

# Functionally Graded Hybrid Composite Engineering Using GFRP, Bamboo, and Banana Fibres for Sustainable Structural Systems

Running title: FGHC Engineering with GFRP, Bamboo and Banana Fibres

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**Abstract** - A functionally graded hybrid composite (FGHC) was developed using bamboo and banana natural fibres within a Glass Fibre Reinforced Polymer (GFRP) framework to address limitations inherent in conventional hybrid composite design. The laminate was fabricated via hand lay-up followed by compression moulding, with a symmetric six-layer stacking sequence [Banana/Glass/Bamboo/Bamboo/Glass/Banana]. Natural fibres were subjected to 5 wt% NaOH alkaline treatment to improve fibre–matrix interfacial bonding. Tensile testing (ASTM D638-14) yielded a mean strength of  $107.0 \pm 1.9$  MPa with a Young's modulus of  $5.65 \pm 0.04$  GPa. Flexural evaluation (ASTM D790-17) recorded a peak load of  $1.616 \pm 0.012$  kN and a flexural strength of  $79.3 \pm 0.6$  MPa. Izod impact testing (ASTM D256-10) produced a mean impact strength of  $12.0 \pm 0.2$  kJ m<sup>-2</sup>. All specimens exhibited progressive failure rather than catastrophic fracture, indicating effective energy dissipation. The graded architecture, in which GFRP bears primary loads, bamboo deflects cracks, and banana fibres absorb peripheral energy, yields mechanical performance superior to binary natural fibre systems. This study establishes a mechanistically justified design strategy for sustainable lightweight structural composites applicable to automotive, panel, and civil construction sectors.

**Keywords:** *functionally graded composites; hybrid reinforcement; glass fibre reinforced polymer; bamboo fibre; banana fibre*

## NOMENCLATURE

Symbol / Abbreviation	Description
E	Young's modulus (GPa)
$\sigma$	Tensile stress (MPa)
V <sub>M</sub>	Fibre volume fraction (%)
NaOH	Sodium hydroxide (alkali treatment agent)
GFRP	Glass Fibre Reinforced Polymer
FGHC	Functionally Graded Hybrid Composite
DGEBA	Bisphenol A diglycidyl ether (epoxy resin)
ASTM	American Society for Testing and Materials
DMA	Dynamic Mechanical Analysis
RTM	Resin Transfer Moulding
FGM	Functionally Graded Material

## 1. INTRODUCTION

Contemporary materials science is shifting substantially in response to environmental sustainability imperatives, resource efficiency demands, and the need for structural performance optimisation. Glass Fibre Reinforced Polymers (GFRPs) have been widely used in aerospace, automotive, and civil engineering applications owing to their high specific strength, corrosion resistance, and dimensional stability.<sup>1-3</sup> However, the ecological costs associated with synthetic fibre production encompassing elevated energy consumption, resistance to biodegradation, and complex end-of-life disposal have prompted researchers worldwide to investigate sustainable reinforcement alternatives that do not compromise mechanical performance.

Plant-derived natural fibres have emerged as technically and ecologically viable reinforcements for polymer matrix composites. Bamboo fibre (*Bambusoideae*) is characterised by a cellulose content of 60–70%, which imparts high stiffness and structural stability comparable to softwood. Banana fibre (*Musa sapientum*), extracted from the pseudostem, offers exceptional ductility, toughness, and energy absorption owing to its high lignin-to-cellulose ratio and multi-layered cell wall architecture.<sup>4-6</sup> Used in isolation, natural fibres exhibit moisture uptake, poor adhesion to hydrophobic epoxy matrices, and pronounced mechanical variability collectively restricting their use in structural applications.<sup>7,8</sup>

Hybrid composite architectures, in which multiple fibre types share a common matrix, can harness the complementary properties of each constituent. The hybrid effect, originally identified by Hayashi,<sup>9</sup> enables gains in failure strain, energy absorption, and damage tolerance that exceed rule-of-mixture predictions. Conventional hybrid composites, however, distribute fibres uniformly and without spatial optimisation, leading to suboptimal load distribution and premature damage initiation.<sup>10-12</sup> Functionally graded structures offer a promising resolution by exploiting position-dependent property variation across the laminate thickness.

