Research Article

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Influence of *Cordia dichotoma* Fibers and Zinc Oxide Nanoparticles on the Mechanical and Thermal Behavior of Epoxy Hybrid Composites

S. Seenivasan[1*], V. Sathya[2], M. Jegadeeswaran[2], B. Nanthini[2], T. Prabhu[2] and Kelin S. Johnson[2]

[1]Department of Mechanical Engineering, Rathinam Technical Campus, Coimbatore, TN, India

[2]Department of Agricultural Engineering, Rathinam Technical Campus, Coimbatore, TN, India

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*seenikct@gmail.com

ABSTRACT

Recently, natural fibers have been increasingly used in lightweight applications to reduce the reliance on synthetic materials. The reinforcing phase in this study consists of *Cordia dichotoma* fiber (CDF), while the matrix material is an epoxy polymer composite with zinc oxide (ZnO) nanofiller. To determine the mechanical properties of the hybrid composites, five composite laminates were made with different weight ratios of filler-to-fiber. The results indicate that the composite laminate sample (S1) showed better mechanical properties with a higher weight ratio of CDFs. These attributes include tensile strength (22.45 MPa), flexural strength (26.14 MPa), and impact energy absorption (25 J). Moreover, the addition of ZnO nanofiller contributed to improved thermal stability, with higher filler content elevating the degradation temperature to 454 °C. Scanning Electron Microscopy (SEM) was employed to analyze the surface interactions among the CDFs, ZnO nanofiller, and epoxy matrix, as well as to determine the failure modes of the composite laminates during mechanical testing.

Keywords: ZnO nanoparticles; SEM analysis; Flexural strength; Mechanical properties; Thermal stability.

1. INTRODUCTION

Researchers are developing natural fiber-reinforced composite alternatives to replace the synthetic fiber composites used in the study. Biodegradable and environmentally friendly components have been incorporated to substitute both the matrix and fibers. Composites are increasingly used in the construction of bridges and in various structures such as boat hulls, swimming pool panels, racing car bodies, shower stalls, bathtubs, storage containers, and basins. The incorporation of filler, typically fine glass, quartz, or silica, enhances the elastic modulus, tensile strength, hardness, and abrasion resistance of the material. The filler also reduces polymerization shrinkage. Common internal components, such as cable linings, cargo compartments, seat upholstery, backrests, dashboard elements, and door panels, are fabricated from composite materials reinforced with natural fibers. The stringent demand for mechanical strength restricts its application to interior settings. Natural fiber composites are not only durable, cost-effective, lightweight, and non-abrasive with excellent mechanical properties, but also biodegradable, environmentally sustainable, and non-toxic to the ecosystem. Eco-friendly composites were prepared using fibers reinforced with nano-SiO_2 filler to enhance mechanical properties. The hybrid ratio was found to significantly affect tensile, flexural, and impact strengths (Harak *et al.* 2024). Natural fibers and nano-filler are blended into epoxy to create sustainable bio-composites for engineering applications. These composites exhibit enhanced viscoelastic, thermal, and antimicrobial properties (Ben *et al.* 2021). Hybrid polymer composites reinforced with sisal and pineapple leaf fibers (PALF), along with SiO_2 nanoparticles, were developed to achieve enhanced strength. Surface treatment and sonication helped improve the dispersion of the nanoparticles in the polymer matrix (Mayakannan *et al.* 2023). Hybrid natural fibers treated with NaOH and reinforced with nanoparticles were used to optimize lightweight composites for automotive structures (Gupta *et al.* 2024). Zinc oxide nanoparticles (ZnO) were integrated with alkaline-treated soybean husk fibers to enhance their antibacterial properties and thermal stability (Sakti *et al.* 2025).

