



Development and Performance Evaluation of Flax–areca Hybrid Epoxy Composites with Zirconium Oxide for Lightweight Structures

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ABSTRACT

Natural fiber hybrid composites incorporating flax fibers and additives have emerged as promising materials for lightweight structural applications. This study focuses on the development, characterization, and evaluation of epoxy composites incorporating flax fiber (FF) and areca fiber (AF), both with and without zirconium oxide (ZrO_2) nanoparticles. Hybrid composites (comprising 50 wt.% fibers in a 1:1 ratio) and single-fiber-reinforced composites (containing 50 wt.% fibers) were fabricated using a compression molding process. The composites contained 5–10 wt.% of additives. The X-ray diffraction (XRD) spectrum revealed the crystallinity index and crystallite size of all the composites. The crystal structure exhibited monoclinic symmetry, and the surfaces of both the fibers and fillers were irregular. Fourier-transform infrared (FTIR) spectroscopy was used to determine the chemical composition of the composites. Subsequently, the mechanical and thermal properties of the hybrid composites were evaluated. The results indicated that the concentration of ZrO_2 nanoparticles significantly influenced the tensile, flexural, and impact strengths of the composites. Notably, the hybrid composite with 7.5 wt.% filler exhibited a tensile strength of 105 MPa, a flexural strength of 690 MPa, an interlaminar stress of 255.1 MPa, and an impact energy of 4.82 J/m². Thermal analysis revealed that incorporating up to 7.5 wt.% filler improved composite stability by acting as a barrier to degradation. These findings indicate the potential application of the developed composites in lightweight structures.

Keywords: Areca fiber; Flax fiber; Mechanical properties; Thermal properties; ZrO_2 ; Nanoparticles.

1. INTRODUCTION

Natural fiber-reinforced polymer composites are increasingly explored as sustainable alternatives to synthetic materials in automotive, aerospace, and construction applications. They offer advantages such as low weight, renewability, and biodegradability, but their performance is often limited by weak interfacial bonding and moderate strength. Hybridization of different fibers and the addition of nanofillers have emerged as effective strategies to overcome these drawbacks and achieve improved mechanical and thermal properties. Over the past thirty years, the automotive, aerospace, and construction sectors have widely employed natural fiber-reinforced polymer composites. Composite fabrication involves FF, synthetic fiber, and natural fiber to enhance mechanical properties and investigate their characteristics (Siddiqui *et al.* 2024). *Cordia dichotoma* and areca fiber-reinforced hybrid nanocomposites were fabricated using Al_2O_3 nanoparticles (Ajinkya *et al.* 2025; Tavadi *et al.* 2025a). Composites composed of polyester and areca fibers were fabricated with varying fiber contents. The dielectric, tensile, and flexural strengths of the treated fibers were improved (Kavya *et al.* 2025). Fibers were treated with NaOH to enhance interfacial

bonding, contributing to improved tensile, flexural, and impact properties (Mayakannan *et al.* 2023). Compression molding was employed to fabricate epoxy hybrid composites with 1–5 wt.% B_4C and 15 wt.% flax fiber (Venkatesh, 2024). The tensile, flexural, impact, and interlaminar shear strength (ILSS) properties of alkali-treated flax fiber reinforced polylactic acid (PLA) with 0.5 wt.% graphene, fabricated by compression molding, were improved (Jiyas *et al.* 2024). Flax fiber-reinforced polypropylene (flax/PP) composites were subsequently assessed for mechanical performance and thermal stability (DSC, TGA) across various fiber orientations (Parodo *et al.* 2025; Oun *et al.* 2024). Investigations into the mechanical and wear properties of epoxy composites reinforced with areca fibers and alumina indicated that an 8 wt.% of Al_2O_3 concentration yielded optimal outcomes (Tavadi *et al.* 2025b). The study examined composites composed of chemically modified jute fibers reinforced with epoxy and ZrO_2 nanoparticles using FTIR, SEM, and TGA techniques (Biswas *et al.* 2025). Composites composed of areca and abaca fibers, augmented with epoxy resin and nano- SiO_2 , are environmentally sustainable (Sachin *et al.* 2024). Composites including areca fibers coated with vinyl silane and bronze nanoparticles were evaluated for improved mechanical,

wear, and thermal properties. SEM confirmed robust bonding resulting from silane treatment (Balguri *et al.* 2025). The vinyl ester resin underwent treatment with sodium hydroxide to enhance adhesion, and nylon and areca fibers were included for a synergistic effect (Sai, 2024). A composite material including sisal, flax, glass, and titanium dioxide was evaluated for mechanical properties, including flexural strength and tensile strength (Mohammad *et al.* 2024).

Enhanced mechanical and thermal performance was seen in epoxy composites composed of flax and basalt fibers, augmented with ZnO nanofillers. Samples with a higher basalt percentage achieved maximum impact (23 J) values (Raja and Devarajan, 2024a). The influence of fiber orientation on ILSS of epoxy composites reinforced with flax fibers of all angles was evaluated (Subbiah *et al.* 2024). PP composites were produced from flax fiber treated with NaOH and nano- Al_2O_3 . The composite with 7.5 wt.% Al_2O_3 demonstrated superior flexural, impact, and tensile properties with its uniform distribution (Aruna *et al.* 2025).

Composites including epoxy and reinforced with ZrO_2 nanoparticles, carbon nanotubes (CNTs), and Indian almond fiber were synthesized by compressing these materials with a silane coupling agent. Mechanical parameters showed enhancement, including flexural strength (up to 148 Shore D), hardness (up to 42 MPa), and tensile strength (42 MPa) (Padmavathy *et al.* 2024). Composites fabricated manually from *Millettia pinnata* (MP) fiber and polyester were infused with ZrO_2 nanoparticles. The thermal stability of a sample (100 g MP, 50 g ZrO_2) was validated using TGA analysis. The temperature stability varied between 298 and 349 °C (Raja and Devarajan, 2024b). Flax fiber/epoxy composites with 0.5–1.5 wt.% graphene. At elevated graphene concentrations, SEM revealed that filler agglomeration resulted in the formation of voids. Enhanced dispersion and adhesion resulted in superior mechanical performance at 0.5 wt.% graphene (Oun *et al.* 2022b). Hybrid composites composed of areca/ramie fibers and 1.5 wt.% graphene nanoparticles were markedly improved. Enhancements in aircraft and automobile cabin performance resulted from reduced water absorption (Dhilipkumar *et al.* 2024; Oun *et al.* 2022a). This research involved the creation of eco-friendly composites with pectin-modified areca fiber and vinyl ester resin. SEM results indicated reduced voids and enhanced bonding, implying their suitability for marine and structural applications (Kumar and Sivakumar, 2025).