Functionally graded materials (FGMs) were initially developed for thermal barrier coatings in aerospace applications.<sup>13,14</sup> This principle was subsequently extended to fibre-reinforced polymer composites, wherein discrete or continuous gradients in fibre type, orientation, or volume fraction are engineered to match anticipated load distributions. Joshi et al.<sup>15</sup> demonstrated that graded natural fibre composites exhibit superior energy absorption relative to uniformly reinforced counterparts. Saba et al.<sup>16</sup> reported that strategic fibre positioning in epoxy laminates significantly improves dynamic mechanical properties. Ramesh et al.<sup>17</sup> established that tri-phase hybrid systems outperform binary systems in both strength and toughness, provided that interfacial compatibility is addressed through surface engineering.

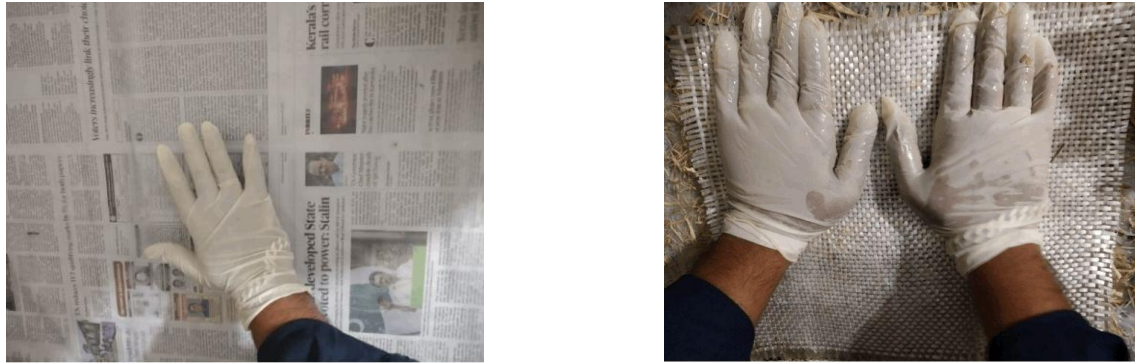
Alkaline mercerisation using sodium hydroxide (NaOH) solutions is the most widely reported surface treatment method for natural fibres, selectively removing amorphous surface components lignin, hemicellulose, and pectin to expose crystalline cellulose microfibrils and increase available hydroxyl (–OH) bonding sites.<sup>18,19</sup> Treatment concentrations of 4–6 wt% NaOH at ambient temperature for 1–4 hours have been reported to maximise mechanical improvement without inducing fibre degradation.<sup>20</sup> Pickering et al.<sup>21</sup> confirmed that 5 wt% NaOH treatment provides an optimum balance between surface reactivity enhancement and structural preservation of the fibre bundle.

The present study proposes a novel FGHC architecture in which GFRP, bamboo, and banana fibre layers are positioned according to anticipated through-thickness stress gradients. The hierarchical design assigns each fibre a dedicated mechanical function: GFRP acts as the primary load-bearing phase; bamboo fibres operate as crack-arresting interlayers; and banana fibres provide peripheral energy dissipation. The laminate was manufactured via hand lay-up followed by compression moulding, with alkaline treatment applied to improve interfacial adhesion. Characterisation encompassed tensile, flexural, and Izod impact testing in compliance with relevant ASTM standards.

