OWEN, M.M., WONG, L.S., ACHUKWU, E.O., ROMLI, A.Z., AMETEFE, D.S. and SHUIB, S. 2025. Comparative evaluation of the performance properties of resin-infused plain-woven jute reinforced thermoset composites for energy infrastructure: experimental analysis, finite element modelling and statistical validation. *Results in engineering* [online], 26, article number 105620. Available from: https://doi.org/10.1016/j.rineng.2025.105620

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2025

Results in Engineering 26 (2025) 105620

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Research paper

Comparative evaluation of the performance properties of resin-infused plain-woven jute reinforced thermoset composites for energy infrastructure: Experimental analysis, finite element modelling and statistical validation

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ARTICLE INFO

Keywords:
Plain-woven jute
Vacuum-assisted resin infusion
Thermoset resin
Finite element analysis
Statistical analysis

ABSTRACT

This study presents a comprehensive experimental and numerical evaluation of resin-infused plain-woven jute fiber composites reinforced with thermoset epoxy and polyester matrices in 2-, 4-, and 6-ply configurations, produced via vacuum-assisted resin infusion. The aim is to assess the influence of matrix type and ply architecture on the mechanical, thermal, and microstructural behavior of sustainable composites for renewable energy infrastructure. Mechanical characterization involved tensile, flexural, impact, and hardness tests, while thermal and microstructural properties were evaluated using thermogravimetric analysis (TGA) and scanning electron microscopy (SEM). Finite Element Analysis (FEA) was used to simulate stress distribution, and Analysis of Variance (ANOVA) determined the statistical significance of ply count and matrix effects. The 6-ply epoxy composite exhibited the highest structural performance, achieving tensile and flexural strengths of 76.85 MPa and 90.48 MPa with improvements of 19.3 % and 31.8 % over polyester counterparts. Although polyester-based composites exhibited lower strength, they showed higher impact resistance (1.15 J, +33.9 %). Peak hardness (114.4 HRB) was recorded in 4-ply epoxy laminates, and density increased with ply count, with polyester showing slightly higher values. TGA confirmed enhanced thermal stability in epoxy systems, with onset degradation at 341.5 °C versus 304.3 °C in polyester. SEM revealed superior fiber–matrix bonding and fewer voids in epoxy composites. FEA predictions were within 5 % of experimental results, and ANOVA confirmed statistically significant effects ($p \leq 0.05$) of matrix and ply count. These findings position 6-ply epoxy laminates as promising candidates for structural applications in renewable energy systems.

1. Introduction

Natural fiber-reinforced composites (NFRCs), particularly those incorporating jute, coir, sisal, and kenaf, have garnered increasing attention for structural and infrastructure applications due to their environmental sustainability, low weight, and favorable mechanical and tribological properties [1–6] When embedded in polymer matrices, natural fibers like jute offer enhanced mechanical performance, enabling their use in automotive, construction, and renewable energy sectors [3–5,7–10]. However, the performance of NFRCs is strongly

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https://doi.org/10.1016/j.rineng.2025.105620
Received 10 April 2025; Received in revised form 26 May 2025; Accepted 2 June 2025
Available online 3 June 2025

influenced by matrix type, fiber architecture, and laminate configuration, with typical failure modes including matrix cracking, fiber fracture, and interfacial delamination [11–14].

Due to their relatively lower mechanical performance, natural fiber composites are often unsuitable for high-load structural applications. To address these limitations, strategies such as using unidirectional fiber preforms [15], varying fabric weaves [16–18] and hybridization with synthetic fibers have been explored [19,15–18] While hybrid jute-glass systems have shown improved strength (e.g., a 40 % increase in flexural strength), such approaches often undermine sustainability due to disposal challenges and the high cost of synthetic fibers [19–24].

Jute remains a promising reinforcement due to its biodegradability, availability, and favorable strength-to-weight ratio [27,28], However, further improvements in laminate strength, particularly in woven configurations, are essential to meet structural application standards [25, 26–28,29] Woven architectures offer superior in-plane properties, dimensional stability, and damage resistance compared to random or unidirectional fibers [30,34,36,37]. Woven fabrics provide superior reinforcement compared to nonwoven or mat structures, particularly in enhancing the tensile properties of fiber-reinforced composites. Plain-woven fabrics are particularly attractive for their balanced load distribution and fabrication simplicity [38,39]. Yet, few studies have systematically explored the influence of ply stacking and resin selection on the thermomechanical behavior of woven jute composites [40–42].

Earlier work by Gopinath et al. [31] investigated jute/epoxy and jute/polyester composites in fibrous form, reporting moderate superior tensile strength in epoxy systems (12.46 N/mm^2 vs. 9.23 N/mm^2) and comparable hardness in both. While polyester composites showed marginally better impact resistance, epoxy outperformed in stiffness and strength, favoring its application in load-bearing contexts. However, the critical deficiency in existing literature is the non-integration of numerical modeling and statistical validation in experimental composite research. The lack of validated computational models restricts the ability to generalize performance predictions or optimize material design for industrial scalability. Similarly, the omission of statistical robustness (e.g., ANOVA) in prior works undermines the reliability of observed mechanical trends and their sensitivity to material configurations. To complement experimental findings, finite element analysis (FEA) has become an indispensable powerful tool for evaluating and predicting composite performance under various loading conditions [26]. FEA simulations enable researchers to predict tensile, flexural, and impact behavior, providing insights into stress distribution, failure mechanisms, and material deformation. Other studies [33,35,39,45–49] have highlighted the impact of weave architecture and stacking sequence on the mechanical behavior of NFRCs, yet the influence of matrix-ply interactions in plain-woven jute laminates remains underexplored.

Epoxy and unsaturated polyester resins are widely used thermoset matrices in NFRCs due to their mechanical integrity and thermal stability [40,41]. Epoxy is particularly prized for its cross-linked architecture, chemical resistance, and superior fiber adhesion [51]. Vacuum-assisted resin infusion (VARI) has further enhanced composite quality by improving fiber wetting and minimizing voids [52]. However, a direct comparative analysis of epoxy and polyester matrices in plain-woven jute laminates of varying ply count under controlled fabrication conditions is notably lacking. Moreover, the combined use of Finite Element Analysis (FEA) and statistical modeling in natural fiber composite research is still rare. While FEA has proven effective in simulating mechanical behavior in synthetic fiber composites [26,44, 53–55], its application in woven NFRCs is limited. Few studies have validated FEA models with experimental and statistical data, thus limiting predictive optimization for real-world deployment.

This study addresses these critical gaps by conducting a comparative experimental and numerical investigation of resin-infused woven jute composites fabricated with epoxy and polyester matrices in 2-ply, 4-ply, and 6-ply configurations. The mechanical (tensile, flexural, impact, hardness) and thermal behaviors are systematically evaluated, supported by Scanning Electron Microscopy (SEM) for microstructural analysis and Thermogravimetric Analysis (TGA) for thermal stability assessment. Finite Element Analysis (FEA) simulations, developed in ANSYS and parameterized with experimental data, are used to predict stress-strain responses and failure mechanisms. Statistical validation via ANOVA further substantiates the significance of ply count and matrix selection on composite performance. The novelty of this study lies in the integration of standardized textile architecture, resin-infusion processing, and multi-ply stacking to develop high-performance jute-based thermoset laminates. The ply configurations (2-ply, 4-ply, and 6-ply) were selected to investigate the nonlinear effects of fiber volume fraction and stacking architecture on mechanical and thermal performance. These configurations are representative of industrial laminate thicknesses used in renewable energy and lightweight infrastructure applications. Prior studies have largely overlooked this configuration gradient within plain-woven jute systems under controlled VARI processing [14,56,57]. This study distinguishes itself by combining ply-level experimental characterization with FEA-based stress prediction and ANOVA statistical validation, offering a holistic insight into the structural viability of jute thermoset composites. Epoxy and polyester thermosets were selected based on their superior wetting behavior, cross-linked molecular architecture, and compatibility with vacuum-assisted resin infusion (VARI). Compared to thermoplastics, these matrices ensure dimensional stability, higher modulus, and fewer voids during low-pressure infusion, making them industrially relevant for structural laminates. This work directly informs the matrix material selection and ply configuration strategies for renewable energy housing panels, wind turbine nacelles, and light structural shells, providing validated FEA models and statistically robust data for design engineers. The findings contribute to the optimized design of bio-based structural composites for lightweight, thermally stable, and mechanically robust applications in construction, automotive, and renewable energy infrastructure sectors.

2. Experimental

2.1. Materials

This study employed plain-woven jute fabrics, with fabric construction details provided in Table 1, as the reinforcing phase. and two thermoset resins epoxy (Epotec YD-128) and unsaturated polyester as matrix binders. The jute fabrics were configured into 2-ply, 4-ply, and 6-ply laminates. Epoxy resin was cured using triethylene tetramine (Aradur LY-556/Araldite HY-951) in a 1:2 wt ratio, while the isophthalic polyester resin (VBR-4301, viscosity 0.3 Pa·s, supplied by Vasavi Bala Resins) was prepared with methyl ethyl ketone peroxide (MEKP) and cobalt naphthanate as catalyst and accelerator, respectively, mixed in a 1:1.5 wt ratio. All materials were procured from certified industrial sources to ensure batch consistency and material integrity throughout the fabrication process.

2.2. Composite fabrication via vacuum-assisted resin infusion (VARI)

The resin-infused woven jute fiber composites were fabricated using the vacuum-assisted resin infusion (VARI) technique to minimize void content and enhance fiber-matrix bonding. The process involved fabric preparation in which plain-woven jute fabrics were cut into dimensions of 300 mm × 300 mm for all configurations (2-ply, 4-ply, and 6-ply). This was followed by mold Setup where the woven jute was laid in a flat mold lined with release agents to facilitate demolding. The vacuum bagging system was used to encase the mold, ensuring complete sealing. A vacuum pump was connected to evacuating air from the system. The resin infusion comprises of epoxy and polyester resins were prepared with their respective hardeners and infused into the fabric layers under vacuum, ensuring uniform distribution. Finally, followed by curing in

Table 1
Fabric construction details.

Sample	Weave type	EPI	PPI	Areal Density (g/m^b)	Thickness (mm)	Thread counts (Ne)	Thread direction	Tensile properties	
								Strength (MPa)	Elongation at break (%)
Woven Jute	1 × 1 plain	12	10	315	0.53	20	Warp	16.73	49.00
							Weft	13.77	20.00

Note: EPI = Ends per inch; PPI = Picks per inch.

which the infused laminates were left to cure under vacuum pressure for 24 hour at room temperature, followed by post-curing at 80 °C for 2 hour to enhance matrix cross-linking. The physical properties of the resin-infused fabricated composite laminates are presented in Table 2. Fig. 1

2.3. Composites characterization

Tensile, Flexural, Izod Impact, and Rockwell Hardness: Tensile tests were performed on composite specimens according to ASTM D3039. Dog-bone-shaped samples with dimensions of 200 mm × 20 mm × 3 mm (based on laminate configuration (Table 2)) were tested using a universal testing machine (UTM) at a crosshead speed of 5 mm/min with a gauge length of 120 mm. Tensile strength and modulus were recorded for all configurations and matrix types. Flexural tests followed ASTM D790. Rectangular flat specimens of 200 mm × 20 mm × 3 mm were tested in a three-point bending configuration. Impact resistance was measured using an Izod impact tester in accordance with ASTM D256. Five composites' specimens of 63.5 mm × 12.7 mm × 3 mm dimension were tested, and the absorbed energy (J) was recorded for each configuration. Hardness measurements were conducted on composite specimens using a Rockwell Instron hardness tester in compliance with ASTM D785. The sample specimens' dimensions were 25 mm diameter and 20 mm length were used to evaluate surface hardness. All mechanical tests, tensile, flexural, impact, and hardness were conducted in the warp direction, which corresponds to the machine direction of the plain-woven jute fabric (1 × 1 plain weave). This choice ensured consistent fiber alignment and stress propagation along the dominant load-bearing axis.

Density test: Density was determined using the Archimedes' principle as per ASTM D792–91. The composites with dimensions of 20 mm x 20 mm were measured using the digital densimeter, and the average value determined.

