Mechanical Characteristics of the Jute Fibre Reinforced Polymer Composites

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Abstract - Fiber-reinforced polymer composites have played a dominant role for a long time in a variety of applications due to their high specific strength and modulus. The fiber which serves as a reinforcement in reinforced plastics may be synthetic or natural. Past studies show that only synthetic fibers such as glass and carbon have been widely used in fiber-reinforced plastics. Although these synthetic fiber-reinforced plastics possess high specific strength, their fields of application are limited because of their inherently higher cost of production. In this context, an investigation has been carried out to make use of jute, a natural fiber abundantly available in India. Natural fibers are not only strong and lightweight but are also relatively very cheap. The present work describes the development and characterization of a new set of natural fiber–based polymer composites consisting of jute as reinforcement and epoxy resin. The newly developed composites are characterized with respect to their physical and mechanical characteristics. Experiments are carried out to study the effect of fiber loading on the physical and mechanical behavior of these epoxy-based polymer composites. This work also includes the comparison of elastic properties of composites using micromechanical models with experimental and existing analytical formulations such as the rule of mixtures, Halpin–Tsai, and Lewis–Nielsen models, which are extensively used in material modeling.

Key Words: *Jute fiber, epoxy composites, natural fiber composites, mechanical properties, micromechanical modeling, Halpin–Tsai model, Lewis–Nielsen model, rule of mixtures.*

1. INTRODUCTION

Composite materials have emerged as one of the most significant developments in modern material science and engineering due to their superior mechanical and physical properties. Their high tensile strength, impact resistance, flexural strength, stiffness, and fatigue characteristics make them suitable for a wide range of engineering applications, including aerospace structures, automotive components, machine parts, pressure vessels, drive shafts, electronic packaging, and railway coach manufacturing.

A composite material is formed by combining two or more distinct materials with different physical or chemical properties to obtain enhanced performance characteristics that cannot be achieved individually. Typically, composites consist of strong load-bearing reinforcements embedded in a relatively weaker matrix material. The matrix transfers stresses between the fibers and protects them from mechanical and environmental damage, while the fibers significantly improve mechanical properties such as tensile and flexural strength, stiffness, and impact resistance.

Composite materials can be classified based on the nature of the matrix into metal matrix composites (MMCs), ceramic matrix composites (CMCs), and polymer matrix composites (PMCs). PMCs, composed of thermoset or thermoplastic polymers reinforced with fibers, are the most widely used because of their low density, ease of fabrication, dimensional stability, and cost-effectiveness. The performance of polymer matrix composites depends heavily on the polymer type, reinforcement type, fiber orientation, and fiber–matrix interfacial bonding. Natural fibers such as jute, sisal, banana, and hemp have gained increasing attention as reinforcements in polymer composites. These fibers offer advantages including low density, biodegradability, renewability, low cost, good specific mechanical properties, and reduced environmental impact when compared to synthetic fibers such as glass and carbon. Jute, in particular, is abundantly available in India and offers promising mechanical performance, making it a viable reinforcement for polymer composites in structural and semi-structural applications.

However, the mechanical and physical properties of natural fiber–reinforced polymer composites depend on multiple factors such as fiber loading, fiber dispersion, fiber–matrix adhesion, and the fabrication process. Understanding these parameters is critical for optimizing composite performance and expanding the use of natural fibers into advanced engineering applications.

The present study focuses on the development and characterization of jute fiber–reinforced epoxy composites and investigates the influence of fiber loading on their physical, mechanical, and micromechanical behavior.

1.1 OBJECTIVES OF THE STUDY

- To develop unidirectional jute fiber–reinforced epoxy composites using the hand lay-up fabrication technique with varying fiber loadings.
- To evaluate the physical characteristics of the developed composites, including density, void content, and water absorption behavior, and to analyze the influence of fiber loading on these properties.
- To investigate the mechanical performance of the composites by determining tensile strength, flexural strength, impact energy, hardness, and inter-laminar shear strength (ILSS).
- To analyze the effect of fiber content on overall composite behavior, particularly focusing on the correlation between increased fiber loading and changes in mechanical and physical properties.
- To perform micromechanical modeling using analytical approaches such as the Rule of Mixtures, Halpin–Tsai, and Lewis–Nielsen models, and compare these predictions with experimental results.
- To construct and simulate a Representative Volume Element (RVE) using finite element analysis (FEA) in ANSYS to predict longitudinal and transverse elastic moduli of the composites.
- To assess the applicability and accuracy of micromechanical models by comparing theoretical, numerical, and experimental values for elastic properties.
- To identify potential engineering applications for the developed natural fiber–reinforced composites based on the observed mechanical and physical performance.