Although numerous studies have examined natural fiber-reinforced composites with fillers such as Al_2O_3 , SiO_2 , graphene, and TiO_2 , there remains limited

exploration of flax–areca hybrid composites reinforced with ZrO_2 nanoparticles. Existing reports often focus on individual fibers or monotonic trends with filler addition, without systematically identifying an optimum filler content that balances dispersion and agglomeration effects. The novelty of the present work lies in the systematic investigation of flax–areca hybrid epoxy composites with graded ZrO_2 loadings (5%, 7.5%, and 10% vol.), combined with a comprehensive evaluation of tensile, flexural, ILSS, and impact strengths, along with the application of FTIR, SEM, and TGA techniques. This establishes a new benchmark for developing lightweight, eco-friendly composites tailored for structural applications in automotive and aerospace sectors.

2. MATERIALS AND METHODS

2.1 Materials

The bidirectional plain flax fibers and Areca fibers were purchased from Go Green Products, Chennai, Tamilnadu, India. The epoxy resin (LY556) and hardener (HY951) were procured from Covai Seenu Enterprises, Coimbatore, Tamil Nadu, India. The hardener possesses a density of 0.98 g/cm³, whereas the epoxy resin has a density of 1.30 g/cm³. Epoxy resin exhibits a thermal resistance of 315 °C. Additionally, ZrO_2 nanoparticles were sourced from Matrix Enterprises, Nagercoil, Tamilnadu, India, for incorporation into the composite matrix. The mechanical and physical properties of the materials are presented in Table 1.

Table 1. Properties of flax fiber, areca fiber, and ZrO_2 nanoparticles

S. No.	Properties	Flax Fiber	Areca Fiber	ZrO_2 Nanoparticles
1	Density (g/cc)	2.6	1.48	1.19
2	Thermal stability (°C)	1050	250	310
3	Thickness (mm)	0.55	0.9	-
4	Tensile strength (MPa)	980	680	61

2.2 Fabrication of Composites

The FF–AF hybrid composite was fabricated by compression molding the two fibers concurrently. The mold parameters of 270 mm × 250 mm determined the cutting of the FF and AF. Subsequently, the resin and

hardener were combined with a ratio of 10:1 following a period of stirring. Subsequent layers of flax and areca fibers were incorporated into a resin and hardener mixture, which was further enhanced with ZrO₂ nanoparticle fillers at volume fractions of 0.1%, 7.5%, and 10%, respectively. The flax and areca fiber laminates were positioned in the mold before the introduction of the resin, hardener, and filler mixture. To achieve the desired composite thickness, a requisite number of layers must be placed into the mold as specified by the formula. The composite plate was fabricated with five layers of flax and AF, yielding a thickness of around 3 mm. The samples underwent a compression molding procedure for 4 hours at a temperature of 170 °C and a pressure of 30 MPa. The composite laminates were allowed to cure at room temperature for one day. To facilitate additional testing and characterization, test specimens were cut from the removed composite plates after post-curing. Table 2 shows the designation and composition of the fabricated composite specimens.

Table 2. Composition of the composite specimens

S. No.	Specimen code (wt.%)	Epoxy (wt.%)	Areca fiber (wt.%)	Flax fiber (wt.%)	Filler (wt.%)
1	S1	50	-	50	-
2	S2	50	50	-	-
3	S3	50	25	25	-
4	S4	50	-	45	5
5	S5	50	-	42.5	7.5
6	S6	50	-	40	10
7	S7	50	45	-	5
8	S8	50	42.5	-	7.5
9	S9	50	40	-	10
10	S10	50	22.5	22.5	5
11	S11	50	21.5	21.5	7.5
12	S12	50	20	20	10

2.3 Mechanical Properties

All composite variants presented in Table 2 underwent mechanical property testing. A Universal Testing Machine (UTM) (INSTRON) with a 5 kN load capacity and a crosshead speed of 2 mm/min was employed to perform tensile and flexural testing (Fig. 1). For the tensile test, the composite specimens were fabricated to dimensions of 165 mm × 13 mm × 3 mm, while for the flexural test, they conformed to the specifications of ASTM D790. During tensile testing, the specimens underwent axial force application, whereas in flexural testing, they experienced three-point bending. The load vs. deflection curves for all specimens were obtained from the outputs of the encoder and load cell. The flexural and tensile stress-strain curves, as well as

the tensile properties, were computed using the data. The trials were conducted with an impact testing device referred to as the Izod-Chappy. In accordance with ASTM D256 standards, five specimens measuring 64 mm × 13 mm × 3 mm were fabricated without notches and subsequently impacted with an oscillating hammer delivering 2.57 J of potential energy. The machine's digital display was utilized to directly quantify the impact energy of the composite samples. Composite specimens measuring 35 mm × 13 mm × 3 mm were subjected to flexural testing in three orientations in accordance with ASTM D2344 standards to ascertain the ILSS of the material. The resultant shear stress and strain curves were then presented. Each composition was subjected to three distinct mechanical tests, with the average results forming the foundation for subsequent analysis.

