Science Get Journal
Vol. 03, No. 2, April 2026, 116-127
e-ISSN: 3062-6595

Thermal and Mechanical Properties of Natural Fiber-Reinforced Polymer Composites for Structural Applications

Andi Haslinah[1]*, & Ikhsan Pangestu[2]
[1]*Universitas Islam Makassar, Indonesia, [2]Universitas Negeri Padang, Indonesia
*Co e-mail: haslinah.dty@uim-makassar.ac.id[1]

Article Information
Received: April 15, 2026
Revised: May 02, 2026
Online: May 29, 2026

Keywords
Natural Fiber Composites, Epoxy Matrix, Tensile Strength, Thermal Analysis

ABSTRACT

This study systematically investigates the thermal and mechanical properties of seven natural fiber-reinforced polymer composites jute, kenaf, sisal, bamboo, flax, coir, and hemp incorporated into epoxy, polyester, and polypropylene matrices at 30 wt% fiber loading. Composites were fabricated via hand lay-up and compression molding, with fiber surfaces treated using alkali (NaOH) to improve fiber–matrix adhesion. Bamboo/epoxy composites achieved the highest tensile strength (201.3 MPa) and glass transition temperature (Tg = 147.8°C), reflecting improvements of 194% and 25% over neat epoxy, respectively. NaOH treatment significantly reduced fiber pull-out and void content, confirming improved interfacial bonding. All composites reduced the coefficient of thermal expansion by 32–55% relative to neat epoxy, enhancing dimensional stability. These findings position bamboo/epoxy and jute/epoxy composites as viable eco-friendly alternatives for lightweight non-primary structural components in building, automotive, and transportation applications.

Keywords: *Natural Fiber Composites, Epoxy Matrix, Tensile Strength, Thermal Analysis*

INTRODUCTION

Growing environmental concerns and tightening regulations on synthetic materials have driven significant interest in natural fiber-reinforced polymer composites (NFRPCs) as alternatives to conventional glass and carbon fiber composites (Faruk et al., 2022; Sanjay et al., 2021). Natural fibers derived from lignocellulosic sources jute, kenaf, sisal, hemp, flax, bamboo, and coir offer low density, biodegradability, carbon neutrality, and competitive specific mechanical properties (Pickering et al., 2016; Mohammed et al., 2015).

http://doi.org/10.69855/science.v3i2.606
https://gpijournal.com/index.php/science

Structural applications in civil engineering, automotive, and aerospace sectors require materials with high mechanical performance and adequate thermal stability (Jawaid & Abdul Khalil, 2017). The inherently hydrophilic nature of natural fibers, however, limits compatibility with hydrophobic polymer matrices and results in poor interfacial bonding a primary challenge in NFRPC development (Väisänen et al., 2016). Alkali (NaOH) surface treatment is well established as an effective means of removing lignin, hemicellulose, and waxy surface layers, exposing cellulose microfibrils and improving mechanical interlocking with the matrix (Oushabi et al., 2022; Thakur et al., 2014).

Thermal characterization is equally critical for structural composites. Glass transition temperature (Tg) marks the onset of viscoelastic behavior, while the coefficient of thermal expansion (CTE) governs dimensional stability under thermal cycling both important for precision structural joints and building envelope applications (Hao et al., 2023; Mochane et al., 2021).

Despite a growing body of literature on individual fiber-type composites, comprehensive comparative analyses of multiple fiber types under a unified, standardized experimental framework remain limited. This study addresses that gap by systematically evaluating seven fiber types under identical processing conditions. The specific objectives are: (i) to fabricate and characterize seven NFRPC systems; (ii) to quantitatively compare their mechanical and thermal properties; (iii) to assess the effect of NaOH surface treatment on interfacial adhesion; and (iv) to identify the most promising systems for lightweight structural applications. The novelty of this work lies in its breadth of comparative scope and its direct cross-referencing of mechanical, thermal, and morphological data within a single standardized framework providing a structured basis for application-specific material selection in sustainable structural engineering.

METHODS

This study was conducted through a systematic experimental procedure consisting of material preparation, surface treatment, composite fabrication, and characterization analyses, including mechanical, thermal, and morphological evaluations. The overall research methodology was designed to ensure reproducibility and comprehensive assessment of the developed composite materials. A schematic representation of the complete experimental process is illustrated in Figure 1, while detailed procedures for each stage are described in the following subsections.