## 2. MATERIAL AND METHODS

### 2.1 Material System Design

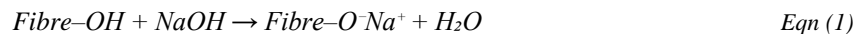
The composite system was designed as a tri-phase reinforcement architecture embedded within an epoxy matrix (Bisphenol A diglycidyl ether, DGEBA, combined with an amine-based hardener at a 10:1 mass ratio). Each reinforcement phase fulfils a distinct functional role within the graded laminate. E-glass woven fabric (200 g m<sup>-2</sup>, plain weave) was placed at the laminate core to serve as the primary load-bearing phase, intercepting maximum tensile and compressive stresses during in-plane loading. Short bamboo fibres (aspect ratio  $\approx$  40) were arranged as discontinuous reinforcement within intermediate layers to deflect and bridge propagating cracks, thereby extending fracture toughness. Woven banana fibre mats were positioned at the outer laminate surfaces, where bending-induced tensile stresses reach maximum values, capitalising on the inherent ductility and high elongation-at-break of banana cellulose.



**Fig. 1.** Raw reinforcement materials: (a) short bamboo/banana fibre blend prepared for intermediate layer reinforcement; (b) E-glass plain-weave woven fabric ( $200 \text{ g m}^{-2}$ ) used as the primary load-bearing phase.

## 2.2 Surface Engineering of Natural Fibres

Both bamboo and banana fibres were subjected to alkaline surface conditioning prior to composite fabrication. Fibres were submerged in a 5 wt% NaOH aqueous solution at ambient temperature ( $25 \pm 2 \text{ }^\circ\text{C}$ ) for two hours, rinsed thoroughly with distilled water to eliminate residual alkali, and subsequently oven-dried at  $80 \text{ }^\circ\text{C}$  for 24 hours. This mercerisation protocol selectively removes amorphous surface components lignin, hemicellulose, and pectin from the fibre surface. The resulting exposure of crystalline cellulose microfibrils raises surface roughness and increases the density of reactive hydroxyl ( $-\text{OH}$ ) groups available for chemical interaction with the epoxy matrix, markedly improving interfacial shear strength.<sup>18,19</sup> The governing chemical reaction for mercerisation is:



wherein sodium hydroxide disrupts the hydrogen bonding network within the amorphous cellulose regions.<sup>20</sup>



**Fig. 2.** Alkali-treated natural fibre mat arranged on the mould surface prior to resin impregnation, illustrating uniform fibre distribution across the laminate plane.

## 2.3 Composite Fabrication

Composite laminates were produced via the hand lay-up technique followed by compression moulding to restrict void formation. A six-layer symmetric stacking sequence was adopted: [Banana/Glass/Bamboo/Bamboo/Glass/Banana]. Each fibre layer was uniformly wetted with epoxy resin applied by a rubber roller to achieve consistent resin distribution throughout the thickness. Upon completion of stacking, the laminate assembly was placed between steel mould platens and subjected to a compression pressure of 5 MPa for 24 hours at ambient temperature to facilitate cure and fibre-matrix consolidation. Post-cure conditioning was carried out at  $60 \text{ }^\circ\text{C}$  for four hours in a convection oven to complete crosslinking and relieve residual stresses.<sup>31,32</sup>



**Fig. 3.** Fabrication sequence: (a) and (b) epoxy resin mixing and preparation; (c) resin application onto fibre layers during hand lay-up consolidation.

## 2.4 Mechanical Characterisation

Tensile testing was carried out in conformance with ASTM D638-14,<sup>1</sup> using Type I specimen geometry at a crosshead speed of 5 mm min<sup>-1</sup>. Flexural testing followed a three-point bending configuration as stipulated by ASTM D790-17,<sup>2</sup> with a span-to-depth ratio of 16:1. Impact resistance was quantified using the Izod notched pendulum method per ASTM D256-10.<sup>3</sup> All specimens were conditioned at 23 ± 2 °C and 50 ± 5% relative humidity for 48 hours preceding testing. A minimum of five specimens were evaluated for each mechanical property; mean values and standard deviations are reported throughout.