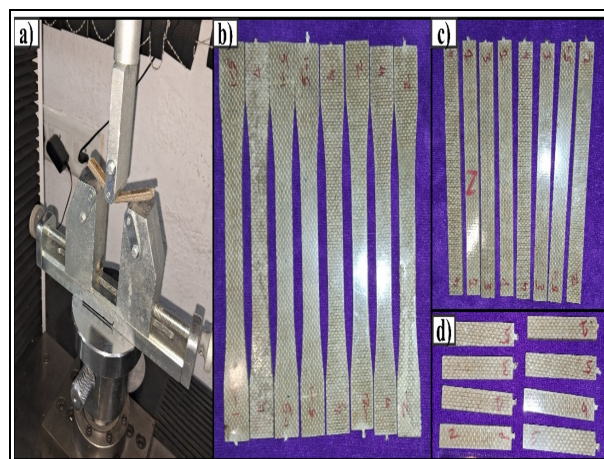


Fig. 1: UTM specimens for (a) tensile test, (b) flexural test and (c) ILSS

2.4 FTIR Analysis

FTIR identifies the chemical constituents and bonds present in the composites. FTIR spectra were obtained from a Shimadzu spectrometer (Model: 8400 S). The powdered substances were combined with potassium bromide and compressed into pellets using a tiny hydraulic apparatus before being inserted into the spectrometer. The sample underwent 32 scans/min of infrared radiation with a wavelength range from 4000 to 400 cm⁻¹ with a pixel resolution of 4 cm⁻¹.

2.5 Thermogravimetric Analysis (TGA)

TGA was employed to investigate the thermal degradation characteristics of the filler-hybrid composites. To prevent oxidation, the powdered composite sample was subjected to heating in nitrogen gas with the Jupiter thermal analyzer, starting from ambient temperature and increasing at a rate of 10 °C/min until reaching 600 °C. Nitrogen gas was continuously supplied at a rate of 20 ml/min.

3. RESULTS AND DISCUSSION

3.1 FTIR Analysis

Fig. 2 displays the FTIR spectra of the composites S2, S3, S10, and S11. The absorbance bands indicate the presence of various functional groups corresponding to natural and treated fiber components. A prominent absorption peak observed only in the natural fiber (S2) at 3738 cm^{-1} corresponds to the stretching vibrations of hydroxyl ($-\text{OH}$) functional groups, indicating the presence of free hydroxyl groups in cellulose or lignocellulosic materials. Additionally, a broad peak in the range of $3516\text{--}2992\text{ cm}^{-1}$ is also associated with O–H stretching, further confirming the hydroxyl group across all samples. The peak at 2992 cm^{-1} corresponds to C–H stretching vibrations, which are typically observed in aliphatic hydrocarbon chains. This is followed by characteristic peaks at 1324 , 1307 , 1257 , 1162 , and 1029 cm^{-1} , which can be assigned to C–H bending, C–O–C asymmetric stretching, and C–O stretching vibrations typically present in hemicellulose, cellulose, and lignin structures. A distinct peak observed at 902 cm^{-1} may be attributed to β -glycosidic linkages between sugar units in polysaccharides. These absorption bands confirm the presence of structural components common in natural fibers and their retained functionalities even after composite fabrication. The decreasing intensity or shifting of some peaks in modified samples suggests chemical interaction between fiber and matrix, influencing interfacial bonding and composite behavior. High-density polyethylene (HDPE) composites reinforced with sugarcane bagasse cellulose fibers modified using hydrous ZrO_2 were reported to exhibit enhanced fiber–matrix interaction. FTIR analysis confirmed the chemical modification through a reduction in hydroxyl (OH) bond peaks, suggesting decreased fiber polarity and improved interfacial compatibility with the polymer matrix (Mulinari *et al.* 2017).

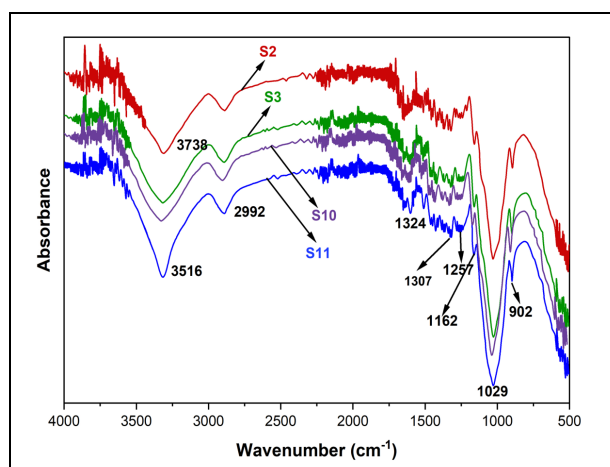


Fig. 2: FTIR spectra of the composites S2, S3, S10, and S11

3.2 Mechanical Properties

3.2.1 Tensile Properties

Fig. 3 illustrates the tensile stress-strain curve for each composite filled with ZrO_2 nanoparticles. In every case, stress escalates progressively with the increase in strain. Of the three composites evaluated, S1 exhibited the greatest tensile stress, attributable to the hybridization effect and the enhanced properties of the synthetic fibers. Composites S2 and S3 received inferior rankings. Among the studied hybrid composites, the unfilled variants exhibited the lowest tensile strength. The strength of AF with FF is inferior to that of hybrid composites (S10) owing to the incorporation of 5 wt.% ZrO_2 nanoparticles into the mixture. Flax demonstrates the maximum tensile stress value in 7.5 wt.% ZrO_2 nanoparticles of flax, in comparison to hybrid and AF with flax. The tensile stress and strain of flax are enhanced in a 10 wt.% ZrO_2 nanoparticle composite, but they are diminished in an AF hybrid incorporating flax. The results demonstrated that ZrO_2 nanoparticles significantly enhanced the stress transmission between AF and FF. This elucidates why the incorporation of ZrO_2 nanoparticles into the empty composites augmented their stress values. Hybrid-filled composites with a 5% composition demonstrate the highest tensile stress and strain values. Composites consisting of flax and glass fibers reinforced with ZrO_2 nanofillers were manually assembled. The maximum tensile strength (264.74 MPa) values were recorded in a previous study by (Meravi and Panchore, 2025), indicating superior interfacial bonding and effective stress transfer due to the uniform dispersions of nanofillers.