1.2 SCOPE OF THE STUDY

- Material Selection and Fabrication: The study is limited to the fabrication of unidirectional jute fiber–reinforced epoxy composites using the conventional hand lay-up technique. Fiber loadings of 0 wt.%, 10 wt.%, 20 wt.%, 30 wt.%, and 40 wt.% are considered.
- Physical Characterization: The scope includes determination of physical properties such as density, theoretical and experimental void content, and water absorption behavior of the fabricated composites.
- Mechanical Characterization: Mechanical testing is carried out to evaluate tensile strength, flexural strength, inter-laminar shear strength (ILSS), impact resistance, and micro-hardness of the composites. The influence of fiber loading on these properties forms a major part of the analysis.
- Micromechanical Modeling: The study examines micromechanical predictions for the elastic behavior of composites using established analytical models including the Rule of Mixtures, Halpin–Tsai model, and Lewis–Nielsen model.
- Finite Element Simulation: A Representative Volume Element (RVE) for the composite is generated using a square fiber arrangement. Finite element analysis (ANSYS) is performed to predict the longitudinal and transverse elastic moduli of the composites.
- Comparative Evaluation: Experimental results are compared with analytical and numerical predictions to assess the accuracy and applicability of the micromechanical models for natural fiber–reinforced composites.
- Application Assessment: The scope includes identifying potential applications of the developed jute fiber–reinforced composites in automotive, structural, and insulation-related sectors based on performance outcomes.
- Limitations: The study does not incorporate fiber surface treatments, chemical modifications, hybrid fiber combinations, or alternative manufacturing techniques. These aspects are identified as potential future research areas.

Table 1 Physical Properties of Natural Fibres

Fibre	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Density (g/cm3)
Abaca	400	12	03-Oct	1.5
Alfa	350	22	5.8	0.89
Bagasse	290	17	----	1.25
Bamboo	140-230	Nov-17	-----	0.60-1.10
Banana	500	12	5.9	1.35
Coir	175	04-Jun	30	1.2
Cotton	287-597	5.50-12.60	07-Aug	1.50-1.60

Curaua	500-1150	11.8	3.70-4.30	1.4
Date palm	97-196	2.50-5.40	2-4.50	1-1.20
Flax	345-1035	27.6	2.70-3.20	1.5

2. SUMMARY OF LITERATURE REVIEW

The literature on natural fiber–reinforced polymer composites (NFRPCs) has expanded significantly over the past decades due to increasing demand for sustainable, low-cost, and lightweight engineering materials. This section reviews previous research related to (i) natural fiber composites, (ii) mechanical behavior of natural fiber–reinforced polymers, and (iii) micromechanical modeling approaches used for predicting composite properties. The review synthesizes the state-of-the-art relevant to the development and performance evaluation of jute fiber–reinforced epoxy composites.

A. Studies on Natural Fiber–Reinforced Polymer Composites

Natural fibers such as jute, sisal, coir, banana, and flax have been extensively investigated due to their advantageous characteristics including biodegradability, low density, renewability, low cost, and acceptable mechanical strength. Biswas *et al.* studied the influence of fiber length on the mechanical behavior of coir fiber–reinforced epoxy composites and reported a reduction in hardness with increasing fiber length up to 20 mm. A study on pulp fiber-reinforced thermoplastic composites demonstrated significant improvements in stiffness and strength when compared to virgin polymers.

Gowda *et al.* examined jute fabric–reinforced polyester composites and reported superior strength compared to wood-based composites. Similarly, coir fiber–polyester composites showed improvements in flexural strength under optimized molding pressures. Luo and Netravali analyzed the tensile and flexural behavior of pineapple fiber composites and observed substantial enhancements relative to the unreinforced matrix.

Amash and Zugenmaier reported that cellulose fibers significantly increased stiffness and reduced damping in polypropylene–cellulose composites. Dynamic mechanical analyses of natural fibers such as sisal, pineapple, bamboo, and oil-palm fibers embedded in various matrices have further highlighted the suitability of natural fibers for composite applications.

Multiple studies on banana fiber–reinforced composites have demonstrated their potential as viable reinforcement alternatives. For instance, Tobias observed increased impact strength with higher fiber content and lower fiber length. Santulli investigated the post-impact behavior of jute–polyester composites and found relatively low impact resistance.

B. Mechanical Behavior and Interface Characteristics

The mechanical properties of natural fiber composites depend strongly on fiber strength, modulus, aspect ratio, orientation, fiber–matrix adhesion, and interfacial bond quality. Strong interfacial bonding is crucial for enhancing stress transfer and maximizing composite strength.

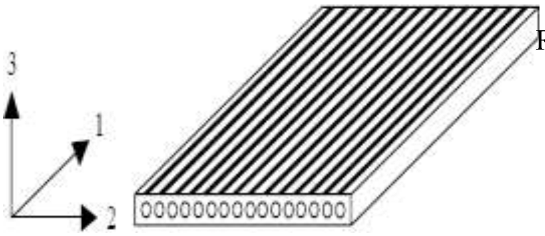
Several researchers have reported the benefits of chemical treatments such as alkalization, silane coupling, isocyanate application, peroxide treatment, and acetylation in improving fiber–matrix adhesion. Sreekala *et al.* demonstrated that treated oil-palm fibers significantly improved tensile behavior. Joseph and Thomas observed enhanced tensile and dynamic mechanical properties in treated sisal–LDPE composites.