Statistical Analysis: The statistical analysis employed one-way ANOVA to assess the impact of laminate configuration and matrix type on the mechanical properties of the composites, with a significance threshold set at $p \leq 0.05$. Tensile strength and elastic modulus data from composite specimens with varying ply counts (2-ply, 4-ply, and 6-ply) were analyzed using Microsoft Excel 365 Pro Plus, following standard ANOVA protocols. Key statistical parameters, including p-values and F-statistics, were computed and compared against the critical F-value (*F*_{crit}) to determine statistically significant differences of the composites' mechanical behavior.

SEM Microstructural Analysis: A detailed microstructural examination of the tensile fracture surfaces of the composite specimens was performed using a Hitachi 3400 Scanning Electron Microscope (SEM) (Chiyoda, Tokyo, Japan). The analysis aimed to investigate fiber-matrix interfacial adhesion, failure mechanisms, and morphological features associated with mechanical deformation. Prior to imaging, the composite samples were sputter-coated with a thin layer of gold to enhance electrical conductivity and minimize charging effects.

Thermogravimetric Analysis: The thermal stability and degradation kinetics of the composite specimens were evaluated using Thermogravimetric Analysis (TGA) in accordance with ASTM D3850 standard procedures. A precisely measured sample mass (5 mg) was subjected to a controlled heating regime from 30 °C to 600 °C at a uniform heating rate of 10 °C/min under an inert nitrogen atmosphere to prevent oxidative degradation. Data processing and thermal event characterization were performed using Proteus software, ensuring precise interpretation of thermal resistance and degradation behavior

Finite Element Analysis (FEA) Modeling: Finite Element Analysis (FEA) was performed using ANSYS R23.2 to simulate the tensile and flexural behavior of plain-woven jute reinforced thermoset composites. Experimentally determined material properties, including Young's modulus and Poisson's ratio, were used as input parameters. Geometric models representing 2-, 4-, and 6-ply laminate configurations were constructed under isotropic material assumptions to ensure consistency across the 3D domain. Appropriate boundary conditions and loading schemes, derived from experimental setups, were applied to replicate actual test conditions. Quadratic meshing was utilized to optimize computational efficiency and improve deformation accuracy. Static structural simulations were carried out to evaluate stress-strain distributions under tensile and flexural loading, enabling detailed assessment of mechanical response and structural integrity.

The FEA outputs were compared with experimental results to validate the accuracy of the model. The close agreement between simulated and observed data confirms the reliability of the FEA approach in predicting the mechanical behavior of natural fiber composites under varying laminate configurations.

Fig. 2 presents the schematic workflow of the FEA experimental simulation and validation stages of the plain-woven jute reinforced thermoset epoxy and polyester composite laminates. The simulation process as illustrated in Fig. 2, began with the generation of composite beam geometry (Section A) and ply stack-up configuration in the ANSYS Composite PrepPost (ACP) module (Section B), using experimentally derived material properties presented in Table 2. Single-ply beam models were used as a base to sequentially construct 2-ply, 4-ply, and 6-ply laminates, ensuring accurate representation of the composite architecture.

In Section C, boundary conditions and loading scenarios were applied to mirror the experimental three-point bending test setup. These conditions, including support spans and central loading, were then

Table 2
Resin-infused plain-woven composites properties.

Sample ID	Laminate configuration	Stacking (layering) Sequence	Composite thickness (mm)	Fiber volume fraction	Composite density (g/cm^c)
Jute/Epoxy	2-ply	J/J	3.25	0.48	1.21 ± 0.05
	4-ply	J/J/J/J	3.30	0.69	1.24 ± 0.02
	6-ply	J/J/J/J/J/J	3.44	0.79	1.24 ± 0.01
Jute/PES	2-ply	J/J	3.34	0.46	1.26 ± 0.03
	4-ply	J/J/J/J	3.39	0.66	1.25 ± 0.02
	6-ply	J/J/J/J/J/J	3.43	0.78	1.27 ± 0.01

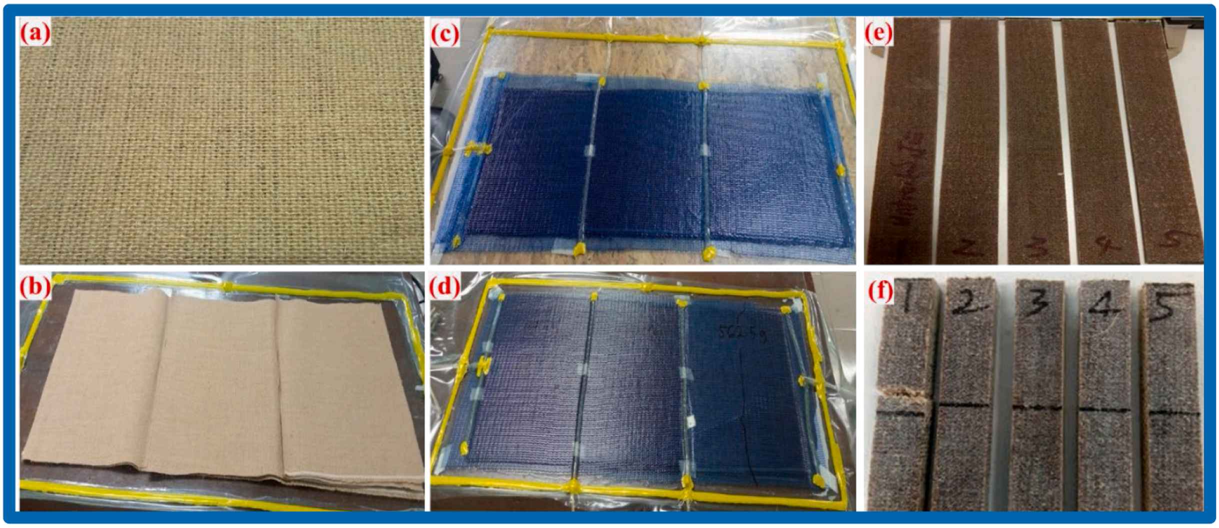

Fig. 1. Pictorial view of (a) plain-woven jute fabric, (b) woven jute laminated (plies) configuration set-up (c) vacuum Resin-infusion fabrication process for 2-ply, 4-ply and 6-ply reinforced thermoset epoxy and polyester composites laminates (e) Composite cut-test specimens for tensile & flexural (f) Composite cut-test specimens for impact test.

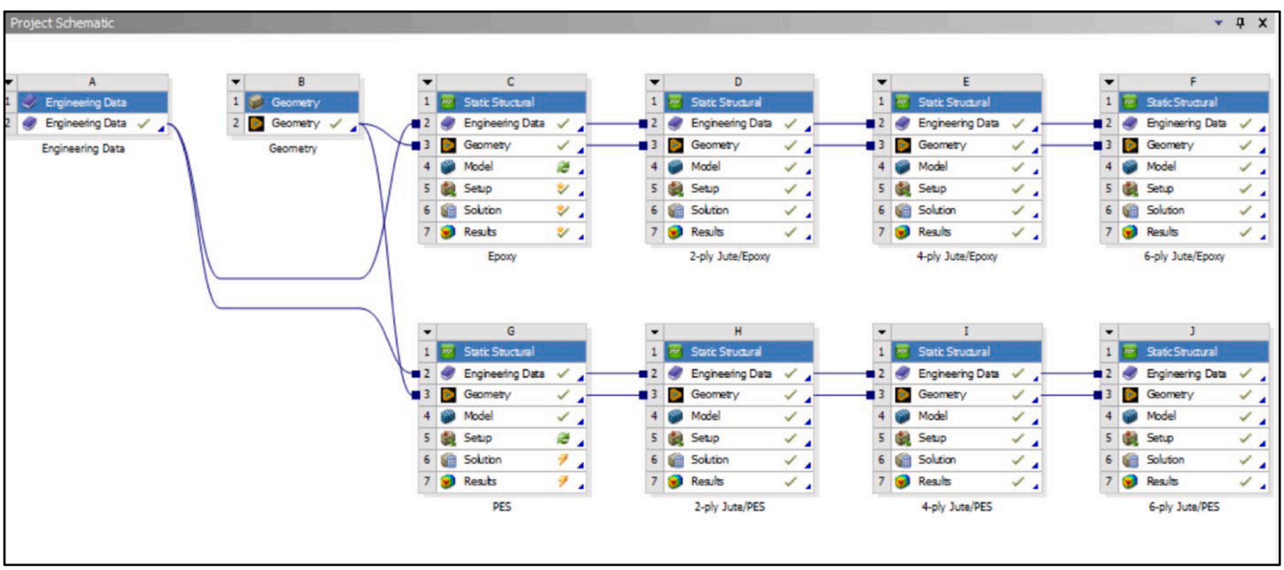

Fig. 2. Schematic workflow of the FEA experimental simulation and validation stages of resin-infused plain-woven jute reinforced thermoset composite laminates.

transferred to Section D, where static structural simulations were conducted. The model incorporated precise layer stacking, material property definitions, and mechanical boundary conditions to ensure fidelity to the physical testing conditions.

ANSYS 2024 R2 was employed to develop geometries for both tensile and flexural (three-point bending) test specimens, as shown in Fig. 3a(i) and 3a(ii). The tensile specimens were modeled with dimensions of 200 mm × 20 mm × 3 mm and included 2-, 4-, and 6-layer woven jute laminates infused with epoxy and polyester matrices. Initial layer geometry was defined in the CAD module, with successive layers generated iteratively to preserve dimensional consistency and laminate symmetry. This approach ensured accurate simulation of material behavior under tensile and flexural loads, enabling reliable stress-strain and failure mode analysis.

The meshing models for tensile and bending simulations are shown in Fig. 3b(i) and 3b(ii). The meshing process commenced with edge-sizing operations, beginning with a coarse mesh size of 32 mm and progressively refined to 4 mm to ensure convergence and computational stability. Quadratic (second-order) meshing was employed for all composite laminate models to accurately capture bending-induced deformations and interlaminar stresses. Frictional contact conditions were applied at the load interfaces to simulate realistic load transfer, while frictionless contact was assigned to the supports to allow unconstrained deformation under applied loads. This setup ensured appropriate boundary interactions for both tensile and three-point bending models.

Following mesh generation, the model was transferred to ANSYS Static Structural for simulation. Boundary conditions, displacement inputs, and tensile stress parameters were applied to evaluate the mechanical response of the woven jute fiber-reinforced thermoset laminates. The simulation framework enabled precise prediction of stress distributions, deformation behavior, and failure initiation under experimental test conditions.

The boundary conditions were defined by fixing one end of the specimen and applying experimentally measured maximum displacements at the opposite end, as depicted in Fig. 4a(i) and 4a(ii). This setup accurately reproduced the mechanical loading experience during tensile

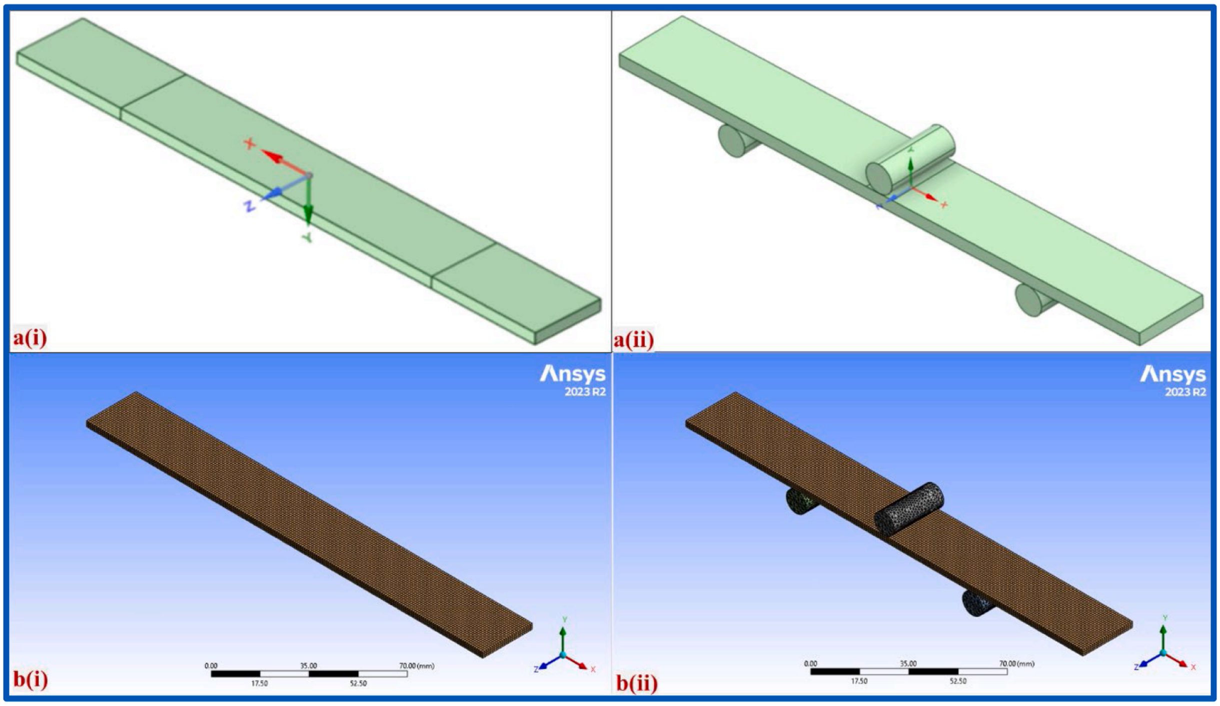

Fig. 3. The geometrical model of resin-infused plain-woven jute reinforced thermoset composite laminates in a(i) tensile stress and a(ii) three-point bending, and the meshing in b(i) tensile and b(ii) three-point bending.