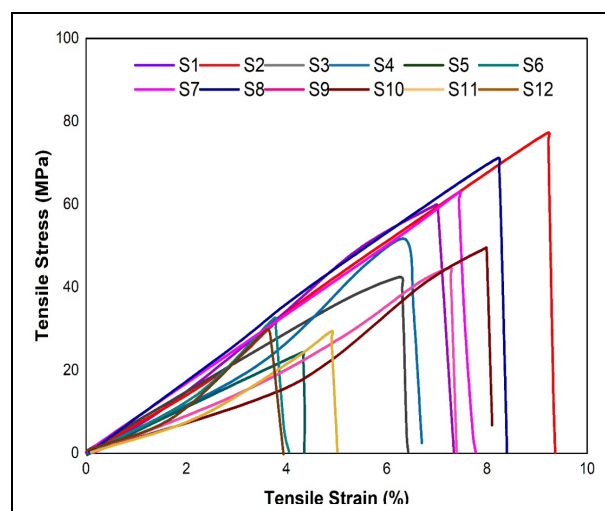


Fig. 3: Tensile stress vs. tensile strain of various composites

SEM images of the tensile fracture surfaces of the hybrid fiber composites are shown in Fig. 4. Figures 4a and 4b depict the hybrid composites without any filler

material. The morphologies indicate that improved interfacial contact enabled the hybrid composites to outperform the individual fiber composites in terms of mechanical strength. The existence of voids in hybrid composites and S1 and S2 fabric composites impedes the composites' capacity to achieve enhanced mechanical properties. The failure morphology clearly indicated that the composite components were incompatible, as seen by matrix cracks and ridges. The initiation of the failure crack from the matrix crack would have substantially diminished the mechanical properties. The hybrid fibers and matrix exhibited inadequate interfacial adhesion, necessitating the incorporation of fillers to rectify this issue. Although hybrid composites outperform single-fiber composites, the incorporation of a filler is necessary to address compatibility issues in NaOH-treated banana–areca fiber epoxy composites. SEM analysis revealed enhanced fiber–matrix adhesion with reduced voids and fiber pull-out. These morphological improvements confirm effective alkali treatment and structural integrity

of the composites, as observed by (Raghavendra *et al.* 2025).

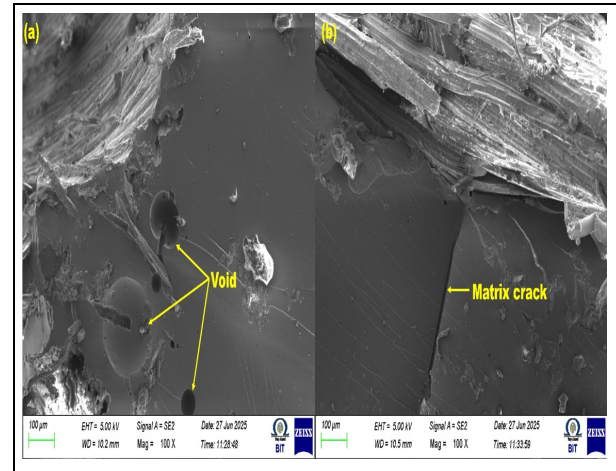


Fig. 4: SEM images of tensile fracture samples of (a) AF and (b) FF composites

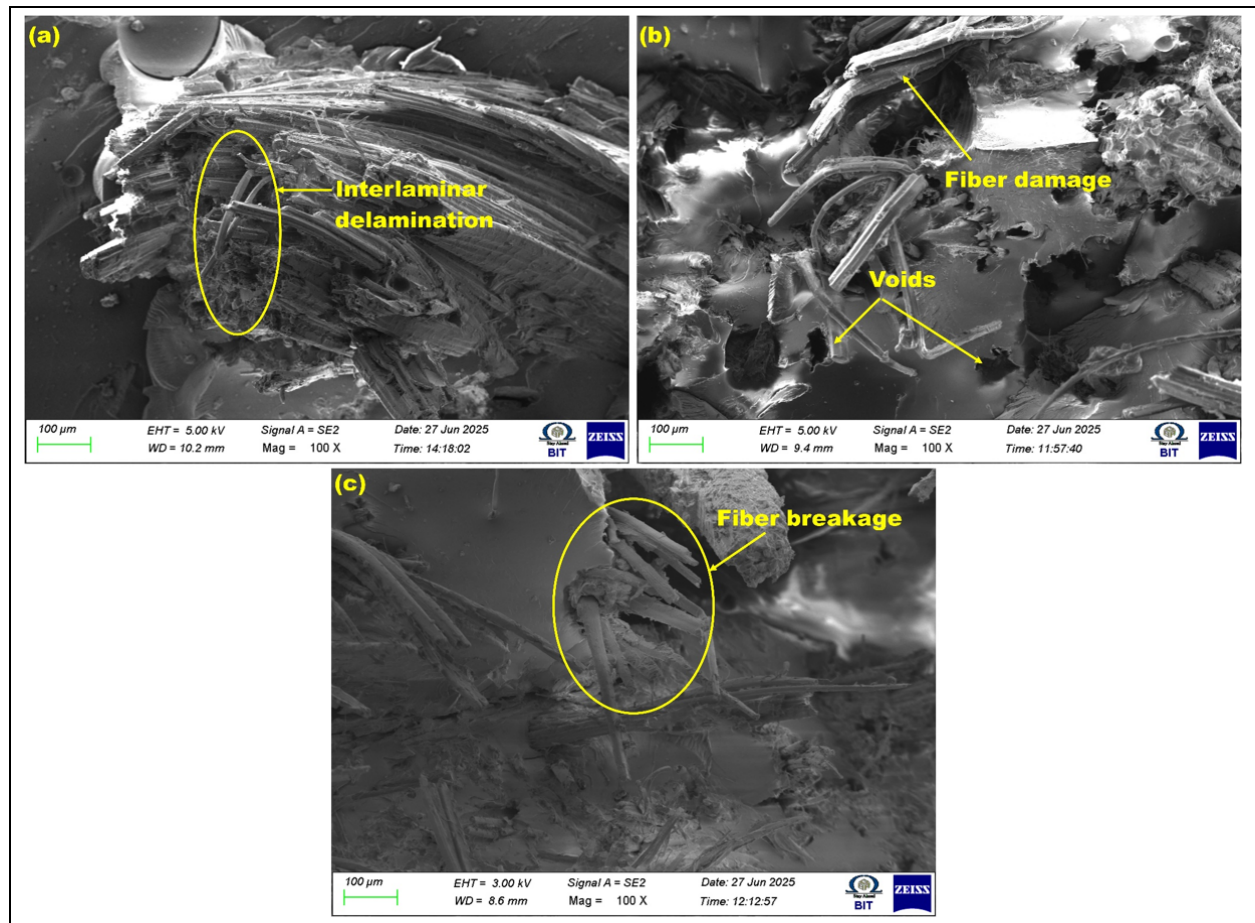


Fig. 5: SEM images of tensile fracture samples of hybridized fiber composite with 7.5% ZrO₂ nanoparticles