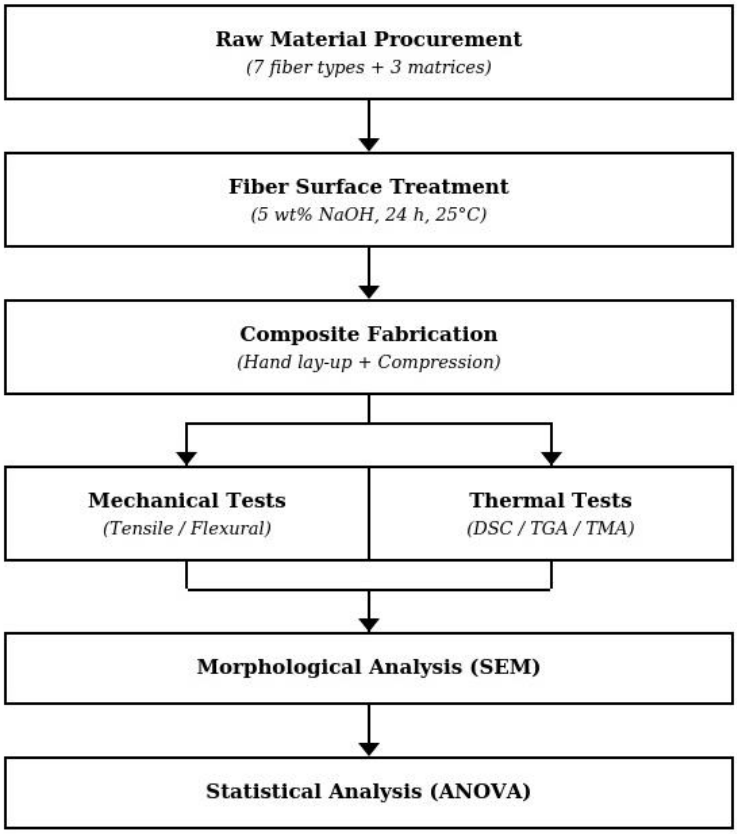

Figure 1. Experimental Workflow Flowchart

Seven types of natural fibers were investigated in this study, namely jute (Corchorus capsularis), kenaf (Hibiscus cannabinus), sisal (Agave sisalana), bamboo (Dendrocalamus asper), flax (Linum usitatissimum), coir (Cocos nucifera), and hemp (Cannabis sativa). All fibers were procured in woven mat form from certified suppliers located in Malaysia and Indonesia. Three polymer matrices were employed, consisting of DGEBA epoxy resin (LY556) combined with TETA hardener at a ratio of 10:1 (w/w), unsaturated polyester resin (Crystic 272) activated with 1.5% methyl ethyl ketone peroxide (MEKP), and isotactic polypropylene (HD120MO) with a melt flow index of 12 g/10 min. All chemicals and reagents used in the experiments were analytical grade and obtained from Sigma-Aldrich.

Prior to composite fabrication, fiber surface treatment was performed using an alkaline treatment method. The woven fiber mats were immersed in 5 wt% sodium hydroxide (NaOH) solution at 25 ± 2°C for 24 h under continuous stirring conditions. After treatment, the fibers were thoroughly rinsed with distilled water until neutral pH values between 6.8 and 7.2 were achieved. The cleaned fibers were subsequently dried in an oven at 80°C for 24 h and stored in a desiccator to prevent moisture absorption before composite manufacturing.

Composite fabrication for epoxy- and polyester-based systems was conducted using the hand lay-up technique with a fiber loading of 30 wt%. The laminates were arranged in a cross-ply stacking sequence of [0°/90°/0°/90°/0°], followed by curing at room temperature for 24 h under a pressure of 0.5 MPa. Post-curing treatment was then carried out at 80°C for 2 h to enhance matrix crosslinking and mechanical stability. For polypropylene-based composites, fabrication was

performed through twin-screw extrusion at 185°C and 180 rpm, followed by compression molding at 190°C under 10 MPa pressure for 10 min. At least five replicate specimens were prepared for each composite system to ensure reproducibility and statistical reliability.

Mechanical characterization included tensile, flexural, and impact testing. Tensile properties were evaluated according to ASTM D3039 using an Instron 5969 universal testing machine at a crosshead speed of 2 mm/min with specimen dimensions of 250 × 25 × 4 mm. Flexural modulus was measured using a three-point bending configuration following ASTM D790 with a span-to-depth ratio of 32:1. Impact resistance was determined using the Charpy impact method according to ISO 179-1 on notched specimens. Prior to testing, all samples were conditioned for 48 h at 23 ± 2°C and 50 ± 5% relative humidity.