Branches of the *Cordia dichotoma* plant were subjected to alkali treatment, yielding natural cellulose fibers with improved heat stability and tensile strength (Jayaramudu *et al.* 2011). The mechanical properties, including tensile and flexural strength, of a polyester matrix reinforced with water-retted, alkali-treated (5% NaOH) *Cordia dichotoma* fibers (CDFs) were examined. To evaluate the mechanical properties, epoxy resin was reinforced with CDF and granite powder. The results indicated an enhancement in impact energy absorption, flexural strength, and tensile strength. Epoxy composites reinforced with CDF exhibited improved flexural and

tensile strengths at concentrations of up to 20 wt. %. The addition of ZnO nanoparticles (up to 0.5 vol. %) improved the flexural strength and hardness of wood dust-epoxy composites (Al-Lhaibi and Al-Shabander, 2022). The incorporation of ZnO nanoparticles into chicken feather and cow hair fibers improved mechanical properties, specifically flexural strength (68.91 N/mm^2) and tensile strength (34.95 N/mm^2) (Ali *et al.* 2024). Jute/banana fiber composites treated with ZnO nanoparticles exhibited a tensile strength improvement of up to 90% and a flexural strength increase of up to 162%. SEM analyses confirmed that ZnO facilitated improved thermal stability (Tasnim *et al.* 2024).

Jute fibers improved the mechanical properties and thermal stability, followed by coating with *in situ* synthesized ZnO (Sun *et al.* 2024). Hybrid polymer composites improved mechanical properties by integrating fiber with granite powder. Thermogravimetric Analysis (TGA) indicated thermal stability up to 430 °C. Chemical resistance and water absorption were both diminished. The tensile strength and thermal stability of treated CDFs with silane were improved, with breakdown temperatures increasing to 355°C. The fibers were prepared for application in high-performance composites following the verification of structural enhancements by SEM and Fourier transform infrared spectroscopy (FT-IR) (Diharjo *et al.* 2025). Composites with *Prosopis juliflora* fiber and a polylactic matrix with ZnO nanofiller were fabricated. SEM analysis validated the effect of ZnO incorporation by demonstrating improved fiber-matrix interaction (Thandavamoorthy *et al.* 2024). Nanocomposites of *Nelumbo nucifera* and ZnO nanoparticles exhibited improved mechanical properties, including thermal stability. Analyses employing SEM revealed that ZnO enhanced char generation while reducing water absorption (Senniangiri *et al.* 2025). Composites made of polylactic acid (PLA) reinforced with natural fibers from *Sida hermaphrodita* demonstrated improved thermal stability and a tensile strength 27.3% higher than that of composites without reinforcement and treated with ZnO (Kovačević *et al.* 2025). The mechanical properties of kenaf fiber composites reinforced with ZnO, TiO_2, and MgO nanoparticles and treated with 6% NaOH were improved. Tensile strength, flexural strength, and impact energy absorption improved due to higher stress transfer and improved fiber-matrix adhesion (Kumar *et al.* 2023).

Surface energy increased by 150%, tensile strength by 16.8%, and thermal stability by 216.9% in jute fibers treated with ZnO nanorods synthesized *in situ*. SEM confirmed the alignment of ZnO, suggesting potential applications in the aerospace and automotive sectors (Yang *et al.* 2023). Composites derived from natural fibers, including coir and palmyra, and treated with flame retardants, showed improved thermal stability. Improved fire resistance was validated using TGA and SEM analyses (Sampathkumar *et al.* 2024). CDFs treated with NaOH and $NaClO_2$ exhibited enhanced tensile strength (152.8 MPa) and heat stability (380 °C). The improved shape was verified using SEM analysis, confirming its potential for composite reinforcement (Andoko *et al.* 2024). The tensile strength (14.2 MPa), flexural strength (29 MPa), and impact energy absorption (1304 J/m^2) of PLA composites were improved with the incorporation of *Cordia dichotoma* filler by 3D printing. The enhanced thermal and electrical properties of the composites support their application in automobiles (Loganathan *et al.* 2024). The tensile strength and thermal stability of CDF composites were analyzed. SEM demonstrated optimal biodegradable packaging and therapeutic options, highlighting enhanced cross-linking (Gapsari *et al.* 2025).

The present study introduces a novel hybrid composite laminate comprising chopped CDFs, ZnO nanofiller, and an epoxy matrix, with a specific focus on optimizing the weight ratios of fiber and filler. This work systematically investigates how varying CDF and ZnO nanofiller content influences the mechanical strength, thermal stability, and failure morphology of the composites. Enhanced mechanical properties and thermal degradation resistance were achieved at higher CDF loadings, while ZnO nanofiller contributed to improved interfacial bonding and thermal performance. SEM was employed to elucidate fiber–matrix interactions and characterize failure mechanisms, highlighting the synergistic effect of bio-based reinforcement and inorganic nanofiller.