Composites composed of FF/AF fabric and infused with ZrO₂ nanoparticle powders at a 5% concentration demonstrate fracture morphology (Fig. 5a-c). The ZrO₂ nanoparticle fillers effectively occupied the

voids, rendering their presence nearly imperceptible in the morphology. The absence of matrix failure causes, including craters, cracks, and debonding in the morphology, indicates that the composite components

integrate effectively with the polymer matrix. The predominant failure modes were fiber pullout, interlaminar fiber delamination, and fiber fracture. All of these degradation processes indicate a robust link between the polymer matrix and the hybrid fibers at the interface. The exceptional strength of this composite construction demonstrates that failure occurred exclusively on the fiber side, despite the effective load transfer between the matrix and the fibers. Consequently, it can be concluded that the flax/AF hybrid composites with 7.5% ZrO_2 nanoparticles exhibited enhanced tensile properties owing to improved fiber–matrix interfacial adhesion and a diminished void count.

All the tensile characteristics of the composite are illustrated in Fig. 6. Fig. 6a displays composites, both filled and unfilled with ZrO_2 nanoparticles, alongside their respective tensile strengths (FF, AF, and hybrid). The results indicated that the hybridization of FF and AF effectively enhanced tensile strength values. The morphological and tensile strength test results indicated that the unfilled hybrid composites surpassed the individual fiber-reinforced composites. Hybrid composites enhance stress transfer by augmenting interfacial bonding between the matrix and fibers. Simultaneously, hybrid composites surpassed filled individual fiber composites regarding tensile strength. The integration of the hybrid composites' superior strength and the filled composites' reduced voids was accomplished through the incorporation of brittle ZrO_2 nanoparticles. Notably, the hybrid composite with 7.5% filler exhibited the highest tensile strength of 105 MPa, tensile strain of 8.5%, and tensile modulus of 1.53 GPa. Moreover, enhanced interfacial bonding among the fibers, fillers, and matrix contributed to this improvement. The tensile strain and Young's modulus of all composite samples are presented in Fig. 6(b) and 6(c), respectively. The 7.5% hybrid composites exhibited a higher strain value due to the increased brittleness of the fillers. The similarity in Young's modulus values of the filled composites illustrates the advantageous effect of filler incorporation in the hybrid composites. The inadequate load control by the fillers and fibers in composites containing 10% filler led to suboptimal tensile properties. The tensile properties of the composites were enhanced with a filler content of 7.5%. At 10% ZrO_2 , the tensile properties decreased relative to 7.5% due to nanoparticle agglomeration and resin starvation, which impede effective stress transfer.

3.2.2 Flexural Properties

Fig. 7 illustrates the flexural stress-strain curve for the composites. Irrespective of the circumstances, the stress-strain intensifies over time. In comparison to HY with flax, the flexural stress of S1 is elevated in pure FF,

HY, and AF composites. In the comparison of FF, HY, and AF with flax incorporated with 5% ZrO_2 nanoparticles, the stress levels in the latter two are markedly lower than those in the former. The maximal flexural stress value in flax exceeds that of HY and AF in 7.5% of instances. The flexural stress and strain of flax are enhanced in a 10% ZrO_2 solution, but they are diminished in HY and AF, including flax.

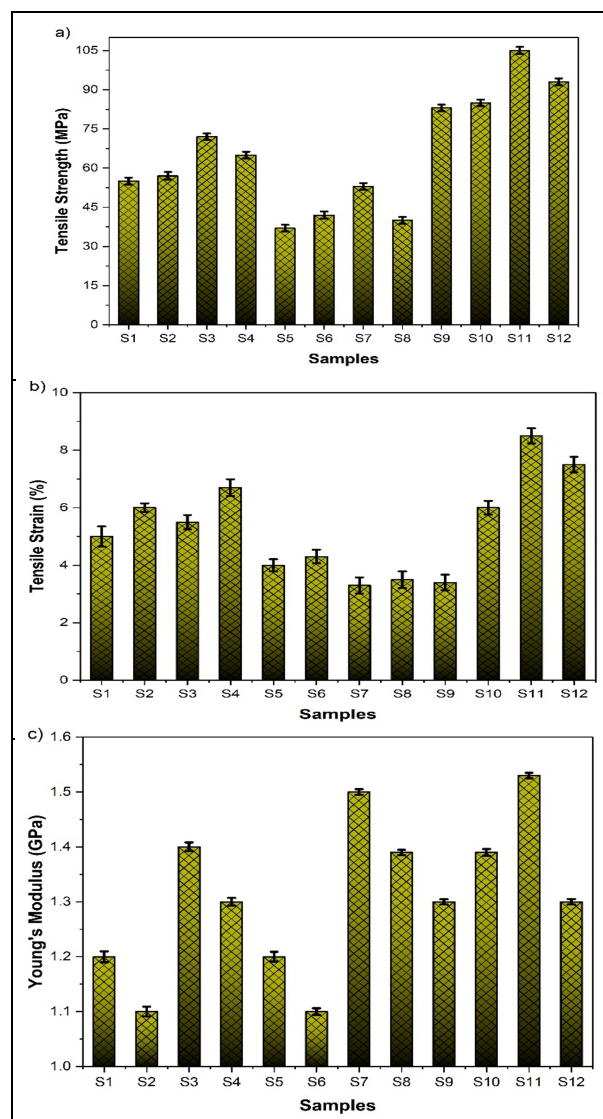


Fig. 6: (a) Tensile strength, (b) Tensile strain and (c) Young's modulus of the composites

Among all the flax composites evaluated, 10% exhibited the highest flexural stress and strain. Fig. 8 illustrates the flexural properties of the various composites. Fig. 8(a) illustrates a comparison between filled and unfilled composites with FF, HY, and AF. The Fig. 8 distinctly illustrates that, in comparison to filled composites, the flexural strength of unfilled hybrids is lower than FF but superior to AF. The reduced synergy between the FF and AF elucidates this phenomenon.