Mohanty *et al.* reported over 40% improvement in tensile strength of biocomposites prepared with alkali-treated jute fibers. Schneider and Karmaker found that jute fiber–reinforced polypropylene composites exhibited better mechanical properties than those reinforced with kenaf.

Studies on banana, sisal, hemp, flax, and henequen fibers have consistently shown competitive specific strength and modulus when compared to synthetic fibers such as glass, making natural fibers strong contenders in lightweight composite applications. Additional research on thermoplastic and thermoset systems has highlighted the effects of fiber surface modifications, processing conditions, and fiber geometry on mechanical performance.

C. Micromechanical Modeling of Fiber-Reinforced Composites

Micromechanical modeling plays a significant role in predicting the elastic properties of fiber-reinforced composites. Classical analytical models such as the Rule of Mixtures (Voigt and Reuss approximations), Halpin–Tsai model, and Lewis–Nielsen model are widely used for estimating longitudinal and transverse elastic properties.



The Rule of Mixtures provides a simplified approach for predicting composite modulus under isostrain and isostress conditions. However, accuracy declines at high fiber volume fractions. The Halpin–Tsai model incorporates fiber geometry and provides improved predictions for unidirectional composites. Lewis and Nielsen further modified this model by including particle packing and shape parameters, yielding higher accuracy over a broader range of reinforcement geometries.

Tucker and Liang conducted an extensive evaluation of micromechanical models and reported that the Mori–Tanaka method and Halpin–Tsai model produce the most reliable predictions for short-fiber composites. Finite Element Analysis (FEA) has also been effectively used to model Representative Volume Elements (RVEs) for natural fiber composites. Studies have shown strong agreement between FEA predictions and experimental results, especially for periodic square or hexagonal fiber arrangements.

Sun *et al.* introduced a Boolean-operation-based method for generating composite unit cells, while Banerjee and Sankar developed micromechanical models for hybrid composites using FEM. Research by Pal *et al.* and Mirbagheri *et al.* confirmed that micromechanical modeling provides reliable predictions of elastic modulus for natural fiber composites at various fiber loadings.

D. Summary of Literature Findings

The reviewed literature highlights the following key insights:

1. Natural fibers exhibit remarkable potential as reinforcement due to their mechanical performance, biodegradability, and availability.
2. Fiber–matrix interface quality is a critical factor, influencing tensile, flexural, and impact properties.
3. Mechanical properties improve with optimized fiber content, but excessive loading can lead to fiber agglomeration, voids, and reduced interfacial bonding.
4. Micromechanical models provide valuable predictive capability, though accuracy varies depending on fiber geometry, volume fraction, and dispersion.
5. Finite element modeling provides enhanced predictive accuracy, especially when fiber distribution and geometry are explicitly modeled.

Figure 1: Axis system used for unidirectional laminate

3. PROBLEM STATEMENT AND METHODOLOGY

This section presents the materials, fabrication procedures, testing methods, and micromechanical modeling techniques employed in the development and characterization of jute fiber–reinforced epoxy composites. The methodology includes material selection, composite preparation through hand lay-up, physical and mechanical testing, and numerical modeling using finite element analysis.

A. Materials

1) Matrix Material (Epoxy Resin)

Epoxy resin (LY 556) is used as the matrix owing to its superior mechanical, thermal, and chemical resistance properties. The resin belongs to the Bisphenol-A-Diglycidyl-Ether (DGEBA) family and provides strong adhesion to natural fibers. The curing agent used is tri-ethylene-tetramine (TETA), commercially designated as HY 951. A mixing ratio of epoxy to hardener of 10:1 (by weight) is adopted. Both materials were procured from Ciba Geigy, India.

2) Reinforcement (Jute Fiber)

Unidirectional jute fibers, procured from local suppliers, are used as reinforcement. Jute is a lignocellulosic fiber composed primarily of cellulose and lignin. The fibers possess a density of 1.4 g/cm³ and a thermal conductivity of 0.036 W/m·K. Their availability, low density, good mechanical properties, and biodegradability make them suitable for composite fabrication.

B. Composite Fabrication

The composites are fabricated using the conventional hand lay-up technique, followed by light compression molding. Five different fiber loadings are used: 0 wt.%, 10 wt.%, 20 wt.%, 30 wt.%, and 40 wt.%.

1. Epoxy resin and hardener are thoroughly mixed at a 10:1 weight ratio.
2. Jute fibers are cut, aligned in unidirectional form, and placed in the mold.
3. The resin mixture is poured to ensure uniform wetting of fibers.
4. Air entrapment is minimized by manual rolling.
5. A compressive pressure of approximately 0.1 MPa is applied.
6. Composites are allowed to cure at room temperature for 48 hours.
7. Samples are cut to standard dimensions using a diamond cutter for testing.