2. MATERIALS AND METHODS

The objective of this work is to produce a composite laminate consisting of natural fibers, filler, and an epoxy matrix. Araldite (HY 951) hardener and Bisphenol-F type epoxy resin (LY 556), constituting the matrix, were provided by Kovai Cheenu Enterprises, Coimbatore, TN, India. ZnO nanoparticles were obtained from Matrics Enterprises, Nagercoil, TN, India, while the *Cordia dichotoma* fibers were purchased from Go Green Pvt. Ltd., Chennai, TN, India. Due to their short length, CDFs were effectively used as chopped reinforcement in the composite. Water retting was employed to extract fibers from *Cordia dichotoma*. This process involves infiltrating the central stem region with water, resulting in the swelling of internal cells and ultimately rupturing the outer layers of plant tissue. Individual fibers can be isolated from the plant structure when moisture and microorganisms collaborate to decompose the cellular tissues and adhesive compounds that bind the fibers. Subsequently, the excised CDFs were sectioned into shorter lengths to facilitate their incorporation into the composite.

ZnO nanoparticles with an average particle size of 50 nm and a density of 0.25 g/cm^3 were used as a filler to improve the properties of the hybrid composite.

Hybrid composites were fabricated using a hybridization of reinforcement, filler, and matrix, followed by the traditional hand lay-up technique. Initially, molten wax was applied to a 300 mm x 250 mm steel mold. A blend comprising 60% epoxy resin and hardener was introduced into the mold, with slurry consisting of chopped CDFs and ZnO nanofiller for reinforcement. The matrix was established at 60% for five samples, while the proportions of chopped CDFs and ZnO nanofiller were adjusted across five distinct weight fractions (%): 38/2, 37/3, 36/4, 35/5, and 34/6 of the total hybrid composite. To optimize the curing process of the hybrid composite, the laminates were heated in a furnace at 50 °C per minute for two hours after fabrication. Subsequently, they were compressed for 24 hours under a pressure of 5 kg/cm^2.

Table 1. Mass fraction distribution of constituents in hybrid composite samples

Sample	Weight Percentage of CDFs	Weight Percentage of ZnO Nanofiller	Weight Percentage of Epoxy Matrix
S1	38	2	60
S2	37	3	60
S3	36	4	60
S4	35	5	60
S5	34	6	60

Table 1 presents the weight ratio of coated dry film (CDF), nanofiller, and epoxy polymer matrix materials. Tensile, flexural, and impact tests, alongside TGA, were conducted on samples of the hybrid composites. The experiment was conducted using the Universal Testing Machine (INSTRON) at a crosshead speed of 2 mm/min with a load of 5 kN. The dimensions were measured in accordance with the ASTM D638 standard, with a positional measurement accuracy of ±0.01% or 0.001 mm. A 0.5% load accuracy of the target load was attained. Then, the flexural test was carried out on specimens with dimensions of 125 × 12 × 3 mm, with a force ratio of 100:1, indicating that the load cell was subjected to 1.0% of its capacity without any loss of precision. The Izod impact test was conducted as per ASTM D256 standard, using specimens with dimensions of 65 × 12 × 3 mm. Thermal stability was evaluated through TGA in accordance with ASTM E1131 standard. SEM (ZEISS) was used to examine the surface morphology and interactions of the hybrid composite. Surface microanalysis is conducted after sputter-coating the hybrid composites with gold particles to enhance visibility. Three specimens were taken from each sample for each test, and the average values were recorded. Fig. 1 illustrates the equipment and specimens employed for tensile and flexural testing.

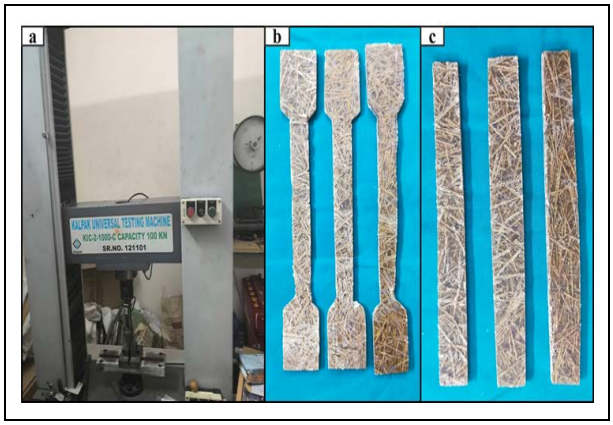


Fig. 1: (a) Universal testing machine, (b) Tensile test specimens, and (c) Flexural test specimens