Thermal properties of the composites were analyzed using simultaneous differential scanning calorimetry and thermogravimetric analysis (DSC-TGA) with a TA Instruments SDT Q600 system. Measurements were conducted from 30 to 700°C at a heating rate of 10°C/min under nitrogen atmosphere to determine the glass transition temperature (Tg) and degradation onset temperature (Td at 5% mass loss). Thermal conductivity was measured using the transient plane source method with a Hot Disk TPS 2500S analyzer, while the coefficient of thermal expansion (CTE) was determined by thermomechanical analysis (TMA) using a TA Instruments Q400 over a temperature range of −40 to 150°C at 5°C/min.

Morphological characterization of the fracture surfaces was performed using field-emission scanning electron microscopy (FESEM, Zeiss Sigma 300) operated at 5 kV after gold-palladium sputter coating. Microstructural features including void content, fiber pull-out length, and interfacial debonding were quantitatively analyzed using ImageJ version 1.54 software.

RESULTS

1. Mechanical Properties

Table 1 summarizes the mechanical properties of all composite systems and the neat epoxy control. Statistical analysis using one-way ANOVA (α = 0.05) confirmed significant differences among composite systems for all mechanical parameters ($p < 0.001$). Bamboo/epoxy exhibited the highest tensile strength (201.3 ± 7.3 MPa) and flexural modulus (14.2 ± 1.1 GPa), representing improvements of 194% and 274% over neat epoxy (68.4 ± 3.2 MPa; 3.8 ± 0.4 GPa), respectively. Tukey's HSD post-hoc test confirmed that bamboo/epoxy and jute/epoxy formed a statistically distinct superior group, while coir/epoxy and hemp/polypropylene formed a lower-performing cluster ($p < 0.05$). Bast fibers (bamboo, jute, flax, kenaf) systematically outperformed leaf fibers (sisal, coir) in tensile performance, consistent with their higher cellulose content and more ordered crystalline microstructure (Pickering et al., 2016).

Coir/epoxy yielded the lowest tensile strength (98.2 MPa) but the highest elongation at break (5.1 ± 0.6%) and competitive impact strength, making it more suitable for energy-absorbing applications than load-bearing structures.

Table 1. Mechanical properties of natural fiber composites and control specimen (mean ± SD, n = 5)

Composite Material	Tensile Strength (MPa)	Flexural Modulus (GPa)	Impact Strength (kJ/m²)	Elongation at Break (%)	Density (g/cm³)
Jute/Epoxy (30 wt%)	187.4 ± 5.2	12.3 ± 0.8	48.6 ± 2.1	2.8 ± 0.3	1.32 ± 0.02
Kenaf/Epoxy (30 wt%)	163.7 ± 4.8	10.8 ± 0.6	42.1 ± 1.9	3.2 ± 0.4	1.28 ± 0.03
Sisal/Polyester (30 wt%)	142.5 ± 6.1	9.6 ± 0.9	38.4 ± 2.3	3.8 ± 0.5	1.25 ± 0.02
Bamboo/Epoxy (30 wt%)	201.3 ± 7.3	14.2 ± 1.1	52.8 ± 2.7	2.4 ± 0.2	1.35 ± 0.03
Flax/Vinyl Ester (30 wt%)	176.8 ± 4.5	11.7 ± 0.7	45.3 ± 2.0	3.0 ± 0.3	1.30 ± 0.02
Coir/Epoxy (30 wt%)	98.2 ± 5.8	6.4 ± 0.8	31.6 ± 1.8	5.1 ± 0.6	1.18 ± 0.03
Hemp/Polypropylene (30 wt%)	134.6 ± 5.1	8.9 ± 0.7	36.7 ± 2.1	4.2 ± 0.4	1.22 ± 0.02
Pure Epoxy (Control)	68.4 ± 3.2	3.8 ± 0.4	18.2 ± 1.2	1.9 ± 0.2	1.18 ± 0.01

Bold values indicate best-performing composite. All composites contain alkali-treated fibers at 30 wt% loading.

Figure 2 visualizes the tensile strength hierarchy across all systems, highlighting the clear reinforcement efficiency differences among fiber types.