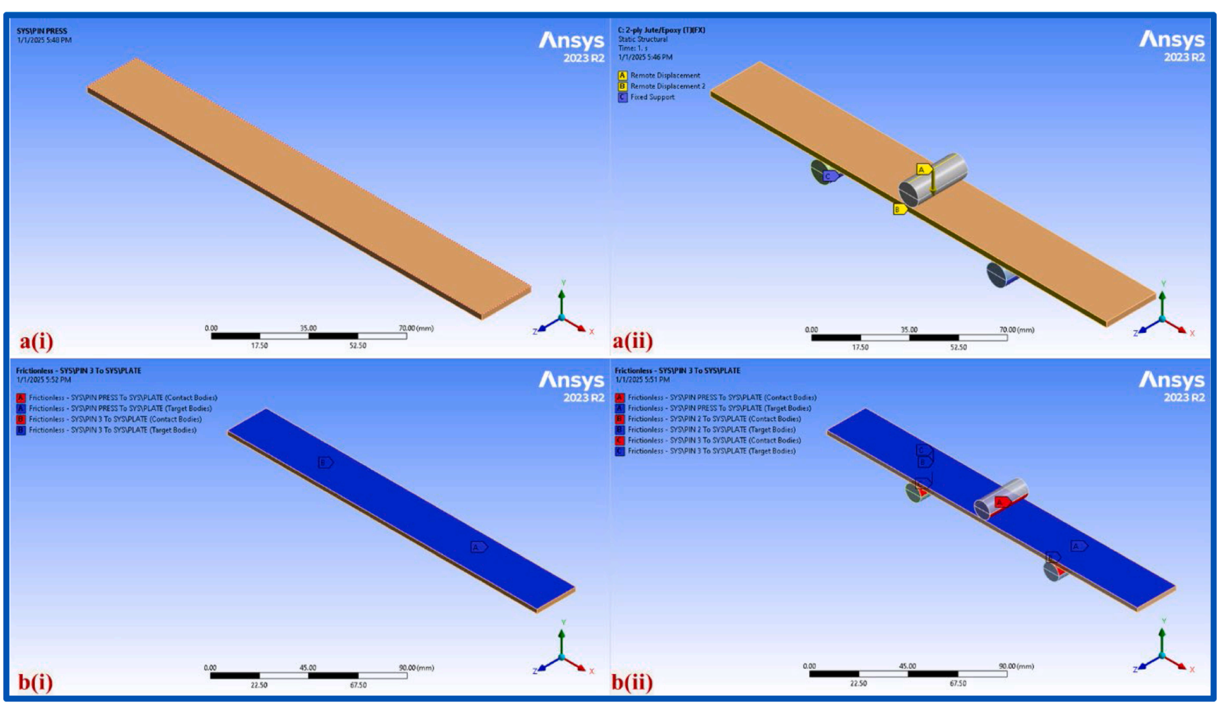

Fig. 4. Boundary conditions and loading configurations for resin-infused plain-woven jute thermoset composite laminates in finite element analysis: (a)(i) fixed support at one end of the tensile specimen; (a)(ii) mid-span displacement applied in three-point bending; (b)(i) contact definitions between laminate, indenter, and supports; and (b)(ii) remote displacement applied at the indenter with fixed boundary conditions at the supports.

and flexural testing, enabling precise simulation of composite behavior under stress. Three-point bending simulations were conducted in ANSYS Workbench to evaluate the flexural response of the woven jute fiber-reinforced thermoset composite laminates. Key structural parameters including flexural stress-strain characteristics, flexural strength, and flexural modulus were computed to assess material performance. The flexural test geometries were modeled in SpaceClaim using the same design protocol as the tensile specimens to maintain consistency across simulation environments. After defining contact interactions, remote displacement boundary conditions were applied at the midspan loading point to replicate the load levels recorded during physical testing. Corresponding displacements for 2-ply, 4-ply, and 6-ply laminates were assigned, while the support nodes were constrained. Fig. 4b(i) and 4b(ii) illustrate the implementation of contact conditions and displacement inputs, ensuring realistic replication of experimental boundary effects within the numerical model.

3. Results and discussion

3.1. Mechanical properties

3.1.1. Effect of laminate configuration and matrix type on tensile properties

The tensile behavior of resin-infused plain-woven jute reinforced thermoset composites, fabricated with epoxy and unsaturated polyester (PES) matrices, was analyzed with respect to ply configuration. As presented in Table 3 and Fig. 5, tensile strength exhibited a progressive increase with the number of plies for both matrix systems, confirming a strong dependency on laminate architecture. The 6-ply jute/epoxy composite recorded the highest tensile strength at 76.85 MPa, followed by the 4-ply configuration (74.57 MPa), while the 2-ply jute/PES laminate showed the lowest tensile performance at 68.23 MPa. The observed trend is attributed to the increased fiber volume fraction (Table 2) and enhanced load transfer across the fiber-matrix interface in higher ply configurations, which collectively reduce stress concentrations and improve tensile capacity.

Unlike tensile strength, the tensile modulus exhibited a more nuanced trend, with values generally increasing with ply count, particularly in epoxy-based systems. The 6-ply jute/epoxy composite recorded the highest tensile modulus at 3.965 GPa, compared to the 2-ply jute/epoxy counterpart (2.919 GPa), and the 2-ply jute/PES laminate (1.395 GPa). This marked enhancement in stiffness is attributed to the increased fiber volume fraction in multi-ply configurations, which promotes more efficient load distribution and improved stress transfer along the fiber-matrix interface owing to increased stacking sequences and orientation in woven jute laminates [47].

Across all configurations, epoxy-based composites outperformed polyester-based ones [14]. At 2-ply, the jute/epoxy laminate exhibited a modulus of 2.919 GPa, approximately 12.9 % higher than the jute/PES counterpart (2.586 GPa). At 6-ply, the epoxy composite reached 3.965 GPa, exceeding 2.078 GPa recorded for 6-ply jute/PES by 90.8 %, indicating epoxy's superior contribution to laminate stiffness. These improvements stem from epoxy's superior mechanical characteristics, including its excellent fiber wetting, reduced shrinkage, and strong interfacial bonding, which collectively enhance load-bearing capacity [50].

Moreover, epoxy composites displayed smaller standard deviations (Table 3) in tensile modulus values compared to PES, suggesting greater uniformity and consistency in mechanical performance owing to improved matrix-fiber compatibility and structural integrity. Polyester matrix composites consistently exhibited lower tensile strength and modulus across all configurations, with the 2-ply jute/polyester laminate recording the weakest tensile performance. Although polyester is cost-effective and easier to process, its relatively higher brittleness and poor interfacial adhesion contribute to early failure under tensile loads, as polyester-based NFRCs are prone to interfacial debonding and microcracking at lower stress thresholds [45,47]. The tensile strength values obtained in this study for plain-woven jute/epoxy composites are consistent with prior work by Gopinath et al. [31] who confirmed that jute fibre reinforced epoxy composites exhibited superior tensile strength compared to jute/polyester composites depending on the strength properties of the random orientation and distribution of the reinforcing fibres in the matrix, processing techniques and fiber treatment. The slightly higher values observed in the present study of up to 76.85 MPa are attributed to the use of vacuum-assisted resin infusion (VARI), which enhances resin penetration, fiber wetting, and reduces void formation, thereby improving mechanical integrity.

When compared to other natural fiber composites such as plain-woven cotton [58,59], plain-woven jute demonstrated competitive tensile performance, reinforcing the viability of jute as a strong, sustainable alternative. The results confirm that careful optimization of laminate configuration and matrix selection can yield a favorable balance between mechanical performance and environmental sustainability. The improvement in tensile properties with increasing ply count and the superior performance of epoxy-based laminates underline the potential of these composites for load-bearing applications.

3.1.2. ANOVA statistical analysis of tensile properties

A one-way analysis of variance (ANOVA) was conducted to statistically evaluate the influence of ply configuration on the tensile strength and elastic modulus of plain-woven jute reinforced thermoset composites. The analysis, summarized in Tables 4 and 5, revealed highly significant differences, as evidenced by p-values of 0.0422 for the jute epoxy tensile strength and 1.40×10^{-09} for the elastic modulus, both well below the critical threshold of $p \leq 0.05$. The polyester jute composites had a tensile strength p value of 1.41521E-10 and a modulus significant value of 1.40319E-06. These results confirm that variations in ply count have a substantial effect on the mechanical properties of the composites.

The F-statistics for tensile strength and elastic modulus exceeded the corresponding critical F-value for both the epoxy and polyester matrix composites, leading to the rejection of the null hypothesis and demonstrating statistically significant variability across different laminate configurations. Specifically, the mean tensile strength of plain-woven jute/epoxy composites increased from 68.23 MPa in 2-ply laminates to

Table 3
Mechanical properties of resin-infused plain-woven jute reinforced epoxy and polyester composite laminates.

Mechanical Properties											
Tensile								Three-point bending (Flexural)			
Sample ID	Laminate configuration	Modulus (GPa)	Poisson ratio	Density (g/cm^c)	Exp. Tensile strength (MPa)	ANSYS FEA tensile strength (MPa)	Standard deviation (SD)	Modulus (GPa)	Exp. Flexural strength (MPa)	ANSYS FEA flexural strength (MPa)	Standard deviation (SD)
Jute/ Epoxy	2-Ply	2.919± 0.07	0.0282	1.21 ± 0.05	68.23 ± 3.0	77.75	6.73	2.890 ± 0.071	62.73 ± 2.5	61.45	0.91
	4-Ply	2.299 ± 0.08	0.0638	1.24 ± 0.02	74.57 ± 4.0	79.18	3.26	3.478 ± 0.085	77.37 ± 3.0	78.98	1.14
	6-Ply	2.165 ± 0.06	0.1175	1.24 ± 0.01	76.85 ± 3.5	78.75	1.35	3.965 ± 0.065	90.48 ± 4.0	93.44	2.09
Jute/ PES	2-Ply	2.586 ± 0.07	0.0180	1.26 ± 0.03	39.05 ± 2.0	41.83	1.97	1.395 ± 0.075	45.62 ± 2.5	45.28	0.24
	4-Ply	2.199 ± 0.05	0.0155	1.25 ± 0.02	30.12 ± 1.5	31.65	1.08	2.648 ± 0.055	56.53 ± 3.0	63.14	4.67
	6-Ply	2.078 ± 0.05	0.0243	1.27 ± 0.01	62.05 ± 2.5	64.90	2.02	2.832 ± 0.070	61.62 ± 2.5	67.37	4.07

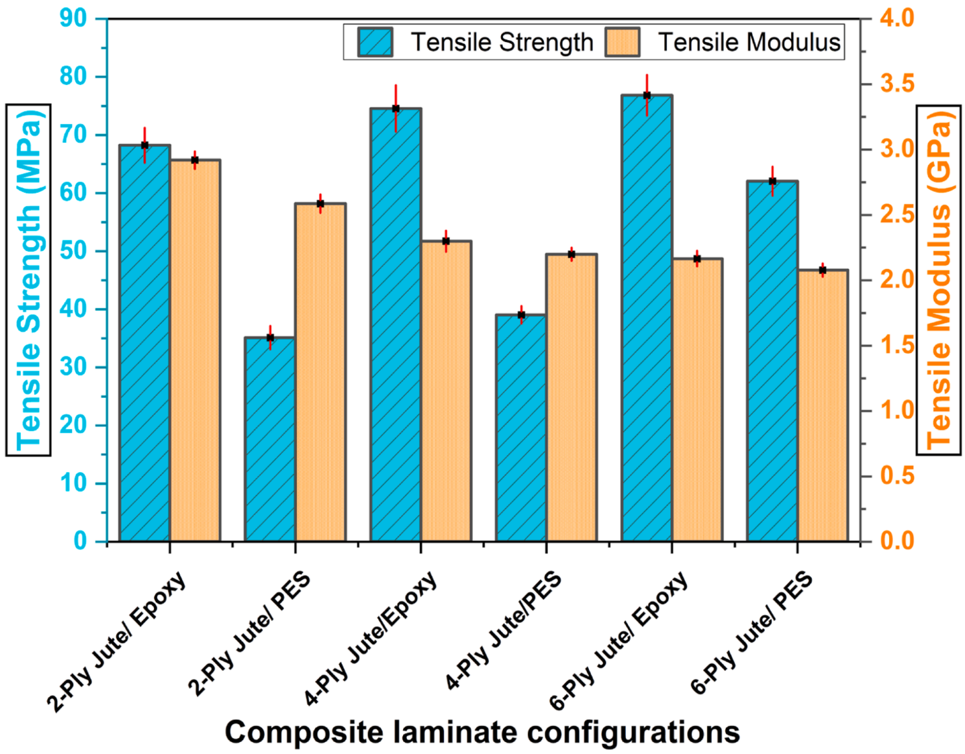

Fig. 5. Comparative **(a)** tensile strength and **(b)** modulus of resin-infused plain-woven jute reinforced thermoset composites.