The designations and compositions of the prepared composites are summarized in Table I.

Table 2 — Composition of Epoxy–Jute Composites

Designation	Composition
C1	Epoxy (100 wt.%)
C2	Epoxy (90 wt.%) + Jute (10 wt.%)
C3	Epoxy (80 wt.%) + Jute (20 wt.%)
C4	Epoxy (70 wt.%) + Jute (30 wt.%)
C5	Epoxy (60 wt.%) + Jute (40 wt.%)

C. Physical Characterization

1) Density Measurement

The **theoretical density** of each composite is calculated using the rule of mixtures:

$$\frac{1}{\rho_{ct}} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}$$

The experimental density is determined using the water immersion (Archimedes) method**.** The void fraction **is** estimated as:

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}}$$

2) Water Absorption Test

Water absorption is evaluated as per ASTM D570. Specimens are immersed in water for up to 408 hours. Weight gain is recorded at regular intervals using:

$$W_a(\%) = \frac{W_2 - W_1}{W_1} \times 100$$

where W1 is the dry weight and W2 is the weight after immersion.

D. Mechanical Characterization

Mechanical tests are conducted to evaluate the effect of fiber loading on material performance.

1) Tensile Testing

Tensile properties are measured according to ASTM D3039 using an Instron 1195 universal testing machine. Flat specimens are subjected to uniaxial loading until failure. Longitudinal and transverse tensile strengths are recorded.

2) Flexural Testing

Three-point bending tests are performed as per ASTM D790. Flexural strength is determined from the peak load during bending.

3) Impact Testing

Impact strength is evaluated using a Charpy/Izod impact tester following ASTM D256. Unnotched specimens (64 mm × 12.7 mm × 4 mm) are tested to record absorbed impact energy.

4) Interlaminar Shear Strength (ILSS)

Short beam shear tests are conducted according to ASTM D2344 using specimens of size 45 mm × 10 mm × 4 mm. ILSS is calculated using:

$$\tau = \frac{3P}{4bt}$$

where P is the maximum load, b is width, and t is thickness.

5) Micro-Hardness Testing

Vickers micro-hardness is measured using a Leitz micro-hardness tester following **ASTM D785**. The hardness value is calculated as:

$$H_v = \frac{0.1889F}{L^2}$$

where F is the applied load (24.54 N) and L is the diagonal length of indentation.

E. Finite Element Modeling (ANSYS)

Micromechanical analysis is performed to predict composite elastic properties using a Representative Volume Element (RVE) approach.

1) RVE Generation

A square array fiber distribution is assumed. Fiber volume fractions from 10% to 40% are modeled. The side length of the RVE is set to 10 units. The fiber diameter is derived from:

$$V_f = \frac{\pi d_f^2}{4a_1a_2}$$

2) Meshing and Element Type

The RVE is modeled using SOLID186 3D 20-node elements, suitable for structural analysis with orthotropic materials.

3) Boundary Conditions

Periodic boundary conditions are applied to simulate continuous composite behavior. Displacements U, V, and W are imposed on corresponding faces according to established micromechanical homogenization theories.

4) Evaluation of Elastic Constants

Average stresses and strains are computed from FEA outputs to determine longitudinal and transverse elastic moduli using:

$$\bar{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij} dV, \quad \bar{\epsilon}_{ij} = \frac{1}{V}\int_V \epsilon_{ij} dV$$

The constitutive equations for transversely isotropic materials are used to compute:

- Longitudinal modulus E1E_1E1
- Transverse modulus E2E_2E2
- Shear moduli and Poisson's ratios (as applicable)

F. Summary of Methodology

The adopted methodology integrates experimental characterization, micromechanical modeling, and numerical simulation to evaluate the structural behavior of jute fiber–reinforced epoxy composites. This comprehensive approach enables comparison between experimental and predicted mechanical properties, thereby validating the suitability of natural fiber composites for engineering applications.

Figure 2: Epoxy resin and corresponding hardener

Figure 3: Jute fiber

4. MECHANICAL CHARACTERISTICS OF COMPOSITES: RESULTS AND DISCUSSION

This section presents the mechanical behavior of jute fiber–reinforced epoxy composites at varying fiber loadings (0–40 wt.%). The properties discussed include tensile strength, flexural strength, impact resistance, interlaminar shear strength (ILSS), and micro-hardness. The influence of fiber content on the composite performance is analyzed and correlated with micromechanical and physical characteristics.

A. Tensile Properties

The tensile behavior of the composites is significantly influenced by jute fiber loading. The neat epoxy (0 wt.% fiber) exhibits the lowest tensile strength due to its brittle nature. With fiber incorporation, the tensile strength increases, reaching a maximum at 30 wt.% jute contents.

