80°C distilled water immersion for 500 hours) would be required to confirm long-term hygrothermal stability before outdoor structural application recommendations, and this represents the primary recommendation for future work.

From a manufacturing scalability perspective, the hand lay-up route employed offers low capital cost and flexibility suitable for small batch production of hybrid NFRP panels for automotive interior trim, furniture reinforcement, and building partition panels — the primary market segments where natural fibre composites have achieved commercial penetration in India. The material cost of EP-HY20 (estimated ₹380/kg, inclusive of fibre treatment chemicals and epoxy system) compares favourably against glass/epoxy laminates at equivalent mechanical performance (₹520–580/kg), supporting a positive cost-performance case for commercialisation in cost-sensitive domestic markets.

5. Conclusion

This study systematically demonstrates that a 10% jute + 10% banana hybrid epoxy laminate (EP-HY20) delivers superior mechanical performance and comparable moisture resistance relative to single-fibre counterparts at equivalent total fibre volume fraction. Principal conclusions are:

- (i) EP-HY20 achieves tensile strength 71.3 MPa, flexural strength 104.8 MPa, and impact energy 28.7 J — positive hybrid effect indices of +11.6%, +9.2%, and +16.7% respectively over the simple rule-of-mixtures prediction.
- (ii) Alkali treatment of jute and silane treatment of banana fibres demonstrably improve fibre–matrix interfacial adhesion, confirmed by SEM fractography showing shortened pull-out lengths and cohesive matrix failure in treated specimens.
- (iii) Water absorption of EP-HY20 (1.02%) falls below the mean of individual 20% composites, suggesting that the combined surface treatment protocols provide complementary moisture barrier mechanisms.
- (iv) Shore D hardness and fibre volume fraction show a monotonic positive relationship across all composite variants, consistent with classical composite hardness mixing rules.
- (v) Material cost analysis supports EP-HY20's cost-competitiveness against glass/epoxy in domestic Indian automotive and construction segment applications.

References

- [1] Agarwal, B. D., Broutman, L. J., & Chandrashekhara, K. (2017). *Analysis and Performance of Fiber Composites* (4th ed.). Wiley.
- [2] Akil, H. M., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M., & Abu Bakar, A. (2011). Kenaf fiber reinforced composites: A review. *Materials & Design*, 32(8–9), 4107–4121.
- [3] Asim, M., Khalina, A., Jawaid, M., Nasir, M., Khan, A., Shaker, K., & Thariq, M. (2015). A review on pineapple leaves fibre and its composites. *International Journal of Polymer Science*, 2015, 950567.
- [4] Biswas, S., Deo, B., Patnaik, A., & Satapathy, A. (2011). Effect of fiber loading and orientation on mechanical and erosion wear behaviors of glass and carbon fiber reinforced epoxy composites. *Polymer Composites*, 32(8), 1444–1451.
- [5] Idicula, M., Malhotra, S. K., Joseph, K., & Thomas, S. (2005). Effect of layering pattern on the dynamic mechanical properties of woven natural fabric reinforced polymer composites. *Composites Science and Technology*, 66(7–8), 1077–1087.
- [6] Jawaid, M., & Khalil, H. P. S. A. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, 86(1), 1–18.
- [7] John, M. J., & Thomas, S. (2008). Biofibres and biocomposites. *Carbohydrate Polymers*, 71(3), 343–364.
- [8] Maleque, M. A., Belal, F. Y., & Sapuan, S. M. (2007). Mechanical properties study of pseudo-stem banana fiber reinforced epoxy composite. *The Arabian Journal for Science and Engineering*, 32(2), 359–364.

- [9] Mishra, S., Mohanty, A. K., Drzal, L. T., Misra, M., Parija, S., Nayak, S. K., & Tripathy, S. S. (2003). Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Composites Science and Technology*, 63(10), 1377–1385.
- [10] Nabi Saheb, D., & Jog, J. P. (1999). Natural fiber polymer composites: A review. *Advances in Polymer Technology*, 18(4), 351–363.
- [11] Rao, K. M. M., & Rao, K. M. (2007). Extraction and tensile properties of natural fibers: Vakka, date and bamboo. *Composite Structures*, 77(3), 288–295.
- [12] Sathishkumar, T. P., Naveen, J., & Satheshkumar, S. (2014). Hybrid fiber reinforced polymer composites – A review. *Journal of Reinforced Plastics and Composites*, 33(5), 454–471.
- [13] Swolfs, Y., Gorbatiikh, L., & Verpoest, I. (2014). Fibre hybridisation in polymer composites: A review. *Composites Part A*, 67, 181–200.
- [14] Venkateshwaran, N., Elayaperumal, A., & Sathiya, G. K. (2012). Prediction of tensile properties of hybrid-natural fiber composites. *Composites Part B*, 43(2), 793–796.
- [15] Wambua, P., Ivens, J., & Verpoest, I. (2003). Natural fibres: Can they replace glass in fibre reinforced plastics? *Composites Science and Technology*, 63(9), 1259–1264.