Table 4
Summary of the analysis for the different test groups.

Sample name	*Sample ID*	Tensile Strength (MPa)			
	Test Groups/Sample	*Count*	*Sum*	*Average*	*Variance*
Jute/Epoxy	2-ply	5	352.04	70.41	18.14
	4-ply	5	371.34	74.27	11.11
	6-ply	5	384.63	76.93	9.41
Jute/PES	2-ply	5	175.24	35.05	5.71
	4-ply	5	196.13	39.23	2.04
	6-ply	5	311.10	62.22	4.75
		Elastic Modulus (GPa)			
	Test Groups/Sample	***Count***	***Sum***	***Average***	***Variance***
Jute/Epoxy	2-ply	5	14.525	2.905	3.327
	4-ply	5	11.495	2.299	6.645
	6-ply	5	10.825	2.165	3.482
Jute/PES	2-ply	5	12.934	2.587	4.901
	4-ply	5	10.996	2.199	2.426
	6-ply	5	10.390	2.078	2.268

76.85 MPa in 6-ply laminates, indicating enhanced structural reinforcement with increasing ply count. However, despite the higher modulus of the 2-ply configuration (2.919 GPa), a marginal decline in elastic modulus was observed in 4- and 6-ply laminates, likely attributable to increased interfacial defects such as void formation and incomplete resin impregnation. A similar decreasing trend was noted in plain-woven jute/polyester (PES) composites, where the elastic modulus reduced from 2.586 GPa in 2-ply laminates to 2.078 GPa in 6-ply laminates. Notably, plain-woven jute/epoxy composites exhibited superior tensile strength and modulus compared to their plain-woven jute/PES counterparts, highlighting the influence of matrix selection on mechanical performance.

ANOVA analysis indicated that both the matrix type and laminate configuration had statistically significant effects on the tensile properties, with the ply count exhibiting a greater influence on tensile modules than tensile strength. The ANOVA findings reinforce the critical role of

Table 5
One-way (single factor) ANOVA for the tensile properties of thermoset composites.

	Tensile Strength (MPa)					
Jute Epoxy *Source of Variation*	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	107.41	2	53.71	4.1674	0.0422	3.8852
Within Groups	154.65	12	12.8872			
Total	262.06	14				
Jute Polyester *Source of Variation*	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	2140.83	2	1070.41	256.83	1.41521E-10	3.8853
Within Groups	50.01	12	4.17			
Total	2190.84	14				
	Elastic Modulus (GPa)					
Jute Epoxy *Source of Variation*	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	1554.474	2	777.237	0.173	1.40319E-06	3.8852
Within Groups	53.812	12	4.484			
Total	1608.286	14				
Jute Polyester *Source of Variation*	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	706.166	2	353.083	0.110	1.8761E-05	3.8852
Within Groups	38.380	12	3.198			
Total	744.546	14				

Note: Statistically significant at $p \leq 0.05$.

ply stacking in optimizing tensile properties, demonstrating that while increasing the ply count generally enhances tensile strength, excessive layering introduce defects that counteract modulus improvement. These observations align with existing literature on fiber-matrix interactions and laminate architecture by Das [40] who reported that one-way ANOVA results revealed statistically significant differences among composite groups. The F-test yielded p-values below 0.05, indicating that variations in tensile strength and modulus across different composite configurations were significant at the 95 % confidence level. Similarly, Jabbar et al. [37] reported statistically significant differences in tensile strength ($p = 0.000$) and tensile modulus ($p = 0.008$) based on ANOVA, confirming significance at the 95 % confidence level. The validated experimental trends highlight the significance of matrix composition, fiber-matrix adhesion, and stacking sequence in optimizing composite strength and stiffness, making them highly relevant for structural applications.

3.1.3. Effect of laminate configuration and matrix type on flexural properties

The flexural performance of resin-infused plain-woven-jute reinforced thermoset composites, fabricated with epoxy and polyester (PES) matrices, was evaluated in terms of flexural strength and modulus. As shown in Table 3 and Fig. 6, a consistent improvement in flexural properties was observed with an increasing fabric ply count across all laminate configurations. The 6-ply jute/epoxy composite exhibited the highest flexural strength at 90.48 MPa, followed by the 4-ply (77.37 MPa) and 2-ply (68.14 MPa) configurations. In contrast, the 2-ply jute/PES composite recorded the lowest flexural strength at 62.73 MPa with 31.8 % improvement. This progressive enhancement in strength with additional plies is primarily attributed to the increased fiber volume fraction, which facilitates more efficient load transfer and mitigates matrix-dominated failure mechanisms. Flexural modulus also showed a similar trend, increasing with ply count. The 6-ply jute/epoxy composite achieved a modulus of 3.965 GPa, while the 2-ply jute/PES laminate exhibited a lower modulus of 2.832 GPa. The improved stiffness in thicker laminates reflects better stress distribution and enhanced fiber reinforcement efficiency, indicating that flexural performance depends on the stacking sequence and the type of thermoset matrix material [47, 48].

Epoxy-based composites consistently demonstrated superior flexural strength and modulus across all laminate configurations when compared to their polyester-based counterparts. The 2-ply and 6-ply jute/epoxy composites recorded flexural strengths of 62.73 MPa and 90.48 MPa, respectively, significantly outperforming the corresponding plain-woven jute/PES laminates, which achieved 45.62 MPa and 61.62 MPa. These values represent approximate improvements of 27.4 % for 2-ply and 31.8 % for 6-ply epoxy composites over polyester equivalents. An indication that flexural performance depends on the stacking sequence and the type of thermoset matrix material [44,46,47,38]. The enhanced performance of epoxy matrix composites is primarily attributed to their superior fiber wetting ability and stronger interfacial adhesion, which promote more effective load transfer and resistance to crack propagation under bending stresses. These results align with that obtained elsewhere [26].

Although polyester composites displayed lower flexural strength, they offer notable advantages in terms of cost-efficiency and ease of processing. The 2-ply jute/PES composite, with a flexural strength of 45.62 MPa, provides sufficient performance for non-critical structural applications. However, its lower flexural modulus of 1.395 GPa indicates a higher susceptibility to deformation under load, which restricts its use in demanding load-bearing environments. Similar trends were reported by Cavalcanti et al. [50] in which polyester-based composites exhibited higher flexural stiffness, as well as greater impact energy absorption, compared to epoxy-based composites. Overall, the results emphasize composites suitability for structural application of higher flexural capacity.

The flexural stress-strain curves in Fig. 7 reveal distinct mechanical responses and failure mechanisms between plain-woven epoxy- and polyester-based composites under bending loads. Epoxy laminates exhibited greater strain energy absorption prior to failure, characterized by a gradual decline in stress after reaching peak strength indicative of a more ductile failure mode. In contrast, polyester composites showed

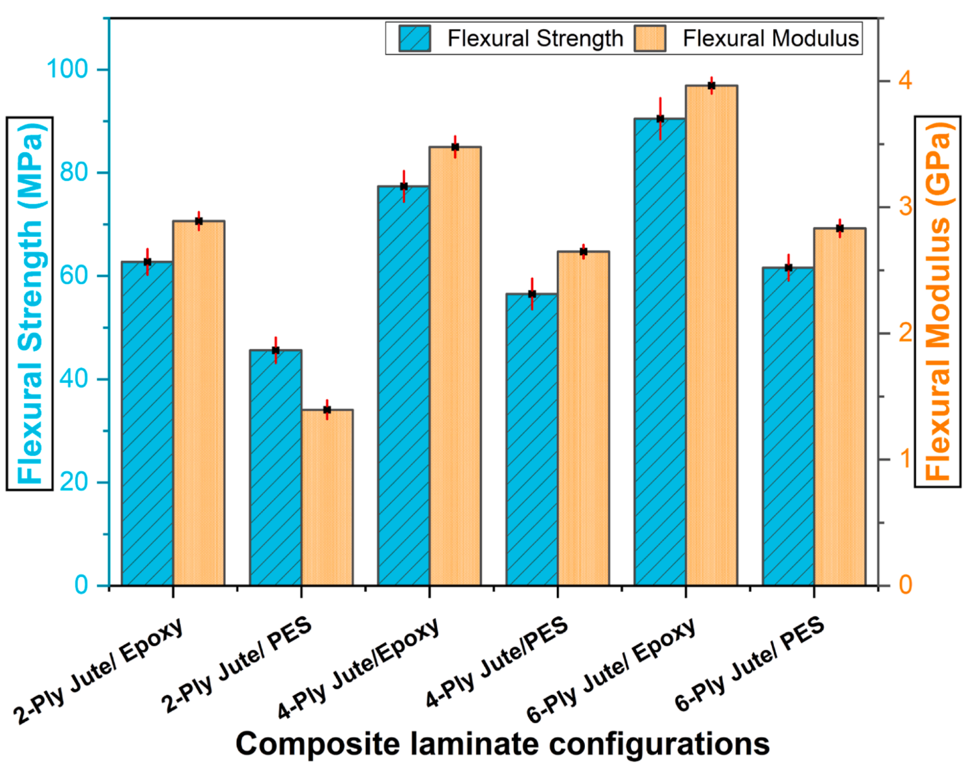

Fig. 6. Comparative **(a)** flexural strength and **(b)** modulus of resin-infused plain-woven jute reinforced thermoset composites.