This behavior can be attributed to efficient stress transfer between the matrix and the aligned jute fibers. Up to 30 wt.% fiber loading, fiber dispersion is uniform and interfacial bonding is sufficiently strong to enhance mechanical performance. Beyond 30 wt.% loading, the tensile strength decreases slightly due to:

- Fiber agglomeration
- Poor resin wetting at high fiber volume
- Increased void content

These factors result in reduced effective stress transfer, leading to premature failure. Similar trends have been reported in earlier natural fiber composite studies.

B. Flexural Strength

The flexural strength improves steadily with increasing fiber content up to 30 wt.%, beyond which a marginal reduction is observed. Since bending induces both tensile and compressive stresses, the presence of strong, stiff jute fibers enhances resistance to bending deformation.

The improvement is governed by:

- Increased stiffness contribution from jute fibers
- Strong fiber–matrix adhesion (up to 30 wt.%)
- Reduced crack propagation due to fiber bridging

However, at 40 wt.% loading, non-uniform fiber packing and insufficient resin distribution reduce flexural efficiency. Micro-level matrix cracks initiate earlier and propagate through fiber-rich zones.

C. Impact Strength

Impact strength exhibits a continuous increase with fiber loading. The neat epoxy absorbs minimal impact energy and fails in a brittle manner. Jute fiber reinforcement enhances:

- Energy absorption capacity
- Crack deflection
- Fiber pull-out energy
- Micro-fibrillation during fracture

Composites with 40 wt.% jute show the highest impact energy absorption. The ability of natural fibers to undergo plastic deformation and fiber bridging improves toughness, making higher fiber loadings more effective in impact-dominated applications.

D. Interlaminar Shear Strength (ILSS)

ILSS is governed by the fiber–matrix interface quality. Results indicate that ILSS increases with fiber content up to 20–30 wt.%, after which a slight reduction is observed.

The initial rise is due to:

- Strong interfacial adhesion
- Increased resistance to interlayer sliding
- Enhanced polymer curing around fibers

The reduction beyond 30 wt.% is associated with:

- Higher void content
- Poor wetting at high fiber volume
- Stress concentration at fiber-rich clusters

Since ILSS depends heavily on matrix continuity, high fiber loading disrupts matrix-rich regions, decreasing shear resistance.

E. Micro-Hardness

Micro-hardness values increase consistently with fiber loading. Jute fibers are inherently harder than epoxy resin, contributing to improved localized hardness. The increase in hardness indicates:

- Better load-sharing capability
- Higher resistance to surface indentation
- Stronger fiber–matrix cohesive bonding

This property is particularly significant for tribological and wear-related applications.

F. Correlation with Micromechanical Predictions

Micromechanical models (Rule of Mixtures, Halpin–Tsai, and Lewis–Nielsen) generally show strong agreement with experimental trends:

- **Longitudinal modulus** E1 increases nearly linearly with fiber volume fraction.
- **Transverse modulus** E2 follows a non-linear trend due to dependence on fiber packing and geometry.
- Halpin–Tsai and Lewis–Nielsen models yield better predictions than the Rule of Mixtures, which tends to overestimate stiffness at high fiber loading.

Finite element simulation of the RVE further validates the micromechanical models, showing close agreement with experimental longitudinal modulus values.

G. Overall Discussion

The mechanical characterization clearly demonstrates that:

- Optimal fiber loading is around 30 wt.%, where most mechanical properties peak.
- Fiber-rich composites (>30 wt.%) suffer from voids and poor wetting, reducing tensile and flexural performance.
- Impact strength and hardness consistently improve with higher fiber content.
- Mechanical behavior correlates strongly with physical parameters such as density, void fraction, and water absorption.
- Micromechanical and numerical predictions support experimental results, confirming the reliability of jute fibers as reinforcement.

These findings establish jute fiber–reinforced epoxy composites as viable candidates for lightweight structural, semi-structural, and impact-resistant applications.

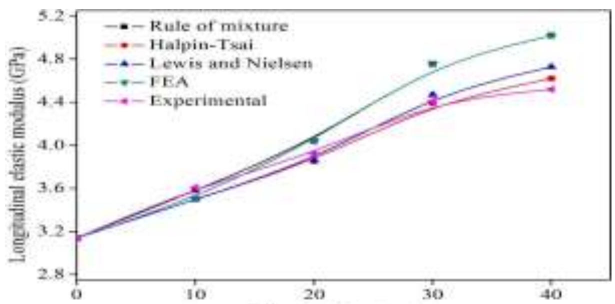


Fig 4: Longitudinal tensile modulus Vs fibre loading

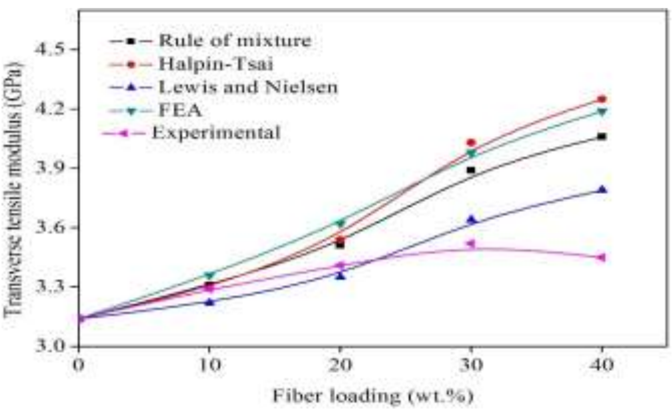


Fig 5: Transverse tensile modulus Vs fibre loading

5. CONCLUSIONS

The present study investigated the fabrication, characterization, and micromechanical modeling of unidirectional jute fiber–reinforced epoxy composites at varying fiber loadings. Based on the experimental, analytical, and numerical analyses, the following conclusions are drawn:

1. Successful Fabrication: Jute fiber–reinforced epoxy composites were successfully fabricated using the hand lay-up technique at fiber loadings of 0–40 wt.%. The fabrication process produced composites with acceptable uniformity and minimal processing defects at moderate fiber contents.
2. Physical Behavior: The density of the composites decreased with increasing fiber loading due to the lower density of jute fibers compared to epoxy resin. Void content increased at higher fiber percentages, influenced by limited resin flow and fiber packing. Water absorption increased with fiber content, attributed to the hydrophilic nature of jute.
3. Mechanical Performance: Mechanical properties showed a clear dependence on fiber loading. Tensile strength, flexural strength, impact resistance, and ILSS increased up to an optimum fiber loading of 30 wt.%. Beyond this point, a reduction in tensile and flexural properties occurred due to fiber agglomeration, insufficient wetting, and increased voids. Impact strength and hardness continued to improve at 40 wt.% owing to fiber-dominated fracture mechanisms.
4. Micromechanical Model Accuracy: Analytical predictions using the Rule of Mixtures, Halpin–Tsai, and Lewis–Nielsen models closely matched the experimental values for longitudinal modulus. Transverse modulus predictions were better captured by the Halpin–Tsai and Lewis–Nielsen formulations. The Rule of Mixtures consistently overestimated properties at higher fiber volume fractions.
5. Finite Element Validation: Representative Volume Element (RVE)-based finite element simulations in ANSYS produced elastic modulus values that closely matched experimental data. This confirms the validity of numerical micromechanical modeling for natural fiber composites.
6. Effectiveness of Jute Fibers: The study demonstrates that jute fibers are effective reinforcements for epoxy matrices, offering improvements in strength, stiffness, impact behavior, and hardness. Their low cost,

availability, and biodegradability further strengthen their applicability in engineering applications.

6. FUTURE SCOPE

- Fiber Surface Modifications: Chemical treatments such as silane, alkali, acetylation, and peroxide can be applied to jute fibers to improve fiber–matrix adhesion and reduce water absorption.

- Hybrid Composites: Fabrication of hybrid composites using combinations of natural fibers (e.g., jute–banana, jute–sisal) or natural–synthetic fiber blends (e.g., jute–glass) may yield improved mechanical and thermal properties.