3. RESULTS AND DISCUSSION

In this study, the mechanical testing of hybrid composites was performed in accordance with ASTM standards. Fig. 2 illustrates the tensile stress-strain curve for the composite laminates. The results elucidate the elastic characteristics of the CDF composites. Sample S1 exhibits a maximum stress of 25.96 MPa and a maximum strain of 14.4%. When a strain in the hybrid composite exceeds its maximum elastic limit, it is subjected to stress that leads to failure. This behavior, where strain increases in correlation with stress until the elastic limit is reached, was observed in all successive samples. The CDF content is higher in samples S1 and S2; consequently, CDF facilitates greater stress transfer than the ZnO nanofiller during tensile loading in the hybrid composites. Similarly, the hybrid laminates containing CDFs and granite powder with polyester resin showed enhancements in mechanical characteristics, with the addition of filler (Reddy *et al.* 2020).

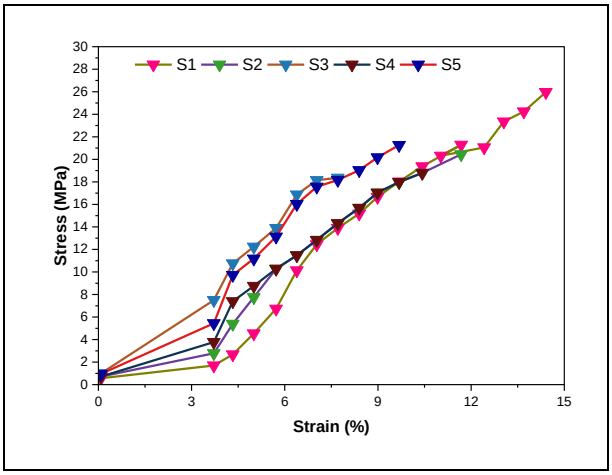


Fig. 2: Tensile Stress *vs.* Strain curve of the hybrid composites

The tensile strengths of the hybrid composite are depicted in Fig. 3. The composite stability of the CDF in terms of TS is presented in Table 2, and the coefficient of variation for the mechanical properties of this hybrid composite has also been calculated.

Table 2. Standard deviation, mean, and coefficient of variation of the composite samples for tensile strength

Sample	SD	Mean	CV
S1	0.27	22.25	0.0129
S2	0.23	20.45	0.0095
S3	0.44	18.25	0.0241
S4	0.15	15.98	0.0093
S5	0.43	13.65	0.0314

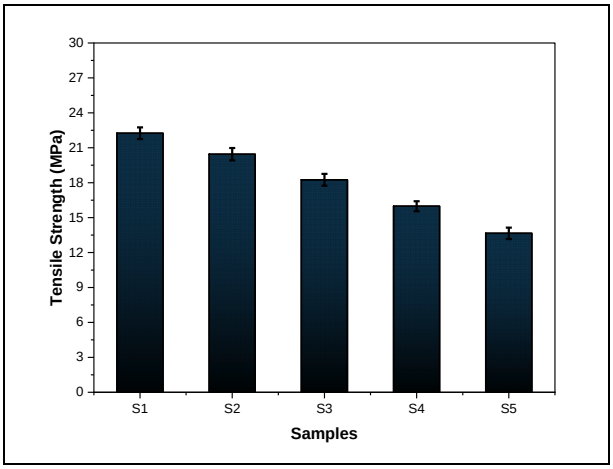


Fig. 3: Tensile strength of composite laminates

The outcomes observed in composite laminates indicated that increasing the weight fraction of fiber reinforcement yielded more advantageous results than increasing the filler percentage. The hybrid composite comprised CDF, ZnO nanoparticles, and an epoxy matrix. Sample S1 exhibited the highest tensile strength among all samples, measuring 22.25 MPa. Its composition consisted of 38 wt. % chopped CDFs and 2 wt. % ZnO nanofiller, indicating that the maximal strength was primarily dependent on fiber reinforcement. Sample S2 exhibited a tensile strength 8.09 % lower than that of sample S1, suggesting that increasing the fiber ratio can enhance the strength of the composite laminates. A 4 wt. % increase in filler in sample S3 may result in a 30% detrimental effect relative to sample S1. In comparison to sample S1, sample S5 exhibited a tensile strength of 13.65 MPa, representing a 39% decrease. To assess the mechanical and structural alterations, CDFs were treated with varying concentrations of NaOH, and 5% NaOH yielded the highest tensile strength, as observed by Hassan *et al.* (2024).