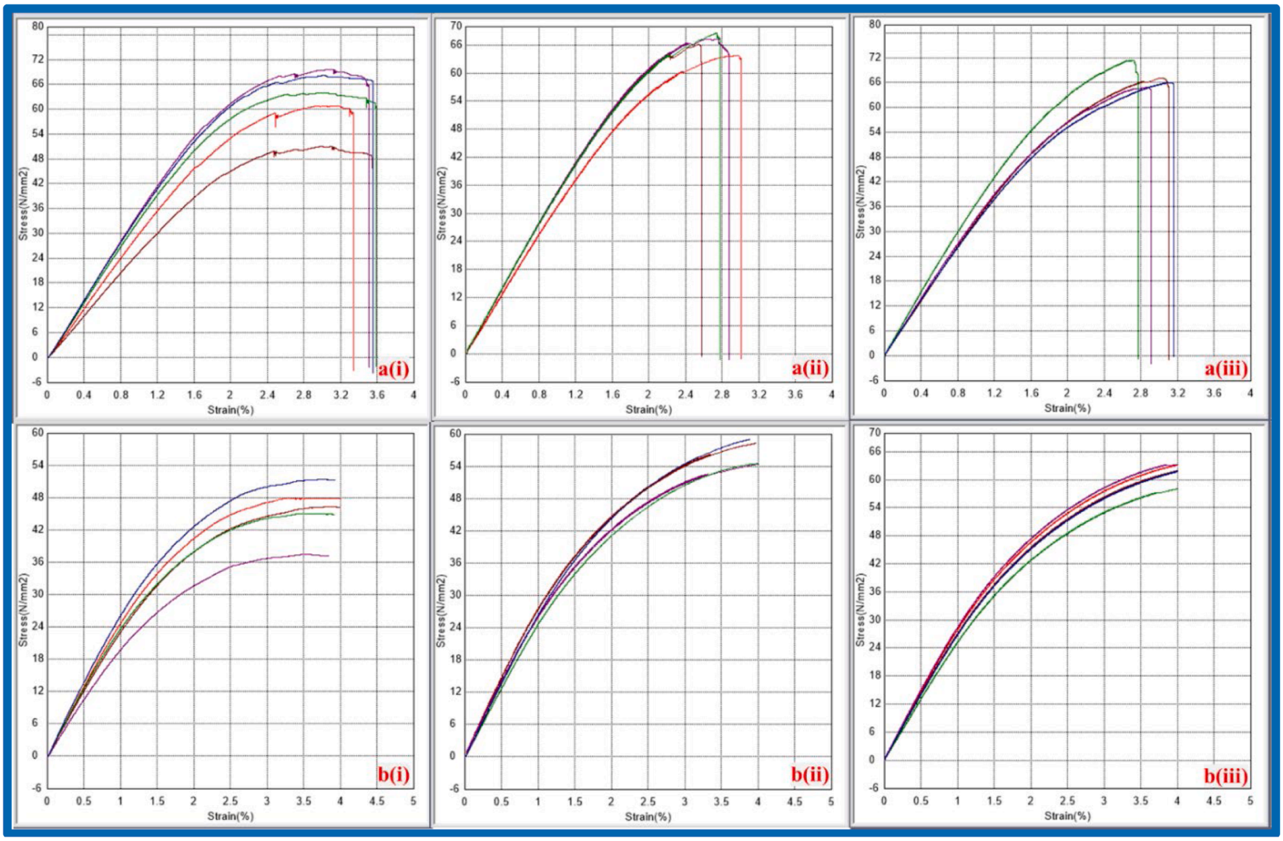

Fig. 7. Flexural stress–strain curves for resin-infused plain-woven jute thermoset composites: (a)(i–iii) 2-ply, 4-ply, and 6-ply jute/epoxy; (b)(i–iii) 2-ply, 4-ply, and 6-ply jute/polyester (PES).

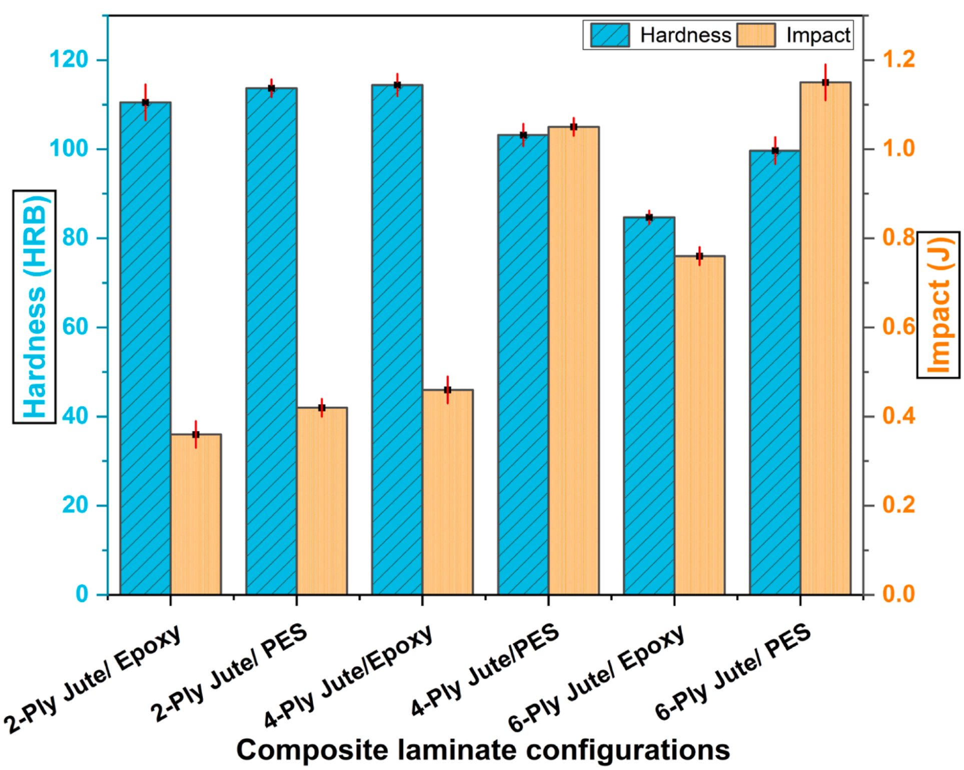

Fig. 8. Comparative hardness and impact energy of resin-infused plain-woven jute reinforced thermoset composites.

abrupt stress drops and brittle failure behavior, reflecting lower energy absorption capacity and limited deformation tolerance and attributed to its brittle behavior characterized by sudden failure, absence of a yield point, and lack of strain hardening [26]. Similar related ANOVA results were reported [32] for flexural strength ($p = 0.000$) and flexural modulus ($p = 0.000$) indicated statistically significant differences at the 95 % confidence level. Furthermore, these mechanical trends are corroborated by their microstructural behaviors, which reveal superior fiber-matrix adhesion and fewer voids in epoxy composites. Polyester composites, on the other hand, displayed microcracking, resin separation, and fiber pull-out hallmarks of weak interfacial bonding. The flexural strength results reported in this study are consistent with other work [60,31].

3.1.4. Effect of laminate configuration and matrix type on density, hardness and impact properties

The density, hardness, and impact properties of resin-infused plain-woven jute reinforced thermoset composites were found to vary significantly with both laminate configuration and matrix type, as presented in Table 3 and Fig. 8. Increasing the number of fabric plies led to a gradual rise in composite density, driven by the increased fiber volume fraction (Table 2) contributing to a higher mass-to-volume ratio. The highest density was recorded in the 6-ply jute/polyester (PES) composite at 1.27 g/cm^3, while the lowest was observed in the 2-ply jute/epoxy composite at 1.21 g/cm^3. The polyester-based composites consistently exhibited higher densities than their epoxy counterparts. This can be attributed to the inherently higher specific gravity and resin-rich zones associated with thermoset polyester systems [61–62]. Polyester's superior impregnation characteristics contribute to its higher composite density. Despite the incremental increase in density with ply number, all measured values remained within the acceptable range for lightweight structural materials.

Hardness values for the resin-infused plain-woven jute reinforced thermoset composites were found to vary with laminate configuration and matrix type. For both epoxy and polyester-based matrix systems, an increase in fabric ply generally resulted in higher hardness due to improved fiber-matrix interactions and greater resistance to surface deformation. In the epoxy composites, hardness increased from 2-ply to 4-ply, peaking at 114.4 HRB for the 4-ply jute/epoxy laminate. This was followed by a decline to 84.7 HRB in the 6-ply configuration, likely due to increased resin-rich zones or internal stress concentrations that reduce surface rigidity.

In contrast, polyester-based composites showed a decreasing trend in hardness with increasing ply count. The 2-ply jute/PES composite exhibited the highest hardness at 113.66 HRB, with values declining in the 4- and 6-ply configurations. The relatively high hardness observed in 2-ply polyester laminates is attributed to the rigid molecular structure of the polyester matrix and its higher density, which contributes to increased resistance to indentation suggesting that composite hardness is primarily influenced by the reinforcing fiber rather than the matrix [26]. Although epoxy-based composites showed slightly lower peak hardness values than their polyester counterparts, they exhibited greater consistency across configurations likely a result of epoxy's superior wetting and adhesion characteristics. The observed decline in hardness at higher ply counts, particularly in the 6-ply composites, emphasizes the need to optimize laminate stacking to maintain surface performance and to avoid the drawbacks of excessive thickness or resin accumulation.

Fig. 8 illustrates the impact resistance of the resin-infused plain-woven jute reinforced thermoset composites as evaluated by the izod impact test, revealing a clear dependence on both laminate configuration and matrix type. Polyester-based (PES) composites consistently demonstrated superior impact behavior compared to epoxy-based counterparts, with impact resistance increasing proportionally with ply count. Cavalcanti et al. [50] also reported greater impact energy absorption with polyester-based composites compared to epoxy-based composites.

The 6-ply jute/PES composite absorbed the highest impact energy at 1.15 J, followed by the 4-ply jute/PES at 1.05 J. In contrast, the 2-ply jute/epoxy composite exhibited the lowest impact energy absorption at 0.36 J. The 6-ply polyester laminate demonstrated a 33.9 % improvement in impact resistance over its epoxy equivalent, stressing the enhanced toughness of the polyester matrix. Several factors might have influenced the impact strength of composite samples, including fiber volume fraction, geometry, and fiber orientation [47]. Hence, the improved impact performance in higher ply laminates is attributed to greater energy dissipation capacity, enhanced interfacial adhesion, and stress delocalization across the composite structure. Polyester composites further benefit from their inherently higher elongation at break and toughness, allowing for more efficient absorption of sudden impact loads. These findings align with work reported by other researchers [26] that Jute/polyester composites exhibit superior impact strength compared to jute/epoxy, primarily due to jute's high cellulose content and low microfibril angle, which enhance the work of fracture during impact. The mechanical behaviours of jute fibers are predominantly governed by their morphology, with stiffness and toughness influenced by the cellulose fraction and fibrillar orientation highlighting the potential of polyester-matrix composites for applications where energy absorption and impact resistance are critical, while epoxy-based laminates remain preferable for stiffness- and strength-dominated applications.

Epoxy-based composites, while exhibiting lower impact energy absorption, demonstrated superior structural integrity post-impact, indicating greater resistance to crack propagation critical for durability under repeated loading. Polyester matrix composites showed higher impact resistance, especially in 6-ply laminates, due to better energy dissipation, though 2-ply variants revealed lower efficiency, emphasizing the role of ply distribution and resin uniformity. Generally, the observed improvements in density, hardness, and impact resistance with increasing ply count further emphasize the role of fiber architecture and matrix selection. Polyester composites exhibited higher hardness and impact energy, while epoxy laminates offered superior dimensional stability and consistency.

3.2. Thermal properties

3.2.1. Effect of laminate configuration and matrix type on thermal stability

The thermal stability of the resin-infused plain-woven jute composites was assessed using thermogravimetric analysis (TGA), and the results are shown in Fig. 9. All samples exhibited a two-stage degradation profile, with the initial mass loss corresponding to moisture and low-molecular-weight volatiles (below 150 °C), and the main degradation event occurring between 250 °C and 400 °C, corresponding to matrix decomposition and fiber pyrolysis.

The thermogravimetric analysis (TGA) results presented in Table 6 and Fig. 9 demonstrate the influence of laminate configuration and matrix type on the thermal stability of resin-infused plain-woven jute reinforced thermoset composites. The thermal degradation behavior of the composites, characterized by onset temperature, endset temperature, and residual mass, varied with increasing ply count and matrix type. The onset degradation temperature, which marks the initiation of thermal decomposition, increased with the number of plies in the plain-woven jute/epoxy composite, reaching a maximum of 341.5 °C for the 6-ply laminate compared to 292.7 °C for the 2-ply configuration. This improvement can be attributed to the higher fiber content, which enhances the composite's resistance to thermal degradation by providing a stronger reinforcement network within the polymer matrix. In contrast, the plain-woven jute/polyester (PES) composites exhibited a decreasing trend in onset temperature with increasing ply count, from 330.2 °C (2-ply) to 304.3 °C (6-ply). This decline suggests that polyester's lower thermal resistance and increased matrix content contribute to earlier thermal degradation compared to epoxy-based composites [41] .