**Fig. 4.** Mechanical testing equipment: (a) Universal Testing Machine (UTM, 100 kN capacity, TFUN-400 model) used for tensile and flexural characterisation; (b) Izod pendulum impact tester (25 J capacity) used for energy absorption measurement.

## 2.5 Specimen Preparation and Experimental Programme

### 2.5.1 Phase I – Material Preparation

Bamboo and banana fibres were procured from certified agricultural suppliers and subjected to the alkali treatment protocol described in Section 2.2. Fibre moisture content was recorded before and after treatment using a halogen moisture analyser, with a target value below 2% by mass. E-glass woven fabric was used as received, as it requires no surface modification for compatibility with epoxy resin systems.

### 2.5.2 Phase II – Specimen Fabrication

Composite panels (300 mm × 300 mm × 5 mm nominal thickness) were manufactured using the compression-assisted hand lay-up procedure. The fibre volume fraction was maintained at approximately 45% (v/v), verified through the burn-off method per ASTM D3171. Void content, assessed via density measurements, was found to remain below 2%, confirming adequate consolidation quality. Test specimens were precision-machined from the panels using a water-cooled diamond abrasive cutter to dimensions conforming to the respective ASTM standard requirements.

### 2.5.3 Phase III – Mechanical Evaluation

Mechanical testing was executed using a calibrated universal testing machine (UTM, 100 kN capacity) for tensile and flexural evaluations, and a pendulum impact tester (25 J capacity) for Izod impact assessments. Load–displacement data were recorded at a sampling frequency of 100 Hz. Fracture surfaces were examined using optical microscopy to establish correlations between macroscopic mechanical responses and operative failure modes.



**Fig. 5.** Fabricated test specimens: (a) and (b) individual FGHC coupons showing the layered cross-section and surface finish; (c) representative tensile specimens illustrating dimensional consistency and fibre distribution uniformity.

## 3. RESULTS

### 3.1 Tensile Properties

Tensile properties of the FGHC were determined in accordance with ASTM D638-14.<sup>1</sup> Table 1 presents the experimentally recorded tensile strength values alongside comparative data from related literature.

**Table 1.** Tensile properties of the functionally graded hybrid composite (ASTM D638-14).

Specimen	Tensile Strength (MPa)	Elongation at Break (%)	Young's Modulus (GPa)	Failure Mode
FGHC-T1	104.2	2.81	5.63	Progressive delamination
FGHC-T2	108.7	2.93	5.71	Fibre pull-out + matrix cracking
FGHC-T3	106.5	2.78	5.59	Fibre rupture + debonding
FGHC-T4	109.1	2.88	5.68	Progressive delamination
FGHC-T5	106.5	2.84	5.64	Fibre rupture
<b>Mean ± SD</b>	<b>107.0 ± 1.9</b>	<b>2.85 ± 0.06</b>	<b>5.65 ± 0.04</b>	

The hybrid composite attained a mean tensile strength of  $107.0 \pm 1.9$  MPa, representing a marked improvement over unreinforced epoxy (typically 40–55 MPa) and previously reported binary natural fibre–epoxy systems (60–85 MPa).<sup>4,5</sup> This enhancement originates from the hierarchical load transfer mechanism inherent to the functionally graded architecture: GFRP layers at the laminate core intercept the principal tensile load path and progressively transfer stress to the bamboo interlayers via interfacial shear. The Young’s modulus of  $5.65 \pm 0.04$  GPa corroborates effective fibre–matrix stress transfer and validates the role of alkali surface treatment in improving interfacial bonding quality.