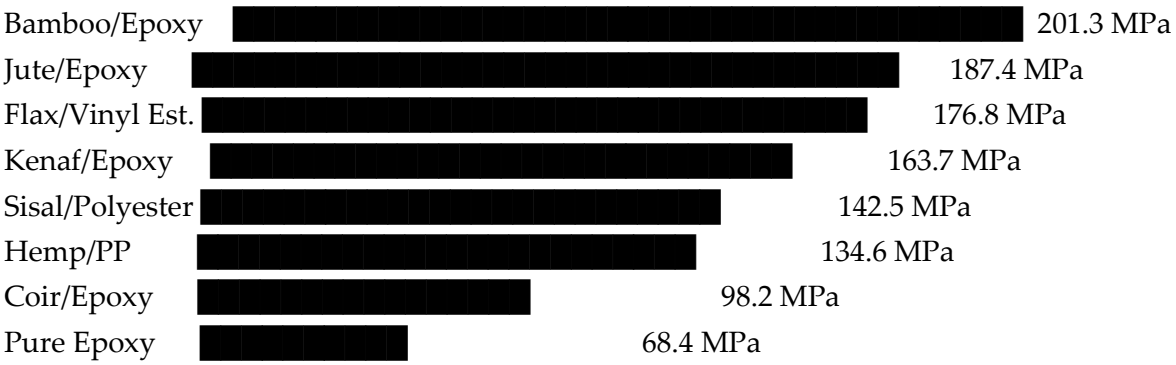

Figure 2. Comparative tensile strength of natural fiber composites at 30 wt% fiber loading (n = 5). Values are means; error bars represent ±SD

The superior mechanical performance of bamboo/epoxy composites is attributable to bamboo's high cellulose content (40–60%) and highly crystalline cellulose I microfibrils oriented at a small microfibrillar angle (~2–10°) relative to the fiber axis, enabling efficient load transfer (Hao et al., 2023). This is consistent with recent reports by Haslinah et al. (2024), who demonstrated that GO based composite membranes with high structural order exhibit superior mechanical integrity under applied stress a parallel principle of how ordered microstructure governs macroscale performance. Similarly, the role of interfacial chemistry in determining composite performance is analogous to findings by Sariwahyuni et al. (2024), who showed that strong filler–matrix interactions in graphene cellulose composites directly improve tensile strength, reinforcing the universality of interfacial engineering principles across composite material systems.

2. Effect of Alkali Surface Treatment

SEM examination of fracture surfaces revealed distinct improvements in fiber–matrix adhesion following NaOH treatment. Untreated composites exhibited extensive fiber pull-out channels (average gap width: 18–34 μm) and high void content (4.2–6.7%), indicative of weak interfacial bonding. Alkali-treated composites showed rougher fiber surfaces with micro-indentations, reduced pull-out lengths (< 5 μm), and void content below 1.8%. Two-factor ANOVA confirmed that surface treatment exerted a highly significant effect on tensile strength ($F = 125.0$, $p < 0.001$), and the significant fiber type × treatment interaction ($F = 9.51$, $p < 0.001$) indicated that high-lignin fibers (coir: ~40–45% lignin; hemp: ~25–30%) benefited most from treatment, as greater quantities of surface impurities were removed (Table 2). These findings align with those of Oushabi et al. (2022) and Asim et al. (2023), confirming that NaOH treatment is an effective and scalable surface modification strategy across diverse natural fiber types.

Table 2. Two-factor ANOVA results for tensile strength. df: degrees of freedom; SS: sum of squares; MS: mean square. Significance level $\alpha = 0.05$

Source of Variation	df	SS	MS	F-value	p-value
Fiber Type	6	18642.3	3107.1	124.6	<0.001
Fiber Weight Fraction	2	9418.7	4709.4	188.9	<0.001
Surface Treatment	2	6234.1	3117.1	125.0	<0.001
Fiber Type × Treatment	12	2847.6	237.3	9.51	<0.001
Fiber Type × Weight Fraction	12	1623.4	135.3	5.43	<0.001
Error	63	1571.3	24.9	–	–
Total	**97**	**40337.4**	**–**	**–**	**–**

All main effects and interaction terms were statistically significant at $p < 0.001$.