The endset degradation temperature, representing the completion of

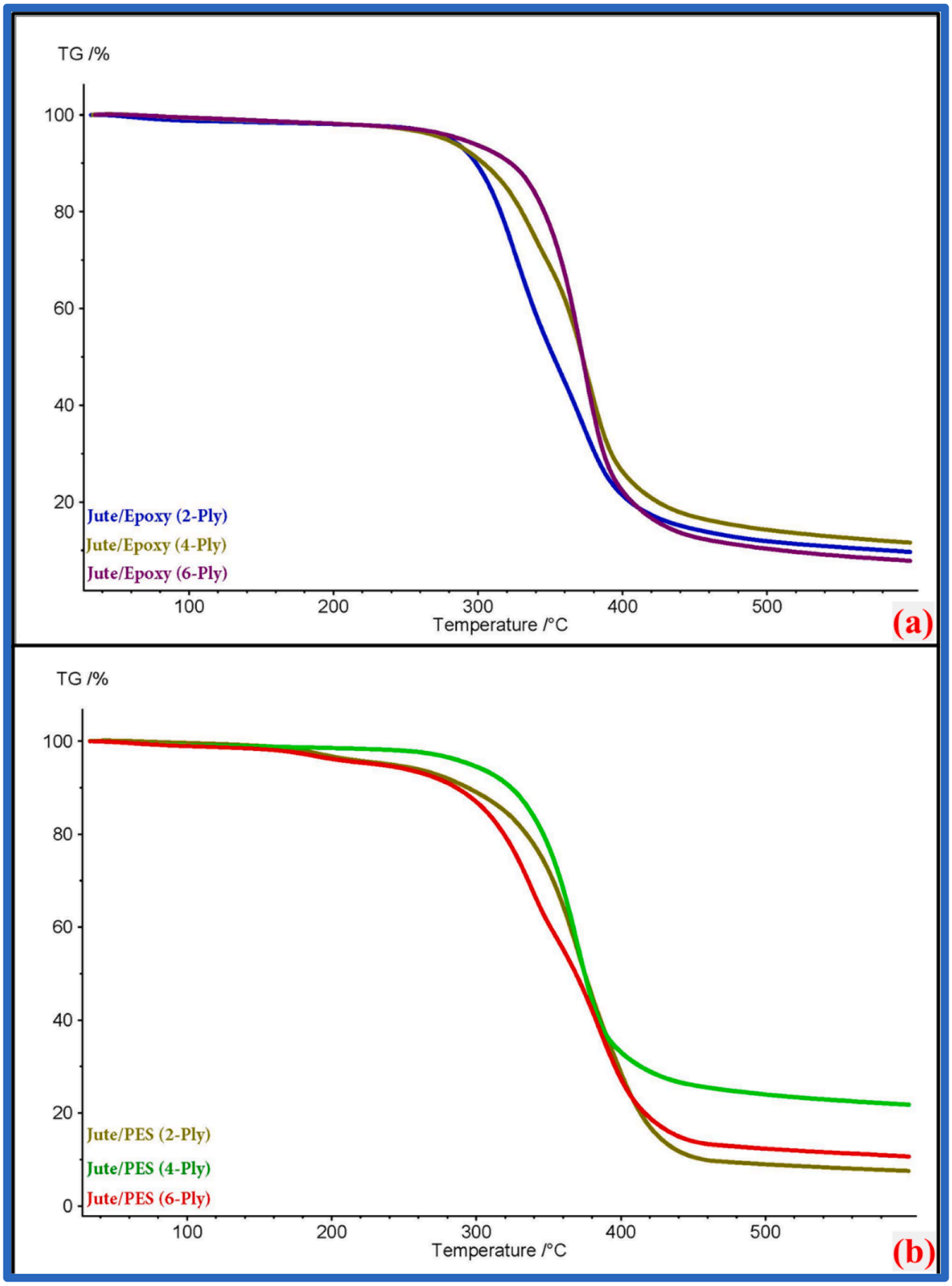

Fig. 9. Combined TGA thermograms of 2-ply, 4-ply, and 6-ply resin-infused plain-woven jute fiber-reinforced thermoset composites with **(a)** epoxy and **(b)** polyester matrices.

Table 6
TGA results of resin-infused plain-woven jute reinforced thermoset composites.

Specimen	Laminate	Onset Temp (°C)	Endset Temp (°C)	Inflection (°C)	Mass change (%)	Residual Mass (%)
Jute/ Epoxy	2-ply	292.7	393.6	328.5	87.02	9.67
	4-ply	327.3	402.0	376.2	85.11	11.59
	6-ply	341.5	395.3	374.7	89.12	7.83
Jute/PES	2-ply	330.2	406.7	367.5	88.44	5.98
	4-ply	328.7	372.5	335.0	61.48	37.10
	6-ply	304.3	357.1	309.8	85.19	12.16

thermal degradation, also exhibited similar trends. The epoxy-based composites showed relatively stable degradation temperatures across different ply configurations, with values ranging from 393.6 °C to 402.0 °C, while the polyester matrix composites exhibited a significant reduction from 406.7 °C (2-ply) to 357.1 °C (6-ply). The decline in the thermal stability of polyester composites be attributed to polymer matrix degradation and weaker interfacial bonding with natural fibers, leading to earlier breakdown at elevated temperatures [43]. The residual mass, an indicator of char formation and thermal stability, was highest for the 6-ply jute/epoxy composite at 7.83 %, indicating better thermal stability due to reduced mass loss. Similarly, Olhan et al. [52] reported a significant mass loss observed between 230 °C and 350 °C, corresponding to the thermal degradation of lignocellulosic components and the matrix. In contrast, the 2-ply jute/polyester composite recorded the lowest residual mass of 5.98 %, suggesting greater volatility and reduced thermal stability due to their thermally stable cross-linked network, which restricted the degree of polymer decomposition.

Thermogravimetric analysis (TGA) revealed that plain-woven jute/

epoxy composites exhibited a non-linear trend in onset degradation temperature, decreasing from 2-ply to 4-ply, then increasing to 341.5 °C at 6-ply. In contrast, plain-woven jute/polyester (PES) composites showed a consistent decline in onset temperatures from 330.2 °C to 304.3 °C as ply count increased from 2 to 6. A similar downward trend was observed in endset degradation temperatures, decreasing from 406.7 °C to 357.1 °C in polyester-based laminates. The 6-ply epoxy laminate demonstrated the highest thermal stability, with an onset temperature of 341.5 °C and a residual mass of 7.83 %, while the 2-ply polyester laminate showed the lowest thermal resistance and char yield (5.98 %). These differences are attributed to the superior thermal resistance and cross-linked molecular architecture of epoxy, whereas the pendant bonds and lower cross-link density in polyester promote earlier degradation and volatilization.

In comparison of thermoset matrices, polyester matrix composites exhibited higher residual masses of 37.10 % at 4-ply compared to epoxy composites counterpart (11.59 %), indicating higher volatility and reduced thermal resistance of polyester in thermal endurance due to their rigid aromatic structure and strong cross-linking capability. The variation in thermal stability between epoxy and polyester matrices can be attributed to the differences in their chemical compositions. Epoxy resins have a higher degree of cross-linking and superior thermal endurance, whereas polyester resins, although having good thermal resistance, tend to degrade more readily under prolonged heating conditions.

For the plain-woven jute/epoxy composites, the increase in ply count from 2-ply to 6-ply resulted in improved thermal stability, with onset temperatures increasing from 292.7 °C to 341.5 °C. This trend suggests that the higher fiber content in multi-ply laminates offers better insulation and structural integrity against thermal degradation. In contrast, the polyester matrix composites exhibited a decrease in onset temperature with increased ply count, indicating a potential trade-off between reinforcement and thermal stability in polyester systems. The inflection temperature, representing the point of maximum degradation rate, followed a similar pattern, with the 6-ply jute/epoxy composite achieving an inflection temperature of 374.7 °C, compared to 328.5 °C for the 2-ply composite. The plain-woven jute/polyester composites, however, showed a decrease from 367.5 °C (2-ply) to 309.8 °C (6-ply), indicating a weaker thermal response as ply count increased. A comparative analysis reveals that epoxy-based composites consistently demonstrated higher thermal resistance than their polyester counterparts across all ply configurations. Specifically, the 6-ply jute/epoxy laminate exhibited an onset degradation temperature of approximately 341.5 °C, whereas the corresponding plain-woven jute/polyester laminate degraded earlier at around 304.3 °C with 12.2 % improvement which can be attributed to the aromatic backbone and higher crosslinking density of epoxy coupling with a stronger matrix-fiber adhesion, which enhances thermal stability through stronger intermolecular cohesion and more stable char formation during decomposition [63,64]. In contrast, polyester composites exhibited lower values due to their aliphatic ester groups, which are more susceptible to chain scission and volatilization at elevated temperatures. Moreover, polyester-based systems demonstrated slightly steeper mass loss curves during the primary degradation phase, indicating faster thermal decomposition kinetics and reduced residual char formation compared to epoxy systems. The observed differences in thermal degradation behavior emphasize the importance of matrix chemistry in tailoring the high-temperature performance of natural fiber-reinforced thermoset composites. The obtained results, in comparisons with other plant-based composites such as kenaf suggest that jute composites exhibit competitive thermal performance, with kenaf-based composites reported to have onset temperatures in the range of 320–350 °C [63], comparable to the jute/epoxy composites observed in this study. The superior performance of epoxy-based composites suggests their suitability for applications requiring prolonged exposure to elevated temperatures, whereas polyester-based composites be more suitable for cost-sensitive applications where moderate thermal resistance is sufficient.

3.3. Morphological properties

3.3.1. Microstructural observations of jute/epoxy and jute/polyester composites

The morphological analysis of the resin-infused plain-woven jute reinforced composites conducted using Scanning Electron Microscopy (SEM), is presented in Fig. 10. The micrographs provide microstructural behaviours which include fiber-matrix interaction, void content, and failure mechanisms across different laminate configurations (2-ply, 4-ply, and 6-ply) for both epoxy and polyester matrix composites. The SEM images of the plain-woven jute/epoxy composites as seen in Fig. 10 reveal improved fiber-matrix adhesion, with minimal interfacial gaps and voids, particularly in the 4-ply and 6-ply configurations. The presence of well-embedded fibers within the epoxy matrix suggests efficient impregnation and effective load transfer leading to enhanced interfacial adhesion, which contributes to the superior mechanical properties observed in tensile and flexural tests. The SEM analysis also provided further insights into the failure mechanisms observed in the tensile fracture surfaces. The micrographs revealed that epoxy-based composites exhibited better fiber-matrix adhesion with minimal voids, whereas polyester-based samples showed signs of fiber pull-out, matrix cracking, delamination, and voids were observed in the composites leading to lower tensile properties [48].

In contrast, the SEM micrographs of the plain-woven jute/polyester (PES) composites Fig. 10 (d-f) exhibit a higher frequency of voids, matrix cracking, and fiber pull-out across all laminate configurations, with the 2-ply in Fig. 10 (d) and 4-ply laminates in Fig. 10 (e) displaying more pronounced interfacial debonding, indicating robust interfacial adhesion and effective fiber–matrix interconnection [13]. The 6-ply jute/PES laminate in Fig. 10 (F) showed improved fiber encapsulation with few fiber agglomeration highlighting weak fiber–matrix adhesion interfered with uniform stress transfer and compromise the composite mechanical performance [26].

In the context of the laminate configuration effect, the number of plies had a significant impact on the morphological characteristics of the composites. The 6-ply laminates for both epoxy and polyester matrices exhibited improved fiber alignment and reduced void formation, contributing to better mechanical integrity. The higher ply count facilitated better stress distribution and reduced localized stress concentrations, thereby mitigating the occurrence of micro-cracks. SEM images highlight enhanced fiber-matrix bonding in epoxy composites, with minimal voids observed in 6-ply laminates. Polyester matrix composites displayed weaker adhesion, leading to premature failure under tensile loading. SEM analysis also revealed that the increasing ply counts enhanced microstructural integrity, particularly in plain-woven jute/epoxy laminates. The 6-ply plain-woven jute/polyester composites exhibited localized delamination, likely due to residual stress and insufficient resin infiltration. Plain-woven jute/epoxy composites showed more fiber breakage, an indicative of stronger interfacial adhesion and effective stress transfer, whereas plain-woven jute/polyester laminates exhibited extensive pull-out and debonding, highlighting weaker bonding and increased stress concentration. The presence of micro-voids in polyester composites likely contributed to premature failure. However, the use of vacuum-assisted resin infusion in this study minimized voids and improved fiber wetting, especially in epoxy-based laminates. These microstructural features critically influence mechanical and thermal performance.