7. REFERENCES

[1] S. W. Gregory, K. D. Freudenberg, P. Bhimaraj, and L. S. Schadler, "A study on the friction and wear behavior of PTFE filled with alumina nanoparticles," Wear, vol. 254, pp. 573–580, 2003.
[2] K. Jung-il, P. H. Kang, and Y. C. Nho, "Positive temperature coefficient behavior of polymer composites having a high melting temperature," J. Appl. Polym. Sci., vol. 92, pp. 394–401, 2004.
[3] S. Nikkeshi, M. Kudo, and T. Masuko, "Dynamic viscoelastic properties and thermal properties of powder–epoxy resin composites," J. Appl. Polym. Sci., vol. 69, pp. 2593–2598, 1998.
[4] K. Zhu and S. Schmauder, "Prediction of the failure properties of short fiber reinforced composites with metal and polymer matrix," Comput. Mater. Sci., vol. 28, pp. 743–748, 2003.
[5] M. Rusu, N. Sofian, and D. Rusu, "Mechanical and thermal properties of zinc powder filled high density polyethylene composites," Polymer Testing, vol. 20, pp. 409–417, 2001.
[6] I. H. Tavman, "Thermal and mechanical properties of copper powder filled polyethylene composites," Powder Technol., vol. 91, pp. 63–67, 1997.
[7] R. N. Rothon, "Mineral fillers in thermoplastics: filler manufacture," J. Adhes., vol. 64, pp. 87–109, 1997.
[8] R. N. Rothon, "Mineral fillers in thermoplastics: filler manufacture and characterization," Adv. Polym. Sci., vol. 139, pp. 67–107, 1999.
[9] L. E. Nielsen and R. F. Landel, Mechanical Properties of Polymers and Composites, 2nd ed. New York, NY, USA: Marcel Dekker, 1994, pp. 377–459.
[10] S. T. Peters, Handbook of Composites, 2nd ed. London, U.K.: Chapman and Hall, 1998, pp. 242–243.
[11] R. J. Young and P. W. R. Beaumont, "Failure of brittle polymers by slow crack growth: Part 3—Effect of composition upon the fracture of silica particle-filled epoxy resin composites," J. Mater. Sci., vol. 12, no. 4, pp. 684–692, 1977.
[12] A. J. Kinloch, D. L. Maxwell, and R. J. Young, "The fracture of hybrid particulate composites," J. Mater. Sci., vol. 20, pp. 4169–4184, 1985.
R. J. Young, D. L. Maxwell, and A. J. Kinloch, "The deformation of hybrid particulate composites," J. Mater. Sci., vol. 21, pp. 380–388, 1986.
[13] S. W. Koh, J. K. Kim, and Y. W. Mai, "Fracture toughness and failure mechanisms in silica-filled epoxy resin composites: effects of temperature and loading rate," Polymer, vol. 34, no. 16, pp. 3446–3455, 1993.
[14] W. J. Cantwell and A. C. Moloney, Fractography and Failure Mechanisms of Polymers and Composites. Amsterdam, The Netherlands: Elsevier, 1994, p. 233.
[15] M. Imanaka, Y. Takeuchi, Y. Nakamura, A. Nishimura, and T. Lida, "Fracture toughness of spherical silica-filled epoxy adhesives," Int. J. Adhes. Adhes., vol. 21, pp. 389–396, 2001.
[16] H. Wang, Y. Bai, S. Liu, J. Wu, and C. P. Wong, "Combined effects of silica filler and its interface in epoxy resin," Acta Mater., vol. 50, pp. 4369–4377, 2002.
[17] I. Yamamoto, T. Higashihara, and T. Kobayashi, "Effect of silica-particle characteristics on impact/fatigue properties of epoxy resins," JSME Int. J., vol. 46, no. 2, pp. 145–153, 2003.
[18] Y. Nakamura, M. Yamaguchi, A. Kitayama, M. Okubo, and T. Matsumoto, "Effect of particle size on fracture toughness of epoxy resin filled with angular-shaped silica," Polymer, vol. 32, no. 12, pp. 2221–2229, 1991.
[19] Y. Nakamura, M. Yamaguchi, M. Okubo, and T. Matsumoto, "Effect of particle size on impact properties of epoxy resin filled with angular-shaped silica particles," Polymer, vol. 32, no. 16, pp. 2976–2979, 1991.
[20] Y. Nakamura, M. Yamaguchi, M. Okubo, and T. Matsumoto, "Effects of particle size on mechanical and impact properties of epoxy resin filled with spherical silica," J. Appl. Polym. Sci., vol. 45, pp. 1281–1289, 1992.
[21] K. G. Satyanarayana, K. Sukumaran, P. S. Mukherjee, C. Pavithran, and S. G. K. Pillai, "Natural fiber–polymer composites," Cem. Concr. Compos., vol. 12, no. 2, pp. 117–136, 1990.
[22] K. G. Satyanarayana, K. Sukumaran, A. G. Kulkarni, S. G. K. Pillai, and P. K. Rohatgi, "Fabrication and properties of natural fiber-reinforced polyester

composites," Composites, vol. 17, no. 4, pp. 329–333, 1986.

[23] M. A. Mansur and M. A. Aziz, "Study of bamboo-mesh reinforced cement composites," Int. Cem. Compos. Lightweight Concr., vol. 5, no. 3, pp. 165–171, 1983.

[24] L. Lundquist, B. Marque, P. O. Hagstrand, Y. Leterrier, and J. A. E. Månson, "Novel pulp fiber reinforced thermoplastic composites," Compos. Sci. Technol., vol. 63, no. 1, pp. 137–152, 2003.

[25] L. A. Pothan, Z. Oommen, and S. Thomas, "Dynamic mechanical analysis of banana fiber reinforced polyester composites," Compos. Sci. Technol., vol. 63, no. 2, pp. 283–293, 2003.

[26] T. Corbière-Nicollier et al., "Life cycle assessment of biofibres replacing glass fibers as reinforcement in plastics," Resour. Conserv. Recycl., vol. 33, no. 4, pp. 267–287, 2001.

[27] L. A. Pothan, S. Thomas, and N. R. Neelakantan, "Short banana fiber reinforced polyester composites: mechanical, failure and aging characteristics," J. Reinf. Plast. Compos., vol. 16, no. 8, pp. 744–765, 1997.

[28] S. Joseph, M. S. Sreekala, Z. Oommen, P. Koshy, and S. Thomas, "Comparison of the mechanical properties of phenol-formaldehyde composites reinforced with banana fibers and glass fibers," Compos. Sci. Technol., vol. 62, no. 14, pp. 1857–1868, 2002.

[29] S. Luo and A. N. Netravali, "Mechanical and thermal properties of environmentally friendly green composites made from pineapple leaf fibres and PHBV resin," Polymer Composites, vol. 20, no. 3, pp. 367–378, 1999.