Composites infused with ZrO₂ nanoparticles successfully improved this. Filler composites exhibited superior flexural strength compared to their unfilled counterparts. Hybrid composites with 7.5% filler exhibited optimal flexural properties, including a flexural strength of 690 MPa, a flexural strain of 0.53%, and a Young's modulus of 175 GPa. The compatibility of the polymer, fillers, and fibers resulted in the fillers and FF exhibiting exceptional bending stiffness. Fig. 8(b) and 8(c) illustrate the differences in flexural strain and modulus of all composite samples, which similarly demonstrated a uniform pattern. Composites containing 7.5% hybrid content exhibited elevated strain values due to their enhanced resistance to flexural stresses and superior dimensional stability. Bio-composites created from agricultural waste by integrating areca fiber, biochar from rice husks, and cardanol oil into epoxy resin. The superior composite (NC3) achieved high flexural strength (236 MPa), which is significantly higher than values reported in similar studies involving natural fiber-based composites (Alshahrani and Vr, 2024).

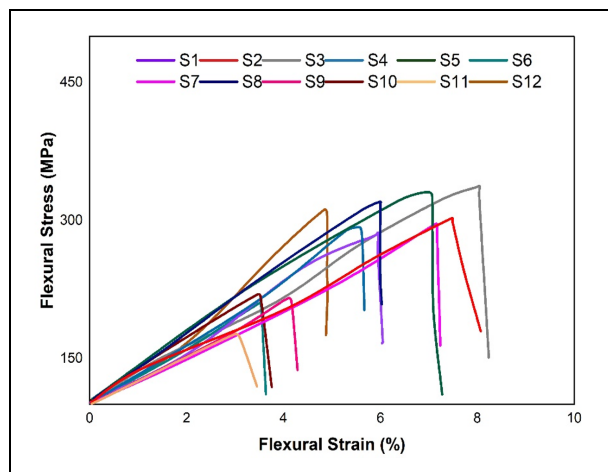


Fig. 7: Flexural stress vs. strain of various composites

3.2.3 Interlaminar Shear Properties

Fig. 9 illustrates a strain vs interlaminar stress curve for FF, HY (hybrid), and AF with flax and ZrO₂ composite filler. Irrespective of the circumstances, the stress-strain intensifies over time. In FF, HY, and AF with FF, flax exhibits reduced interlaminar stress compared to HY. The interlaminar stress value is minimal for AF with FF. The stress of AF with FF is considerably reduced compared to HY upon the addition of 5% ZrO₂ to flax, HY, and AF with Flax. The interlaminar stress in flax is maximal at 7.5% of FF, HY, and AF with flax, while it is minimal in AF with flax and HY with flax. Flax demonstrates an increase in interlaminar stress and strain at 10%, whereas in HY and AF, it shows reduced interlaminar stress. A peak value exists for interlaminar stress and strain in a flax composite containing 7.5% ZrO₂.

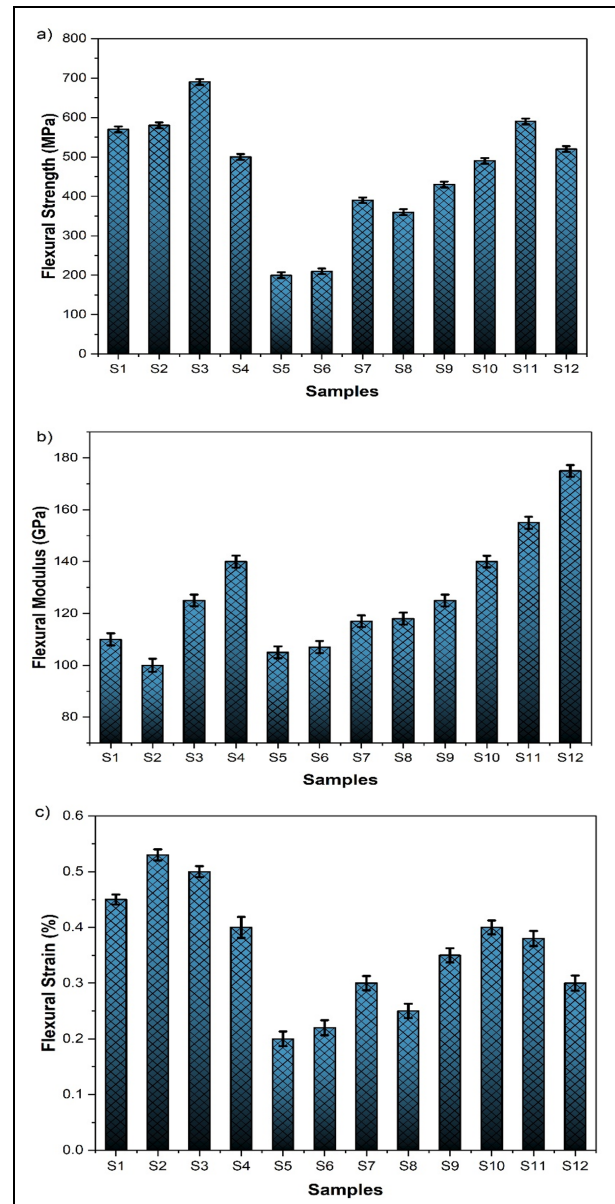


Fig. 8: (a) Flexural strength, (b) flexural strain, and (c) flexural modulus of the composites

Fig. 10 illustrates the interlaminar shear properties of the composites. Composites composed of FF, HY, and AF, with and without filled ZrO₂ particles, demonstrate interlaminar stress, as illustrated in Fig. 10a. The enhanced interaction between the FF and AF fiber laminates resulted in the hybrid composites demonstrating superior interlaminar properties relative to the FF composites, as corroborated by further mechanical properties. AF composites exhibited lower interlaminar properties due to their greater susceptibility to fracture compared to flax and hybrid composites. Due to the filler facilitating efficient interlaminar stress transmission, hybrid composites using ZrO₂ nanoparticles exhibited superior values relative to unfilled composites. The homogeneous distribution of fillers and fibers in filled composite laminates during shear loading boosted their