3.4. Finites element analysis (FEA) simulation approach

The Finite Element Analysis (FEA) performed using ANSYS R23.2 Workbench provided an in-depth simulation of the mechanical behavior of plain-woven jute reinforced thermoset composites under tensile and flexural loading. The results, presented in Fig. 11a and 11b, exhibit a

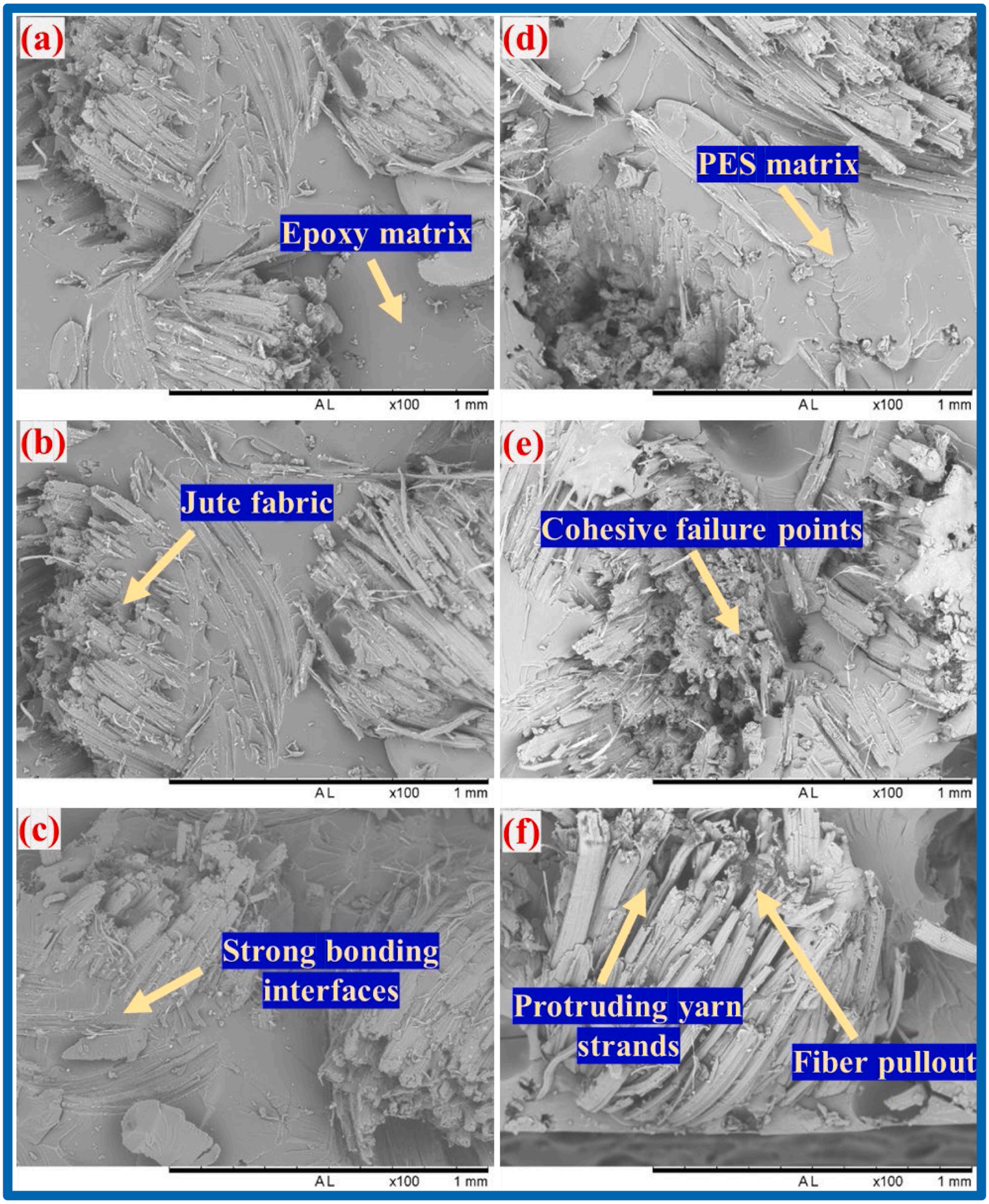

Fig. 10. SEM images of fracture surfaces for resin-infused plain-woven jute composite laminates at 100 × magnification: (**a–c**) 2-ply, 4-ply, and 6-ply jute/epoxy composites; (**d–f**) 2-ply, 4-ply, and 6-ply jute/polyester (PES) composites.

strong correlation between simulated and experimental data, with minor deviations attributed to idealized boundary conditions and the assumption of flawless fabrication.

Experimentally, the tensile strength of the 6-ply jute/epoxy composite was recorded at 76.85 MPa, while the FEA-predicted value was 78.75 MPa, reflecting a deviation of approximately 2.4 %. Similarly, for the same configuration, the experimentally determined flexural strength was 90.48 MPa, compared to the FEA-predicted value of 93.44 MPa, yielding a deviation of about 3.17 %. These variations fall within the standard error margins observed in prior studies [23] with deviations of 3–6 % recorded due to idealized simulation constraints.

Further validation of the numerical model is evident in the tensile strength predictions for the 2-ply jute/epoxy composite, where the FEA-derived value of 77.75 MPa closely matched the experimentally obtained 68.23 MPa, with a deviation of approximately 3.24 %. Likewise, the FEA-predicted flexural strength of 61.45 MPa exhibited a minimal discrepancy of 2.04 % compared to the experimental value of 62.73 MPa. These results confirm the accuracy of the simulation in capturing the stress-strain behavior of natural fiber composites [48] with a minor deviation of about 5–7 % between FEA and experimental, confirming the reliability of numerical modeling. The minor discrepancies were attributed to the simulation's assumption of material homogeneity,

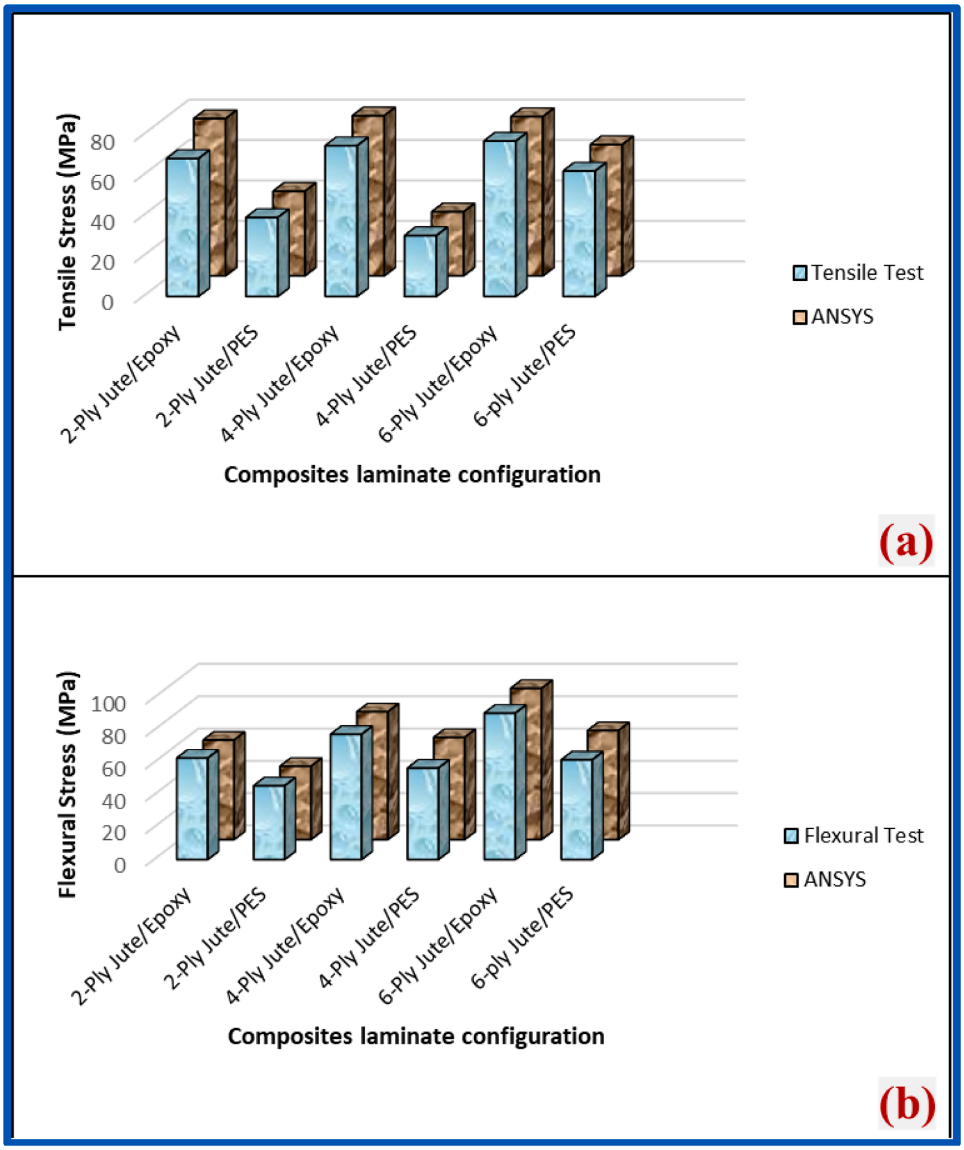

Fig. 11. Comparison of experimental and ANSYS-predicted stress responses for resin-infused plain-woven jute thermoset composites: **(a)** tensile stress and **(b)** flexural stress.

whereas experimental samples exhibited voids, fiber-matrix debonding, and interfacial imperfections. Additionally, for the 6-ply jute/epoxy composite, the FEA-predicted flexural strength was 93.44 MPa, closely corresponding to the experimentally determined 89.48 MPa, yielding a deviation of approximately 5.3 %. This strong correlation validates the robustness of the simulation methodology in accurately capturing the mechanical behavior of the plain-woven jute thermoset composites. Similar observation was made [26] in which the experimental and FEA results showed strong agreement, with a minimum deviation of 1.89 % in equivalent stress prediction and 5–8 % for tensile stress. This further substantiated the validity of FEA in accurately simulating tensile behavior in fiber-reinforced composites with minimal deviation from experimental data.

Overall, the FEA simulations effectively captured the effects of laminate configuration and matrix type on the mechanical performance of plain-woven jute composites. The polyester-based composites in comparison with their epoxy-based counterparts exhibited minor deviations of between 2–5 %. This discrepancy stems from the inherent brittleness and weaker interfacial bonding of polyester matrices. The results reinforced experimental observations, confirming that epoxy-based composites demonstrate superior tensile and flexural properties due to their enhanced load-bearing capacity and lower stress concentrations, facilitated by superior fiber-matrix adhesion. Conversely, polyester matrix composites exhibited greater displacement and deformation under applied loads, corroborating their lower stiffness and impact resistance.

Fig. 12 and 13 illustrate the Finite element analysis contour plots for both tensile and flexural stresses for 2-ply, 4-ply and 6-ply of plain-woven jute reinforced thermoset composites respectively. The contour plots from the FEA simulations provided critical insights into composite failure mechanisms. Tensile failure was predominantly localized at fiber-matrix interfaces, where stress concentrations formed in regions of discontinuity. Flexural analysis revealed higher bending stress accumulation at mid-span, with polyester composites experiencing earlier failure initiation due to their lower modulus and increased brittleness. These stress distribution patterns align with other report [48] on similar delamination and fiber pull-out phenomena in woven composites under flexural loading.