[30] H. Belmares, A. Barrera, and M. Monjaras, "New composite materials from natural hard fibres: Part 2—Fatigue studies and a novel fatigue degradation model," Ind. Eng. Chem. Prod. Res. Dev., vol. 22, pp. 643–652, 1983.

[31] M. Casaurang, P. Herrera, I. Gonzalez, and V. M. Aguilar, "Physical and mechanical properties of henequen fibers," J. Appl. Polym. Sci., vol. 43, pp. 749–756, 1991.

[32] A. A. Khalid, B. Sahari, and Y. A. Khalid, "Environmental effects on the progressive crushing of cotton and glass fibre/epoxy composite cones," in Proc. 4th Int. Conf. Advances in Materials and Processing Technologies, Kuala Lumpur, 1998, pp. 680–689.

[33] M. Y. A. Fuad, S. Rahmad, and M. R. N. Azlan, "Filler content determination of bio-based thermoplastics composites by thermogravimetric analysis," in Proc. 4th Int. Conf. Advances in Materials and Processing Technologies, Kuala Lumpur, 1998, pp. 268–275.

[34] J. P. Schneider and A. C. Karmaker, "Mechanical performance of short jute fiber reinforced polypropylene," J. Mater. Sci. Lett., vol. 15, pp. 201–202, 1996.

[35] M. S. Sreekala, M. G. Kumaran, S. Joseph, M. Jacob, and S. Thomas, "Oil palm fiber reinforced phenol formaldehyde composites: influence of fiber surface modifications on mechanical performance," Appl. Compos. Mater., vol. 7, pp. 295–329, 2000.

[36] S. Mishra et al., "Influence of chemical surface modification on the performance of sisal-polyester biocomposites," Polym. Compos., vol. 23, no. 2, pp. 164–170, 2002.

[37] M. N. Ichazo, C. Albano, J. González, R. Perera, and M. V. Candal, "Polypropylene/wood flour composites: treatments and properties," Compos. Struct., vol. 54, pp. 207–214, 2001.

[38] K. Joseph and S. Thomas, "Dynamic mechanical properties of short sisal fiber reinforced LDPE composites," J. Reinf. Plast. Compos., vol. 12, no. 2, pp. 139–155, 1993.

[39] A. K. Mohanty, M. A. Khan, and G. Hinrichsen, "Influence of chemical surface modification on the properties of biodegradable jute fabrics–polyester amide composites," Compos. A, vol. 31, no. 2, 2000.

[40] P. A. Berenbrok and B. E. Liles, "Effect of WF fillers on polyethylene," in Proc. ANTEC, Toronto, Apr. 1997, pp. 2931–2934.

[41] M. J. Zaini, M. Y. Fuad, Z. Ismail, M. S. Mansor, and J. Mustafah, "Effect of filler content and size on mechanical properties of polypropylene/oil palm flour composites," Polym. Int., vol. 40, pp. 51–55, 1997.

[42] F. P. L. Mantia and M. Morreale, "Accelerated weathering of polypropylene/wood flour composites," Polym. Degrad. Stab., vol. 93, pp. 1252–1258, 2008.

[43] M. Bengtsson, P. Gatenholm, and K. Oksman, "Effect of crosslinking on the properties of polyethylene/wood flour composites," Compos. Sci. Technol., vol. 65, pp. 1468–1479, 2005.

[44] A. K. Mishra and A. S. Luyt, "Effect of sol–gel derived nano-silica and organic peroxide on properties of LDPE/wood flour composites," Polym. Degrad. Stab., vol. 93, pp. 1–8, 2008.

[45] L. Dányádi, T. Janecska, T. Szabó, Z. Nagy, J. Móczó, and B. Pukánszky, "Wood flour filled PP composites: compatibilization and adhesion," Compos. Sci. Technol., vol. 67, pp. 2838–2846, 2007.

[46] K. Friedrich, S. Fakirov, and Z. P. Zhang, Polymer Composites: From Nano- to Macro-Scale. Springer, 2005.

[47] L. E. Nielsen and R. F. Landel, Mechanical Properties of Polymers and Composites. New York: Marcel Dekker, 1994.

[48] J. Varna, R. Joffe, and A. Berglund, "Effect of voids on failure mechanisms in RTM laminates," Compos. Sci. Technol., vol. 53, pp. 241–249, 1995.

[49] M. N. Ichazo et al., “Polypropylene/wood flour composites: treatments and properties,” Compos. Struct., vol. 54, pp. 207–214, 2001.
[50] K. Joseph and S. Thomas, “Dynamic mechanical properties of short sisal fiber reinforced LDPE composites,” J. Reinf. Plast. Compos., vol. 12, no. 2, pp. 139–155, 1993.
[51] A. K. Mohanty, M. A. Khan, and G. Hinrichsen, “Influence of chemical surface modification on properties of biodegradable jute fabrics–polyester amide composites,” Compos. A, vol. 31, no. 2, 2000.