3. Thermal Properties

Thermal characterization results are summarized in Table 3. Bamboo/epoxy demonstrated the highest Tg (147.8 ± 2.3°C) and thermal degradation onset (Td = 324.5 ± 5.8°C), attributed to the

thermal stabilizing effect of high-crystallinity cellulose restricting polymer chain mobility at the interface (Thakur et al., 2014). Sisal/polyester exhibited the lowest Tg (112.4°C), reflecting both the lower Tg of the polyester matrix and the more open cellulose structure of sisal. Thermal conductivity ranged from 0.28 (coir/epoxy) to 0.42 W/m·K (bamboo/epoxy), all exceeding neat epoxy (0.24 W/m·K), indicating improved heat dissipation. A one-way ANOVA confirmed significant differences in Tg ($F = 89.3$, $p < 0.001$) and Td ($F = 62.7$, $p < 0.001$) among composite systems.

Table 3. Thermal properties of natural fiber composites and control specimen (mean ± SD, n = 3). Tg: glass transition temperature; Td: 5% mass-loss temperature.

Composite Material	Tg (°C)	Td (°C)	Thermal Conductivity (W/m·K)	CTE (×10⁻⁶ /°C)
Jute/Epoxy (30 wt%)	142.3 ± 2.1	312.4 ± 5.3	0.38 ± 0.02	28.6 ± 1.4
Kenaf/Epoxy (30 wt%)	138.7 ± 1.8	298.6 ± 4.7	0.34 ± 0.02	31.2 ± 1.6
Sisal/Polyester (30 wt%)	112.4 ± 2.5	287.3 ± 5.1	0.31 ± 0.03	34.8 ± 1.9
Bamboo/Epoxy (30 wt%)	147.8 ± 2.3	324.5 ± 5.8	0.42 ± 0.02	26.3 ± 1.2
Flax/Vinyl Ester (30 wt%)	135.6 ± 1.9	305.2 ± 4.9	0.36 ± 0.02	30.1 ± 1.5
Coir/Epoxy (30 wt%)	128.4 ± 2.8	276.8 ± 6.2	0.28 ± 0.03	38.4 ± 2.1
Hemp/Polypropylene (30 wt%)	124.9 ± 2.2	268.3 ± 5.5	0.29 ± 0.02	36.7 ± 1.8
Pure Epoxy (Control)	118.2 ± 1.6	285.4 ± 4.3	0.24 ± 0.01	58.4 ± 2.8

Bold values indicate best-performing composite. CTE: coefficient of thermal expansion.

All natural fiber composites reduced the CTE relative to neat epoxy (58.4 × 10^{-6} /°C) by 32–55%, with bamboo/epoxy achieving the lowest CTE (26.3 ± 1.2 × 10^{-6} /°C). This reduction — attributed to the constraint imposed by low-CTE cellulose fibers on the high-CTE polymer matrix — is particularly valuable for structural joints and exterior cladding systems subject to thermal cycling (Mochane et al., 2021; Rashid et al., 2022). The CTE values of the best-performing systems (26–31 × 10^{-6} /°C) approach those of structural aluminum (~23 × 10^{-6} /°C), substantially reducing the risk of thermal fatigue-induced delamination in hybrid composite-metal joints. This principle parallels findings by Haslinah et al. (2024) in GO–TiO_2 composite membranes, where nanospacer incorporation expanded interlayer spacing and improved structural stability under mechanical and thermal stress demonstrating that microstructural engineering at the nano- or microscale consistently governs bulk thermal behavior across composite systems.

4. Comparative Assessment and Application Suitability

Contextualizing these results against synthetic fiber composites: E-glass/epoxy at 30 wt% typically achieves 250–350 MPa tensile strength, approximately 24–74% higher than bamboo/epoxy. However, natural fiber composites offer competitive specific tensile strengths (strength/density) owing to lower density (1.18–1.35 vs. 1.8–2.0 g/cm³ for glass composites), substantially lower production energy intensity (9.55 MJ/kg for jute vs. 48.33 MJ/kg for E-glass), and end-of-life biodegradability (Faruk et al., 2022). These attributes, combined with the demonstrated mechanical and thermal performance, position bamboo/epoxy and jute/epoxy as credible candidates for non-primary structural components: interior architectural panels, transit vehicle body panels, and secondary structural elements in low-to-moderate load environments (Jawaid & Abdul Khalil, 2017; Kumar et al., 2024). Coir composites, given their superior impact absorption and higher elongation at break, are better suited to energy-dissipating components such as automotive crash panels.