Fibers composed of *Cordia dichotoma*, subjected to alkali treatment and coated with polycarbonate, demonstrated improved mechanical properties and increased tensile strength of the hybrid composite (Jayaramudu *et al.* 2013). Following curing, alterations may occur in one or both components of the composite if there is a decline in tensile strength and an increase in the cross-linking rate. Hybrid composite laminates demonstrate the significance of reinforcement in the manufacturing of natural composites when exposed to a gradual axial tensile load, as opposed to alternative filler materials. The experimental outcomes of the tensile, flexural, and impact tests on composite laminates were averaged from three distinct specimens per sample. Table 3 presents the flexural strengths of the composite samples.

Table 3. Standard deviation, mean, and coefficient of variation of the composite samples for flexural strength

Sample	SD	Mean	CV
S1	0.17	26.14	0.0065
S2	0.19	25.36	0.0074
S3	0.16	20.05	0.0079
S4	0.27	19.87	0.0135
S5	0.40	15	0.0261

To determine the stress applied under bending conditions, a three-point bending test was conducted. In this experiment, the load corresponding to a 2 mm deflection of the hybrid composites was measured. Fig. 4 illustrates the flexural strength of composite laminates.

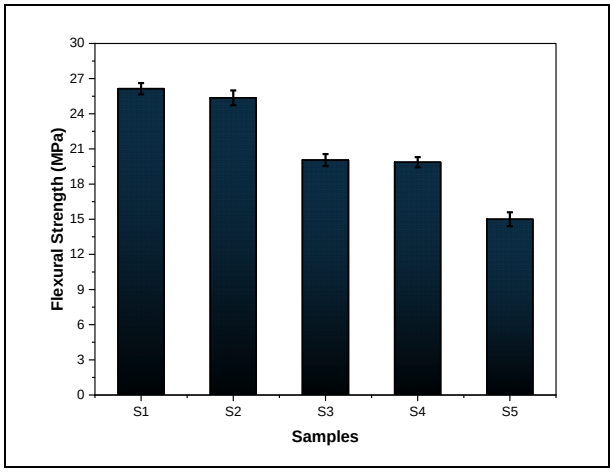


Fig. 4: Flexural strength of composite laminates

The flexural strength of S1, measured at 26.14 MPa, was the highest among all samples. S5, possessing the lowest flexural strength and the highest concentration of ZnO nanofiller, exhibited a 2.9% higher outcome compared to S2. Therefore, rather than adding nanofiller to composite laminates, increasing the amount of chopped CDF material can improve the flexural strength of the hybrid composite under bending loads. A subsequent investigation indicates that incorporating additional CDF into a composite containing ZnO enhances its flexural energy. The presented results are comparable and indicate that the incorporation of fiber reinforcement can substantially enhance the flexural performance. Composite laminates with reduced CDF content exhibit a flexural strength of 15 MPa, representing a 42.61% decrease in bending performance. Hybrid composites incorporating carbon fibers and CDFs exhibited superior flexural strength (29.09 MPa) than natural fiber-only composites, due to improved stiffness and load transfer. Sample S3, exhibiting a flexural strength of 19.5 MPa, indicated that, relative to S4 and S5, an aforementioned ratio of chopped CDFs and ZnO nanofiller may mitigate flexural degradation.

Table 4 presents the impact strength of the fabricated composites. The energy absorption capability of the composite laminates was evaluated using the Izod impact strength (IS) test.