The FEA results further demonstrated that stress distribution in epoxy-based composites was more uniform, facilitating gradual load transfer, whereas polyester composites exhibited localized stress concentrations and increased deformation. This behavior is in strong

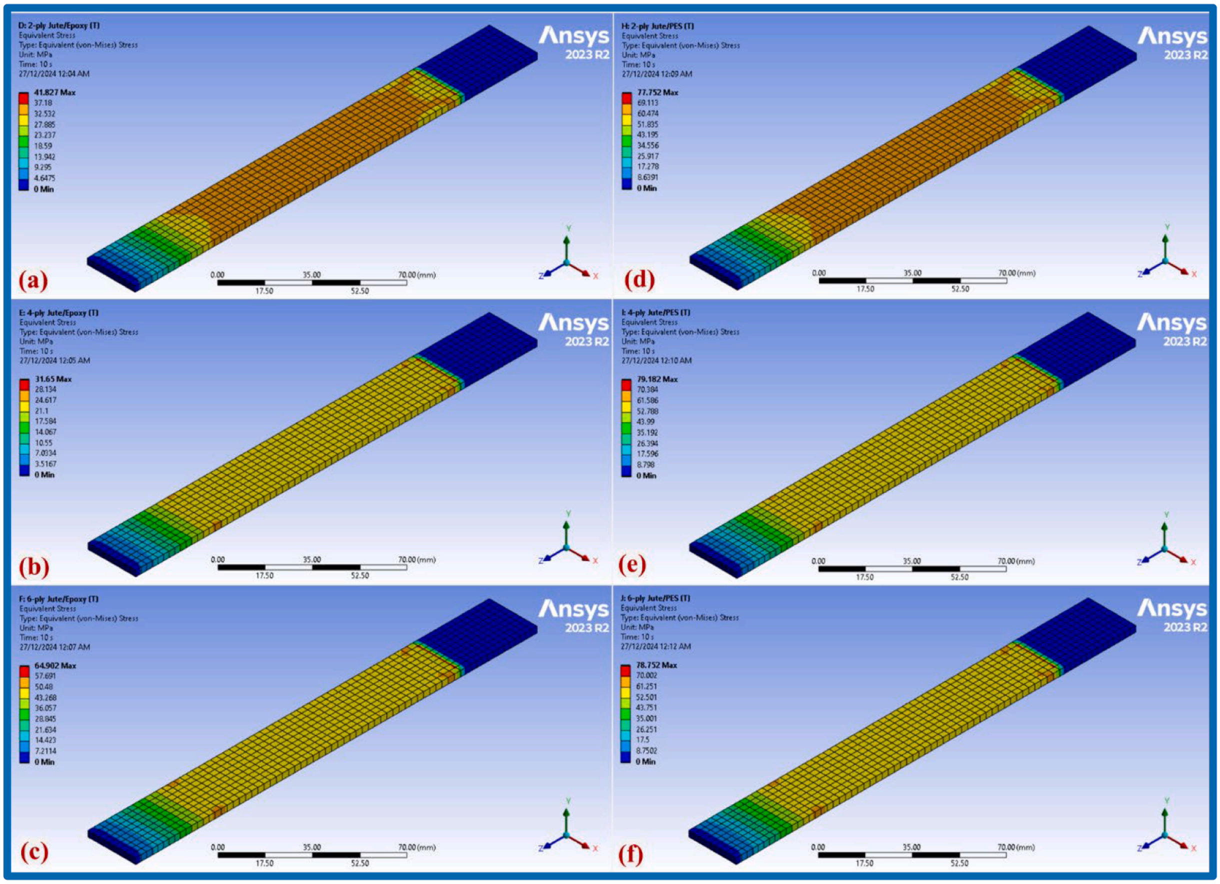

Fig. 12. Finite element analysis (FEA) contour plots of tensile stress distribution in resin-infused plain-woven jute thermoset composites: **(a–c)** 2-ply, 4-ply, and 6-ply jute/epoxy; **(d–f)** 2-ply, 4-ply, and 6-ply jute/polyester (PES).

agreement with experimental findings, substantiating the reliability of FEA modeling in predicting composite behavior confirmed the reliability of the developed FE model [46]. The close correlation between FEA predictions and experimental results highlights the potential of numerical simulations for accurately forecasting the mechanical performance of plain-woven jute fiber composites. The obtained FEA results closely aligned with experimental values, validating tensile and flexural simulations.

The FEA approach using ANSYS R23.2 has enabled accurate prediction and evaluation of the mechanical performance of resin-infused plain-woven jute thermoset composites. Hence, this predictive capability is instrumental in optimizing design parameters and material selection for structural applications, such as in renewable energy infrastructure. Overall, the tensile and flexural stress distributions illustrated in Fig. 11a and 11b validate the robustness of the FEA simulations, with minor deviations attributable to idealized boundary conditions [65].

In summary, the current study systematically evaluated the mechanical and thermal performance of plain-woven jute composites reinforced with epoxy and polyester matrices across 2-ply, 4-ply, and 6-ply configurations. Through experimental testing, SEM analysis, thermogravimetric analysis (TGA), finite element analysis (FEA), and ANOVA-based statistical validation, the research clarified how ply count and matrix type influence structural behavior. Results showed that mechanical strength improved with increasing plies, with epoxy-based 6-ply composites achieving the highest tensile (76.85 MPa) and flexural (90.48 MPa) strengths due to superior fiber-matrix adhesion and load transfer. Polyester composites, while more impact-tolerant, demonstrated lower tensile properties due to poorer interfacial bonding and matrix brittleness. Tensile modulus in epoxy composites declined slightly with higher plies, possibly due to internal stress concentration and structural non-uniformity, though they maintained higher overall stiffness than polyester counterparts. Hardness peaked at 4-ply epoxy laminates (114.4 HRB) but declined at 6-ply, likely from resin-rich zones or interlaminar stress effects. Polyester composites showed higher densities due to their greater specific gravity. Impact resistance favored polyester composites, with the 6-ply jute/PES laminate absorbing up to 1.15 J with 33.9 % higher than epoxy highlighting a trade-off between strength and toughness. SEM analysis revealed strong fiber bonding and minimal voids in epoxy laminates, while polyester composites displayed microcracks, fiber pull-out, and delamination. TGA confirmed superior thermal stability in epoxy composites, with the 6-ply jute/epoxy reaching the highest onset degradation temperature (341.5 °C) and residual mass (7.83 %). Polyester laminates showed decreasing thermal resistance with ply count. FEA results aligned with experimental trends, validating stress distribution and failure behavior, especially in higher-ply epoxy laminates. ANOVA confirmed that both matrix type and ply configuration significantly influenced performance ($p \leq 0.05$), reinforcing the reliability of the findings and their application potential in structural, thermal, and impact-critical environments.

4. Conclusion

This study presented a comprehensive experimental, numerical, and statistical investigation of the mechanical and thermal performance of resin-infused plain-woven jute reinforced thermoset composites using epoxy and polyester matrices across 2-, 4-, and 6-ply configurations. Among all tested systems, the 6-ply epoxy composite exhibited the highest structural performance, achieving tensile and flexural strengths

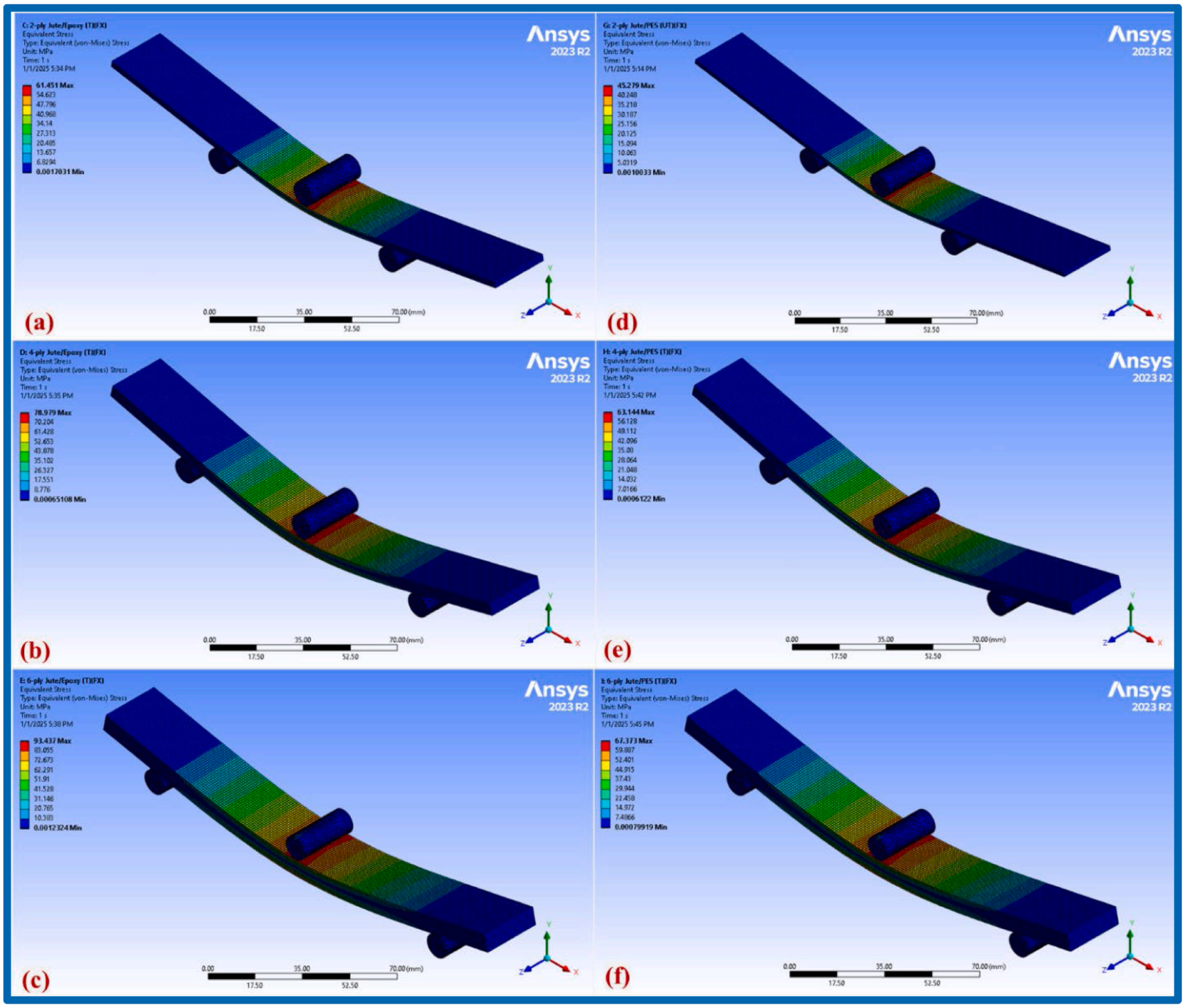

Fig. 13. Finite element analysis (FEA) contour plots of flexural stress distribution in resin-infused plain-woven jute thermoset composites: **(a–c)** 2-ply, 4-ply, and 6-ply jute/epoxy; **(d–f)** 2-ply, 4-ply, and 6-ply jute/polyester (PES).

of 76.85 MPa and 90.48 MPa, respectively. These values reflect a 19.3 % and 31.8 % improvement, respectively, over the corresponding polyester composites. Hardness peaked in the 4-ply epoxy system (114.4 HRB), while impact strength was higher in polyester-based laminates, likely due to their greater matrix ductility. Thermogravimetric analysis further confirmed the superior thermal stability of epoxy composites, with an onset degradation temperature of 341.5 °C, compared to 304.3 °C in polyester systems, indicating a 12.2 % improvement in thermal resistance. SEM analysis revealed more uniform fiber–matrix bonding and reduced void content in epoxy systems, correlating well with the mechanical results. Finite element analysis predicted tensile and flexural stress responses with deviations below 5 % from experimental data, and ANOVA validated the significance ($p \leq 0.05$) of both matrix type and ply configuration on composite behaviour. Overall, the findings highlight the viability of optimizing ply structure and matrix selection to tailor plain-woven jute thermoset composites for targeted deployment in renewable energy infrastructure, offering a sustainable alternative to synthetic fiber-reinforced systems without compromising structural performance. The study is limited by the absence of environmental durability test and dynamic mechanical analysis. Future work will explore hybrid natural-synthetic fiber systems, bio-based resin alternatives, water aging effects, and life cycle assessment (LCA) to broaden sustainability insights and application readiness.

CRediT authorship contribution statement

Macaulay M. Owen: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leong Sing Wong:** Supervision, Resources, Project administration, Funding acquisition. **Emmanuel O. Achukwu:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Ahmad Zafir Romli:** Visualization, Resources, Data curation. **Divine Senanu Ametefe:** Visualization, Validation, Methodology. **Solehuddin Shuib:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors acknowledged and appreciate the technical supports via collaborative research by three universities: Institute of Energy Infrastructure IEI, Universiti Tenaga Nasional UNITEN Kajang Malaysia, College of Engineering, Universiti Teknologi MARA UiTM, Malaysia, School of Computing, Engineering, and Technology, Robert Gordon

University, United Kingdom, Centre for Chemical Synthesis & Polymer Composites Technology, Institute of Science IOS, UiTM, Malaysia, for the use of research laboratories, equipment and other facilities.

Funding

The authors acknowledge the financial support received for this research by Tenaga Nasional Berhad (TNB) and UNITEN through the Higher Institution Centre of Excellence (HICoE), Ministry of Higher Education (MOHE), Malaysia under the project code 2024001HICOE as referenced in JPT(BPKI)1000/016/018/34(5).

Data availability

Data will be made available on request.

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