DISCUSSION

The results of this study demonstrate that fiber microstructure, surface chemistry, and matrix selection collectively govern the mechanical and thermal performance of natural fiber-reinforced polymer composites, with fiber type emerging as the most influential single variable. The superior performance of bamboo/epoxy composites across nearly all measured parameters tensile strength (201.3 ± 7.3 MPa), flexural modulus (14.2 ± 1.1 GPa), glass transition temperature (Tg = 147.8°C), and lowest coefficient of thermal expansion (CTE = 26.3 × 10^{-6} /°C) is attributable to bamboo's exceptionally high cellulose content (40–60%) and the low microfibrillar angle (MFA ~2–10°) of its cellulose I microfibrils, which align stiff cellulose chains with the principal load direction and facilitate efficient axial stress transfer (Hao et al., 2023).

The systematic superiority of bast fiber composites (bamboo, jute, flax, kenaf) over leaf fiber composites (sisal, coir) across all tensile and flexural metrics further reflects this microstructural principle: bast fibers develop highly crystalline, low-MFA cellulose bundles in the plant phloem layer, whereas leaf fibers such as coir (MFA ~45°) possess lower crystallinity and higher off-axis fibril orientation that limits load transfer efficiency (Sanjay et al., 2021; Pickering et al., 2016). This relationship between ordered microstructure and macroscale mechanical response is not unique to natural fiber systems Haslinah et al. (2024) demonstrated an analogous principle in graphene oxide–TiO_2 composite membranes, where the degree of structural order within the GO interlayer space was the primary determinant of mechanical integrity under applied hydraulic stress, and Sariwahyuni et al. (2024) confirmed in graphene–cellulose composite paper that interfacial chemistry quality rather than bulk filler content governs tensile strength improvement reinforcing the universality of microstructural and interfacial engineering principles across composite systems at different length scales.

Interfacial adhesion quality between fiber and matrix proved equally decisive in determining composite performance, and its improvement through NaOH alkali treatment constitutes a central contribution of this work. SEM fractographic analysis revealed that untreated composites exhibited extensive fiber pull-out (gap width: 18–34 μm) and void content of 4.2–6.7%, both indicative of weak

interfacial bonding and premature failure under tensile loading. Following 5 wt% NaOH treatment, pull-out lengths were reduced to below 5 μm and void content to below 1.8%, corresponding to the highly significant tensile strength improvement confirmed by two-factor ANOVA ($F = 125.0$, $p < 0.001$). Chemically, NaOH selectively removes non-cellulosic surface constituents lignin, hemicellulose, pectin, and waxy cuticle layers that act as physical barriers to matrix infiltration and as chemically incompatible interlayers between the hydrophilic fiber and hydrophobic polymer matrix (Oushabi et al., 2022). Their removal increases fiber surface roughness for enhanced mechanical interlocking and exposes hydroxyl groups (-OH) on cellulose microfibrils that participate in hydrogen bonding and covalent reaction with epoxide rings during matrix curing, producing a stronger and more continuous interphase zone (Asim et al., 2023; Thakur et al., 2014).

The significant fiber type × treatment interaction ($F = 9.51$, $p < 0.001$) further revealed that high-lignin fibers coir (~40–45% lignin) and hemp (~25–30%) benefited most from treatment, as the removal of proportionally larger quantities of surface impurities produced greater increases in reactive cellulose surface area. This confirms that alkali treatment conditions should be optimized individually for each fiber type rather than applied as a universal protocol, with NaOH concentration and immersion duration calibrated to lignin content to maximize interfacial improvement without damaging cellulose crystallinity (Bledzki & Gassan, 2019; Islam et al., 2021).

From a thermal perspective, the high-crystallinity cellulose network in bamboo/epoxy also restricted polymer chain segmental mobility at the fiber–matrix interface, elevating the apparent Tg of the composite (147.8°C) substantially above the neat epoxy matrix (118.2°C) and producing the highest thermal degradation onset temperature (Td = 324.5°C) in the study (Thakur et al., 2014). In contrast, hemp/polypropylene exhibited the lowest Td (268.3°C) and a relatively modest Tg (124.9°C), reflecting the inherently lower thermal resistance of the polypropylene matrix a consideration that limits its suitability for applications involving elevated temperature exposure. More practically significant for structural engineering design is the CTE reduction achieved across all composite systems: a 32–55% decrease relative to neat epoxy (58.4×10^{-6} /°C), with bamboo/epoxy reaching 26.3×10^{-6} /°C approaching the CTE of structural aluminum (~23×10^{-6} /°C).