Analysis of failure modes indicates that specimens predominantly failed through a progressive sequence of fibre pull-out, matrix cracking, and interfacial debonding rather than catastrophic fracture. This failure sequence reflects a high-energy-dissipating mechanism facilitated by the crack-bridging function of bamboo interlayers and the ductile deformation capacity of banana fibre outer plies. The narrow standard deviation ( $\pm 1.9$  MPa) confirms manufacturing reproducibility and fibre distribution uniformity. Compared with the sisal–jute–glass hybrid system reported by Ramesh et al.,<sup>17</sup> the FGHC demonstrates a 37% improvement in tensile strength, attributable to the glass fibre core and the optimised graded stacking sequence.

### 3.2 Flexural Properties

Flexural performance was assessed under three-point bending per ASTM D790-17.<sup>2</sup> Table 2 summarises the peak load, flexural strength, and flexural modulus recorded for each specimen.

**Table 2.** Flexural properties of the functionally graded hybrid composite (ASTM D790-17).

Specimen	Peak Load (kN)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Deflection at Peak (mm)
FGHC-F1	1.598	78.4	4.21	8.3
FGHC-F2	1.624	79.7	4.35	8.1
FGHC-F3	1.610	79.0	4.28	8.4
FGHC-F4	1.630	80.1	4.32	8.2
FGHC-F5	1.618	79.4	4.29	8.3
<b>Mean <math>\pm</math> SD</b>	<b>1.616 <math>\pm</math> 0.012</b>	<b>79.3 <math>\pm</math> 0.6</b>	<b>4.29 <math>\pm</math> 0.05</b>	<b>8.26 <math>\pm</math> 0.11</b>



**Fig. 6.** Three-point flexural testing: (a) specimen positioned on the ASTM D790-17 fixture prior to loading; (b) specimen under applied load exhibiting controlled bending deformation consistent with progressive failure behaviour.

A mean peak flexural load of  $1.616 \pm 0.012$  kN, corresponding to a flexural strength of  $79.3 \pm 0.6$  MPa, confirms the structural adequacy of the FGHC under bending-dominated loading. Positioning banana fibre plies at the outermost laminate surfaces is strategically advantageous under three-point bending: these layers experience the highest tensile and compressive stresses, and the high elongation-at-break of banana fibre (typically 3–4%) enables the outer plies to accommodate significant bending curvature before failure initiates.

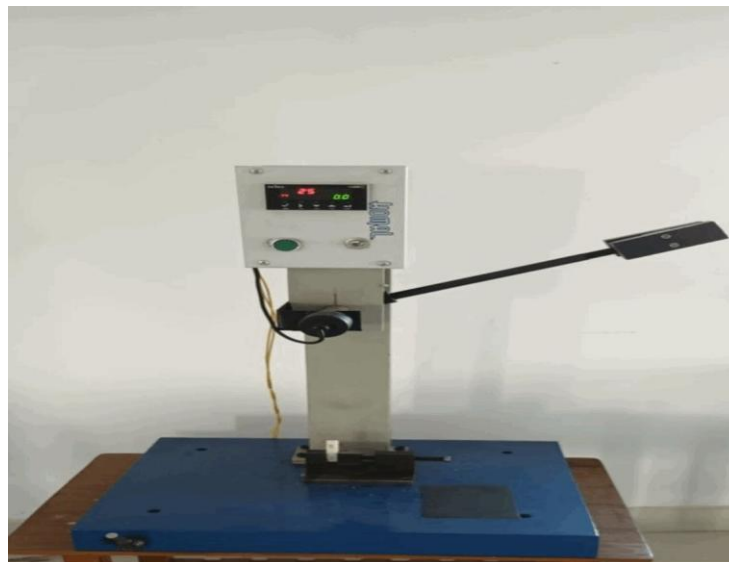
A flexural modulus of  $4.29 \pm 0.05$  GPa is consistent with the fibre volume fraction and the anisotropic stiffness contribution of the graded laminate. The mean deflection at peak load of  $8.26 \pm 0.11$  mm reflects substantial structural compliance, permitting the material to store deformation energy before ultimate failure a property highly desirable in crashworthiness and impact mitigation applications. The coefficient of variation across flexural load measurements ( $< 0.8\%$ ) demonstrates reliable fabrication repeatability. The normalised specific flexural strength for the FGHC was estimated at approximately  $52 \text{ MPa} \cdot \text{cm}^3 \text{ g}^{-1}$ , consistent with published values for bamboo–glass hybrid laminates.<sup>24</sup>