Table 4. Standard deviation, mean, and coefficient of variation of the composite samples for impact energy

Sample	Standard Deviation	Mean	Coefficient of Variation
S1	0.43	25	0.017
S2	0.18	20	0.085
S3	0.16	18	0.008
S4	0.31	14	0.022
S5	0.15	11	0.013

The chopped CDFs can withstand greater impact forces, with S5 absorbing at least 11 J and S1 absorbing up to 25 J. This suggests that the ZnO nanofiller fractures rapidly under sudden loading. S2 absorbed 20 J of energy, indicating that the fiber material can efficiently absorb and withstand impact loads. This result is 20% lower than S1. Results indicate that a 2 wt. % increase significantly impacts the hybrid composite. In previous study, the impact energy absorption (12.17 kJ/m^2) was improved in bio-composites derived from silk waste treated with ZnO nanoparticles, as observed by Tumusiime *et al.* (2023). The impact load can be transferred more swiftly from one area to another in the mat configuration of the composite, which accounts for its reduced response to unexpected loads. Fig. 5 illustrates the impact energy of natural composite laminates.

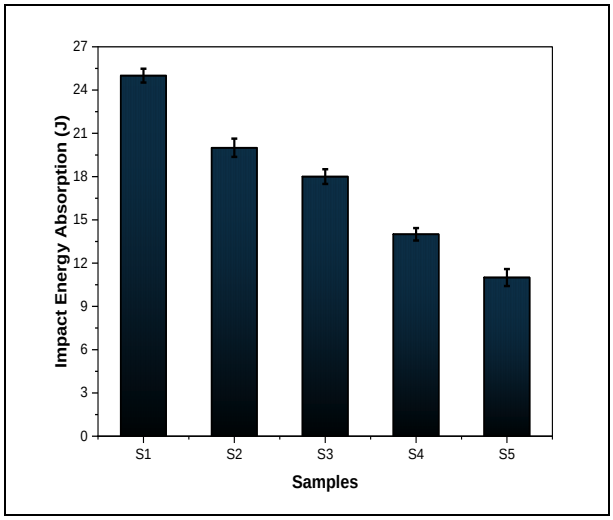


Fig. 5: Impact energy of composite laminates

The utilization of chopped CDF can temporarily alleviate the strain, but it presents a significant limitation. In mechanical tests, the fibers cannot endure significantly greater stress, and filler additions can merely mitigate the rate of thermal breakdown. The mechanical and thermal properties of the hybrid composite are influenced by the type of reinforcement used.

The SEM images in Fig. 6 illustrate the morphological characteristics of the composite laminates, emphasizing the role of epoxy resin in reducing porosity and air entrapment during the fabrication process. The fractured surfaces demonstrate enhanced surface integrity, while specific failure features are evident. The brittle failure observed in the micrographs, including fiber pull-outs, matrix cracking, and void forms, can be ascribed to stress concentration zones, particularly surrounding the short fibers embedded in the matrix. These stress concentration regions often lead to microcrack propagation and localized delamination.

Hybrid flax/glass fiber epoxy composites were improved with the incorporation of ZnO nanoparticles, specifically at a recommended weight percentage of 0.3 wt. %. Field emission scanning electron microscopy (FE-SEM) demonstrated enhanced matrix-fiber adhesion, resulting in improved mechanical properties and thermal performance (Meravi and Panchore, 2025). The SEM images suggest that although fiber-matrix bonding is very robust, the fiber-to-filler interfacial adhesion is comparatively weak, potentially affecting the overall performance of the composite under mechanical stress.