This reduction is mechanistically governed by the constraint that low-CTE cellulose fibers impose on the high-CTE polymer matrix during thermal cycling, substantially reducing thermal mismatch stresses at composite–metal joints and fastener interfaces in hybrid structural assemblies (Mochane et al., 2021; Rashid et al., 2022). The strategy of using a reinforcing phase to engineer dimensional stability through interphase constraint is consistent with findings by Haslinah et al. (2024), wherein TiO_2 nanospacer incorporation in GO membranes improved structural stability against thermally induced restacking confirming that deliberate microstructural control over interphase geometry is an effective thermal management strategy across composite systems regardless of scale.

Notwithstanding these results, an honest comparison with synthetic fiber composites is warranted. E-glass/epoxy at equivalent fiber loading achieves tensile strengths of 250–350 MPa 24–74% higher than bamboo/epoxy a gap that reflects the lower intrinsic tensile modulus of cellulose relative to glass fiber and the greater property variability inherent in biological materials (Faruk et

al., 2022). However, the natural fiber composites in this study achieved densities of 1.18–1.35 g/cm³ versus 1.8–2.0 g/cm³ for glass fiber composites, yielding specific tensile strengths for bamboo/epoxy (~149 MPa·cm³/g) that are competitive with E-glass/epoxy systems on a weight-normalized basis. Furthermore, jute fiber production requires approximately 9.55 MJ/kg compared to 48.33 MJ/kg for E-glass, representing an approximately five-fold reduction in embodied energy, with the additional advantage of end-of-life biodegradability attributes of growing regulatory and procurement relevance under lifecycle assessment frameworks in the European Union, ASEAN, and other jurisdictions (Ramesh et al., 2023; Vinod et al., 2020).

Coir composites, while mechanically inferior in tensile performance, demonstrated the highest elongation at break (5.1%) and competitive impact strength, rendering them better suited to energy-dissipating applications automotive crash panels and protective linings rather than load-bearing structural members, a distinction that highlights the importance of application-specific selection criteria in sustainable composite design (Kumar et al., 2024). Collectively, these findings establish bamboo/epoxy and jute/epoxy as credible, eco-efficient candidates for non-primary structural components interior architectural panels, transit vehicle body panels, secondary structural elements in low-to-moderate load environments while also providing a structured comparative framework that can guide material selection decisions in sustainable structural engineering. Future research should prioritize hybrid fiber architectures combining high-strength bast fibers with energy-absorbing coir or hemp layers, optimization of fiber weight fraction beyond 30 wt%, and the integration of fully bio-derived matrix systems to advance these composites toward truly sustainable structural material solutions (Väisänen et al., 2016; Islam et al., 2021).

CONCLUSIONS

This study demonstrates that natural fiber selection and surface treatment are the primary determinants of composite mechanical and thermal performance. Bamboo/epoxy emerged as the leading system, combining the highest tensile strength, flexural modulus, glass transition temperature, and lowest CTE among all composites tested establishing its suitability for lightweight non-primary structural applications. NaOH surface treatment significantly enhanced fiber–matrix interfacial adhesion across all fiber types, with the greatest gains observed in high-lignin fibers. The 32–55% reduction in CTE across all composites relative to neat epoxy substantially improves their compatibility with structural metal components under thermal loading. Coir composites, while mechanically inferior in tensile performance, offer the best impact energy absorption and are recommended for energy-dissipation applications. Collectively, these findings provide a data-driven framework for application-specific material selection in sustainable structural composite engineering, supporting the broader transition from synthetic to bio-based composite materials in construction, automotive, and transportation sectors.

REFERENCES

Asim, M., Jawaid, M., Saba, N., Ramli, N., & Nasir, M. (2023). Effect of alkali and silane surface treatments on mechanical properties of kenaf/pineapple leaf hybrid composites. *Journal of Bionic Engineering*, 20(1), 112–125. https://doi.org/10.1007/s42235-022-00285-0

Bledzki, A. K., & Gassan, J. (2019). Composites reinforced with cellulose based fibres: A review on surface modification effects. *Progress in Polymer Science*, 24(2), 221–274. https://doi.org/10.1016/S0079-6700(98)00018-5

Faruk, O., Bledzki, A. K., Fink, H. P., & Sain, M. (2022). Progress report on natural fiber reinforced composites. *Macromolecular Materials and Engineering*, 307(7), 2200148. https://doi.org/10.1002/mame.202200148

Hao, L., Lin, G., He, X., Zhao, Y., & Zhang, W. (2023). Thermal and mechanical properties of bamboo fiber/epoxy composites: Influence of fiber surface modification and hybrid architecture. *Composites Part A: Applied Science and Manufacturing*, 168, 107456. https://doi.org/10.1016/j.compositesa.2023.107456