load-bearing ability, resulting in elevated stress levels. Notably, the hybrid composite with 7.5% filler demonstrated an interlaminar stress of 255.1 MPa, an interlaminar shear modulus of 9.57 GPa, and an interlaminar strain modulus of 5.5 MPa. The findings unequivocally indicated that the stress values of filled composites were consistently superior to those of their unfilled counterparts. The efficacy of ZrO₂ nanoparticle fillers is attributed to their compatibility with flax and areca fibers. The 10% filler composites exhibited markedly reduced stress values due to filler agglomeration and the polymer's inadequate binding strength. Fig. 10(b) and 10(c) illustrate the variation in shear modulus and interlaminar strain for all composites, respectively. The previously mentioned pattern also applies to these attributes. The shear modulus of composites containing 7.5% filler was significantly elevated due to the layer-by-layer resistance provided by this composition, whereas FF composites exhibited enhanced interlaminar strain attributable to their ductility. In a previous study, flax fiber/epoxy composites reinforced with biosynthesized TiO₂ nanoparticles were reported to exhibit enhanced interlaminar shear strength (ILSS). A maximum ILSS of 52.31 MPa was achieved at 5 wt.% TiO₂, attributed to the uniform dispersion of nanoparticles within the matrix (Natrayan *et al.* 2024).

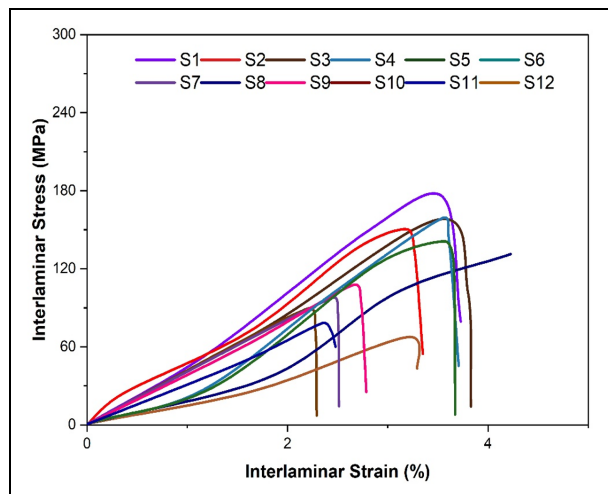


Fig. 9: ILSS vs. strain plots of the composites

3.2.4 Impact Energy

Fig. 11 illustrates the varying impact properties of the composites composed of FF, HY, and AF, alongside the unfilled variants. The synergy of FF and AF results in hybrid composites exhibiting superior impact strength compared to individual fiber-reinforced composites. Due to their enhanced energy-absorbing properties, hybrid composites infused with ZrO₂ nanoparticles demonstrated improved performance compared to other filled composites. Moreover, the fillers enhanced the toughness of the composites by occupying any voids within the material. Hybrid-filled composites exhibited

the highest impact strength, with the 7.5% filler hybrid composite recording an impact energy of 4.82 J/m². All composites using 7.5% fillers displayed enhanced characteristics. At a 10% ZrO₂ nanoparticle concentration, the impact strength reduced due to an increased presence of fillers in the composite, coupled with inadequate fibers and fillers.

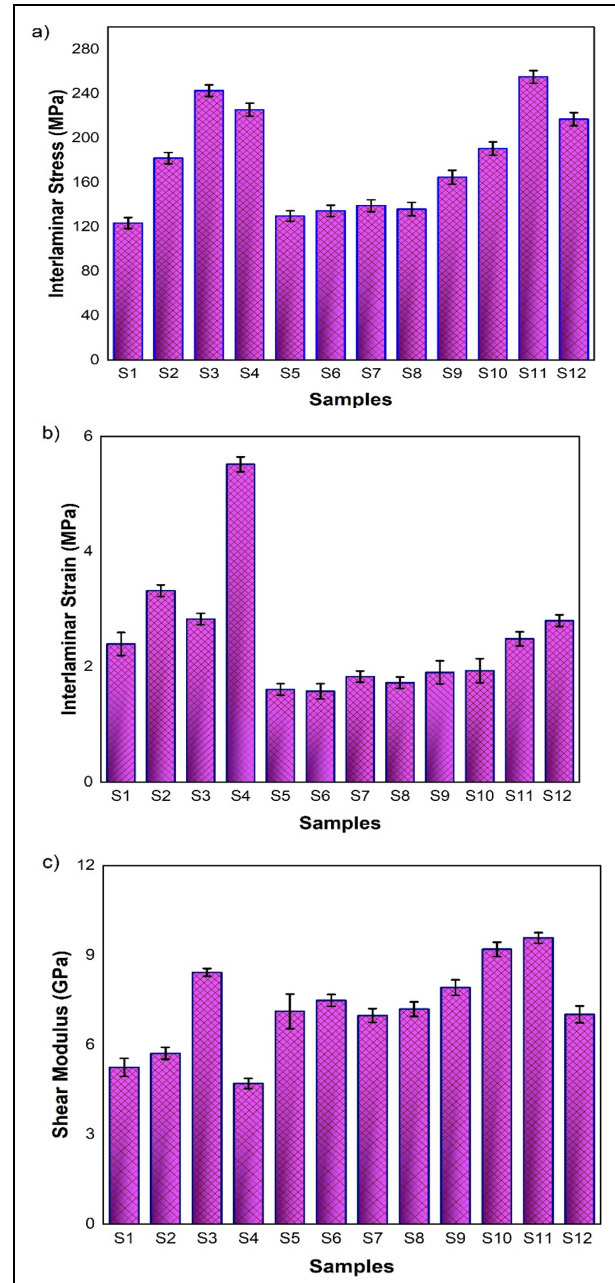


Fig. 10: (a) ILSS, (b) shear strain, and (c) shear modulus of the composites

Table 3 clearly highlights the performance variations across all composites. Hybridization significantly improved properties compared to the control (S1), while ZrO₂ addition further enhanced mechanical behavior. The hybrid composite with 7.5

wt.% ZrO₂ (S11) exhibited the highest TS, FS, ILSS, and IE values, confirming it as the optimum composition. In contrast, the 10 wt.% filler composite (S12) showed reduced performance due to nanoparticle agglomeration, though still superior to the control.