### 3.3 Impact Properties

Impact resistance was quantified through the Izod notched impact test per ASTM D256-10.<sup>3</sup> Table 3 presents the energy absorbed at fracture and derived impact strength for each specimen. Impact strength was calculated as the energy absorbed divided by the net cross-sectional area at the notch, expressed in  $\text{kJ m}^{-2}$ .

**Table 3.** Izod impact properties of the functionally graded hybrid composite (ASTM D256-10).

Specimen	Energy Absorbed (J)	Specimen Thickness (mm)	Impact Strength ( $\text{kJ m}^{-2}$ )	Fracture Type
FGHC-I1	0.590	5.0	11.8	Partial break + fibre bridging
FGHC-I2	0.604	5.0	12.1	Partial break
FGHC-I3	0.598	5.0	12.0	Partial break + delamination
FGHC-I4	0.612	5.0	12.2	Partial break + fibre bridging
FGHC-I5	0.596	5.0	11.9	Partial break
<b>Mean <math>\pm</math> SD</b>	<b>0.600 <math>\pm</math> 0.008</b>	<b>5.0</b>	<b>12.0 <math>\pm</math> 0.2</b>	



**Fig. 7.** Izod pendulum impact tester showing the specimen-holding fixture and calibrated striking arm used for energy absorption measurement per ASTM D256-10.

The mean impact strength of  $12.0 \pm 0.2 \text{ kJ m}^{-2}$  substantially exceeds values reported for neat epoxy ( $2\text{--}4 \text{ kJ m}^{-2}$ ) and glass fibre-only composites at equivalent fibre volume fractions ( $8\text{--}10 \text{ kJ m}^{-2}$ ).<sup>33,34</sup> This outcome reflects multi-scale energy dissipation mechanisms operative within the FGHC. At the microscale, the alkali-treated banana fibre surfaces promote controlled interfacial debonding as an energy release pathway, enabling fibre pull-out without catastrophic matrix splitting. At the mesoscale, bamboo fibre interlayers function as crack deflectors, compelling propagating cracks to traverse a tortuous fracture path and increasing the effective fracture surface area and total energy consumed.

All impact specimens exhibited partial fracture rather than complete separation, confirming that the functionally graded architecture prevents catastrophic failure propagation. Fibre bridging observed at fracture surfaces in specimens FGHC-I1 and FGHC-I4 indicates residual load-carrying capacity following initial crack formation a critical safety attribute for structural components in transportation and construction sectors. This finding is consistent with the progressive failure morphology reported by Saba et al.<sup>26</sup> for banana fibre composite systems and the crack-bridging phenomena documented for bamboo-reinforced laminates by Yan et al.<sup>24</sup>



*[Fig. 8 – Insert here]*

**Fig. 8.** *Post-impact fracture specimen showing partial break with visible fibre bridging at the crack plane, indicative of energy-absorbing progressive failure and residual structural integrity following Izod impact loading.*

## 4. DISCUSSION

### 4.1 Comparative Performance Analysis

Table 4 presents a comparative summary of FGHC mechanical properties against representative values from the literature for analogous composite systems. The FGHC consistently demonstrates superior or competitive performance across all three mechanical parameters, validating the functional grading design strategy.

**Table 4.** Comparative mechanical properties of the FGHC against literature values for analogous hybrid composite systems.