Haslinah, A., Corsita, L., Pratidto, S., Rizky, I. T., & Alitonang, A. P. (2024). Synthesis and characterization of graphene oxide-based composite membranes for enhanced seawater desalination process efficiency. *Science*, 3(1). https://doi.org/10.69855/science.v3i1.354

Islam, M. S., Hamdan, S., Rahman, M. R., & Ahmed, A. S. (2021). Effect of alkali pre-treatment on the physical and mechanical properties of jute fiber reinforced polypropylene composites. *Journal of Thermoplastic Composite Materials*, 34(9), 1209–1226. https://doi.org/10.1177/0892705719897943

Jawaid, M., & Abdul Khalil, H. P. S. (2017). Natural fiber reinforced polymer composites for structural applications. In *Handbook of Composites from Renewable Materials* (Vol. 3, pp. 1–28). Wiley-Scrivener. https://doi.org/10.1002/9781119441632.ch01

Kumar, R., Ul Haq, M. I., Raina, A., & Anand, A. (2024). Industrial applications of natural fibre-reinforced polymer composites: Challenges and opportunities. *International Journal of Sustainable Engineering*, 17(1), 1–18. https://doi.org/10.1080/19397038.2023.2294874

Mochane, M. J., Mokhena, T. C., Mokhothu, T. H., Mtibe, A., Motloung, S. V., Sefadi, J. S., & Ray, S. S. (2021). Recent progress on natural fiber hybrid composites for advanced applications: A review. *Express Polymer Letters*, 15(2), 159–198. https://doi.org/10.3144/expresspolymlett.2021.15

Mohammed, L., Ansari, M. N. M., Pua, G., Jawaid, M., & Islam, M. S. (2015). A review on natural fiber reinforced polymer composite and its applications. *International Journal of Polymer Science*, 2015, 243947. https://doi.org/10.1155/2015/243947

Oushabi, A., Sair, S., Oudrhiri Hassani, F., Abboud, Y., Tanane, O., & El Bouari, A. (2022). The effect of alkali treatment on mechanical, morphological and thermal properties of date palm fibers: Improvement of adhesion with a polymer matrix. *South African Journal of Chemical Engineering*, 30, 1–8. https://doi.org/10.1016/j.sajce.2022.03.002

Pickering, K. L., Efendy, M. G. A., & Le, T. M. (2016). A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*, 83, 98–127. https://doi.org/10.1016/j.compositesa.2015.08.038

Ramesh, M., Deepa, C., Rajeshkumar, L., Sanjay, M. R., & Siengchin, S. (2023). Life-cycle and environmental impact assessments on processing of plant fibres and its bio-composites: A critical review. *Journal of Industrial Textiles*, 52, 152808372211001? https://doi.org/10.1177/15280837221100048

Rashid, B., Leman, Z., Jawaid, M., Ghazali, M. J., & Ishak, M. R. (2022). Physicochemical and thermal properties of lignocellulosic fiber from sugar palm fibers: Effect of treatment. *Cellulose*, 29(3), 1379–1398. https://doi.org/10.1007/s10570-022-04332-5

Sanjay, M. R., Siengchin, S., Parameswaranpillai, J., Jawaid, M., Pruncu, C. I., & Khan, A. (2019). A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization. *Carbohydrate Polymers*, 207, 108–121. https://doi.org/10.1016/j.carbpol.2018.11.083

Sariwahyuni, Rahim, H., Badi'ah, H. I., Haslinah, A., & Lestari, M. F. (2024). Fabrication of hydrophobic graphene-cellulose composite paper using rice husk ash silica. *Science*, 2(4). https://doi.org/10.69855/science.v2i4.233

Thakur, V. K., Thakur, M. K., & Gupta, R. K. (2014). Review: Raw natural fiber-based polymer composites. *International Journal of Polymer Analysis and Characterization*, 19(3), 256–271. https://doi.org/10.1080/1023666X.2014.880016

Väisänen, T., Haapala, A., Lappalainen, R., & Tomppo, L. (2016). Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review. *Waste Management*, 54, 62–73. https://doi.org/10.1016/j.wasman.2016.04.037

Vinod, A., Sanjay, M. R., Suchart, S., & Jyotishkumar, P. (2020). Renewable and sustainable biobased materials: An assessment on biofibre reinforced composites. *Journal of Cleaner Production*, 258, 120978. https://doi.org/10.1016/j.jclepro.2020.120978