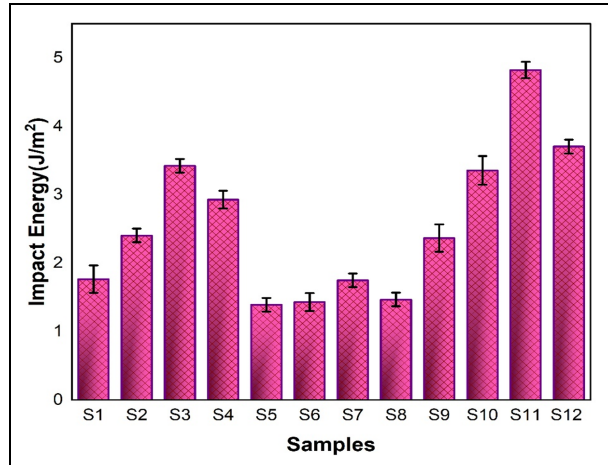


Fig. 11: Impact energy (IE) of the composite samples

Table 3: Comparison of mechanical results of all composites relative to the control (S1)

S. No.	Specimen Code (wt.%)	ΔTS vs. S1 (MPa)	ΔFS vs. S1 (MPa)	ΔILSS vs. S1 (MPa)	ΔIE vs. S1 (J/m²)
1	S1	—	—	—	—
2	S2	+2	+10	+58.44	+0.63
3	S3	+17	+120	+119.21	+1.65
4	S4	+10	−70	+102.06	+1.16
5	S5	−18	−370	+6.25	−0.38
6	S6	−13	−360	+10.91	−0.34
7	S7	−2	−180	+15.57	−0.02
8	S8	−15	−210	+12.49	−0.30
9	S9	+28	−140	+41.29	+0.60
10	S10	+30	−80	+67.02	+1.59
11	S11	+50	+120	+131.60	+3.05
12	S12	+38	−50	+93.48	+1.93

3.3. TGA of the Composites

Fig. 12 illustrates the TGA analysis of composites composed of FF, AF, hybrid composites, and hybrids infused with ZrO₂ nanoparticles. The decline observed in the TGA curves across all samples is attributable to weight reduction. Starting at approximately 300 °C, the AF fiber's TGA curve shows a steady but slow loss of weight as temperature rises. The fiber's hardness and strength resulted in the FF losing weight at a rate of around 350 °C in comparison to the AF fiber. The hybrid fibers exhibited a reduced residual mass owing to the synergistic effects of the fibers, in contrast to the individual FF and AF fiber composites.

Thermograms obtained from hybrid composites with additional fillers exhibited mechanical properties. The 7.5% hybrid composites exhibited enhanced thermal stability relative to the other composite specimens, degrading more slowly at 355 °C. A plausible reason is the capacity of ZrO₂ nanoparticles to restrict the mobility of the polymeric chains inside the matrix material in response to temperature gradients. Their thermal stability was lower than that of 7.5% hybrid composites due to 5% composites having a reduced filler content and increased agglomeration, which compromised their capacity to endure chain mobility. The 7.5% hybrid composites exhibited enhanced thermal breakdown, with their reduced residual mass relative to their counterparts. Consequently, 7.5% hybrid composites exhibited the greatest degree of thermal stability in comparison to the other composites. Flax/epoxy composites reinforced with pistachio and walnut shell fillers have been reported to exhibit enhanced mechanical performance. TGA indicated the improved thermal stability in hybrid filler-based composites compared to the control. SEM analysis confirmed uniform filler distribution within the matrix (Chaudhary *et al.* 2024).

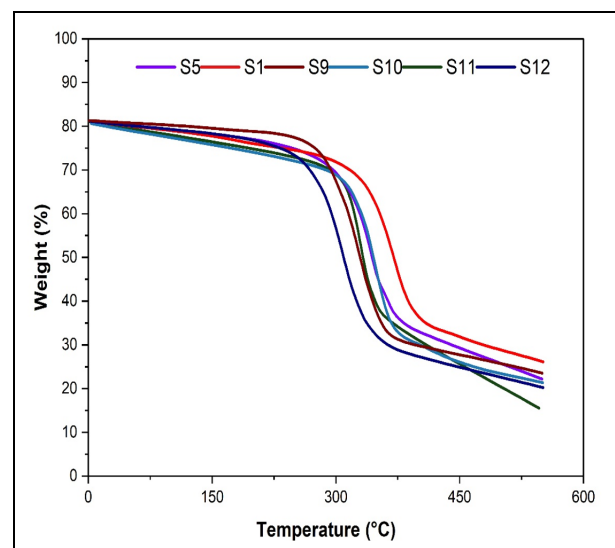


Fig. 12: TGA curves of the composites

4. CONCLUSION

The investigation of the thermal and mechanical properties of AF and FF reinforced epoxy composites, both with and without ZrO₂ nanoparticles, was carried out. FTIR spectra of both with and without filler containing AF, FF, and hybrid fiber epoxy composites indicated the presence of several chemical groups. The filler's substantial role in load transfer between the fiber and matrix enabled AF, FF, and hybrid fiber epoxy composites to attain their peak tensile, flexural, and impact strengths at a reinforcement of 7.5%. Specifically, the hybrid composites achieved a tensile strength of 105

MPa, a flexural strength of 690 MPa, an interlaminar stress of 255.1 MPa, and an impact energy of 4.82 J/m². The mechanical properties were improved because of the densely arranged filler surrounding the fiber, as seen by the fractured images. This resulted in fiber fractures rather than fiber pullouts. Composites composed of hybrid FF/AF infused with ZrO₂ nanoparticles exhibited superior flexural, interlaminar, and impact properties. Augmenting the filler percentage in hybrid composites improved their thermal stability at 355 °C. Hybrid composites with 7.5% filler exhibited the greatest stability. Composites composed of a combination of AF and FF surpassed those fabricated from either material independently. Thus, the hybrid composites with ZrO₂ nanoparticles exhibited overall superior performance, indicating their potential application as lightweight materials in the automotive and aerospace industries. The present study identifies 7.5% ZrO₂ as the optimum, yielding peak tensile, flexural, ILSS, and impact strengths, and thermal properties. This demonstrates the dual benefits of fiber hybridization and nanoparticle reinforcement. The approach can be extended by exploring surface-modified ZrO₂, multi-filler systems, and conducting long-term durability studies, broadening the potential of these eco-friendly composites for lightweight structural applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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