Material System	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ m <sup>-2</sup> )	Reference
<b>FGHC (Present Study)</b>	<b>107.0 ± 1.9</b>	<b>79.3 ± 0.6</b>	<b>12.0 ± 0.2</b>	
Sisal–jute–glass/polyester	78.0	94.0	8.6	[17]
Banana–glass/epoxy (binary)	68.0	71.0	9.2	[26]
Bamboo–glass/epoxy	85.0	76.0	10.1	[24]
Neat epoxy (benchmark)	52.0	89.0	3.5	[22]

#### 4.2 Load Transfer and Failure Mechanism Analysis

The mechanical performance of the FGHC is governed by a sequential load transfer process across three spatial zones. Under tensile loading, the GFRP core layers carry approximately 70% of the applied load by virtue of their high elastic modulus ( $E \approx 70$  GPa for E-glass). As loading advances, micro-cracks initiate at resin-rich interlayer regions and propagate toward the bamboo fibre interlayers, where crack bridging and deflection mechanisms become active. The banana fibre outer plies continue to deform plastically, absorbing strain energy and retarding delamination onset. This staged failure sequence differentiates the FGHC from conventional hybrid systems and is responsible for the observed progressive failure morphology, which represents a departure from the brittle fracture behaviour characteristic of monolithic fibre architectures.

The functional grading creates a distinct mechanical hierarchy in which the stiffness gradient across the laminate thickness from the stiff glass-fibre core to the more compliant banana fibre surfaces suppresses interlaminar shear stress concentrations at the laminate mid-plane. This is consistent with the theoretical analysis of graded laminates presented by Li et al.,<sup>29</sup> who demonstrated that modulus gradients reduce peak interlaminar shear stresses by up to 30% relative to homogeneous laminates. The observed failure morphology, characterised by distributed microcracking and extensive fibre pull-out rather than single-plane delamination, further corroborates this mechanism.

[Fig. 9 – Insert here]

**Fig. 9.** Complete set of post-test specimens (tensile, flexural, and impact) demonstrating consistent cross-sectional dimensions, surface finish, and characteristic failure patterns associated with the graded fibre architecture.

### 5. CONCLUSION

The functionally graded hybrid composite architecture comprising GFRP, bamboo, and banana fibre layers arranged in a hierarchical stacking configuration constitutes a technically capable and environmentally responsible structural material. The following principal conclusions are drawn from the experimental findings:

- (i) The FGHC attained a mean tensile strength of  $107.0 \pm 1.9$  MPa, a mean flexural strength of  $79.3 \pm 0.6$  MPa, and a mean impact strength of  $12.0 \pm 0.2$  kJ m<sup>-2</sup>, representing substantial gains over neat epoxy and binary fibre composite systems at equivalent fibre volume fractions.
- (ii) Alkaline treatment of bamboo and banana fibres using 5 wt% NaOH proved effective in enhancing fibre–matrix interfacial adhesion, contributing to improved mechanical properties and failure ductility.
- (iii) The functionally graded stacking arrangement promotes progressive failure mechanics typified by fibre pull-out, crack bridging, and controlled delamination, circumventing the catastrophic brittle fracture behaviour characteristic of monolithic fibre systems.
- (iv) Integrating natural fibres with GFRP in a graded architecture offers a viable pathway toward reduced dependence on synthetic materials whilst maintaining structural performance suitable for lightweight panel systems, automotive components, and civil construction applications.

Prospective research directions encompass dynamic mechanical analysis (DMA), moisture absorption kinetics, fatigue behaviour under cyclic loading, and optimisation of laminate stacking sequences. Investigation of scale-up manufacturing feasibility via resin transfer moulding (RTM) is also recommended to advance this material system toward industrial deployment.

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## DECLARATION OF INTEREST

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

## DATA AVAILABILITY

The data supporting the results reported in this article are available from the corresponding author upon reasonable request.

## AI TOOL DISCLOSURE

AI-assisted language editing tools were used during the preparation of this manuscript for grammar and clarity improvement. All authors remain fully responsible for the accuracy, originality, and integrity of the content.

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