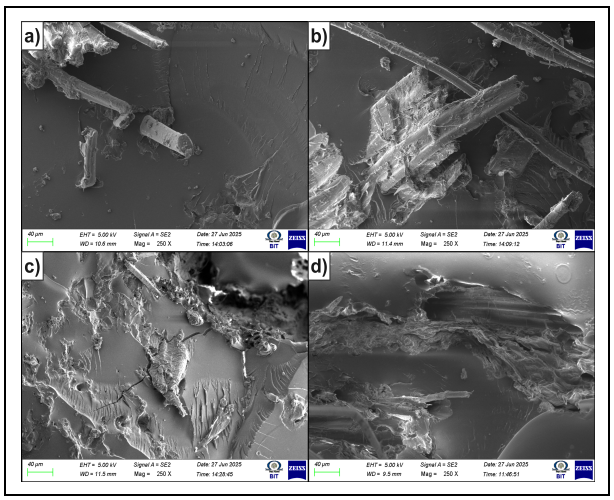


Fig. 6: SEM images of composite laminates

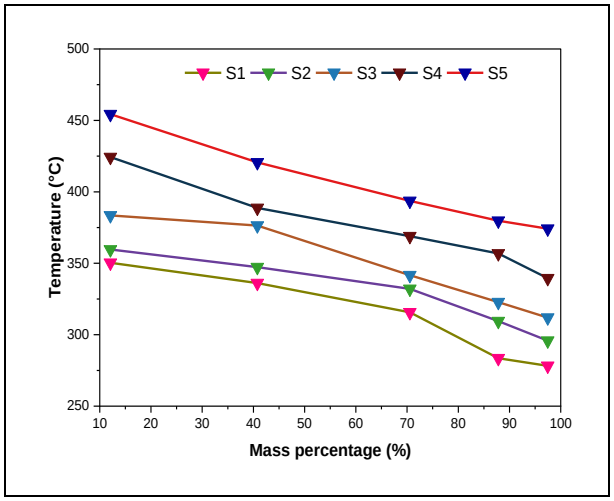


Fig. 7: Mass percentage vs. Temperature of composite samples

3.1 Thermal Stability of CDF Composite Laminates

The thermal stability and material deterioration of the CDF-reinforced hybrid composites were evaluated in TGA experiments for the five samples. This examination determines the stability of the material under varying temperatures and the mass degradation time. For the hybrid composite S5, a mass of 12.07 g was used, heated to 350 °C, and processed for 12.5 minutes. S1 exhibited an initial temperature of 269 °C and was processed for 12 minutes with a material mass of 12.5 g. The TGA results suggest that ZnO nanofiller remains stable up to temperatures as high as 445 °C. Fig. 7 shows the mass percentage *vs.* temperature graph for mass loss at different percentages of hybrid composites, and Fig. 8 illustrates the mass percentage *vs.* time graph for chopped CDFs mixed with ZnO nanofiller in hybrid polymer composites. These graphs demonstrate the thermal durability of the composites. In a study Hybrid composite composed of *Cordia dichotoma* and carbon fibers within an epoxy resin matrix were analyzed. TGA revealed thermal stability up to 415 °C, and alkali-treated fibers enhanced the crystallinity as observed.

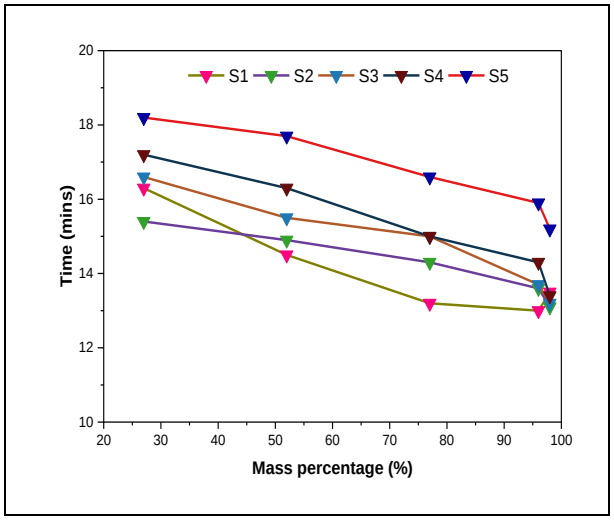


Fig. 8: Mass percentage *vs.* Time of the composite samples

4. CONCLUSION

Chopped *Cordia dichotoma* fibers augmented with ZnO filler and integrated into the epoxy matrix were used to fabricate the composite laminates. The objectives of the mechanical and thermogravimetric experiments were to broadly investigate the thermal and mechanical characteristics of the composite laminates. The incorporation of chopped CDFs, in contrast to ZnO nanofiller, improved TS, FS, and impact energy by an average of 76%. The incorporation of ZnO nanofiller may have adversely affected the mechanical properties of the natural composite, whereas the mechanical properties of the CDF composites were enhanced with the addition of chopped CDF reinforcement. The sample, S1, exhibited significant enhancements in TS (22.25 MPa), impact energy (25 J), and FS (26.14 MPa) compared with the other four samples, indicating that the CDF can serve as an effective reinforcement for polymer composites in lightweight structural applications. The incorporation of ZnO nanofiller improved thermal stability by an average of 61% compared with CDF alone. At a maximum degradation temperature of 454 °C, sample S5 exhibited remarkable thermal stability. The material degradation duration was 15.3 minutes, sufficient to reach a residual mass of 12% for this hybrid composite. Optimal thermal insulation properties in hybrid composites are achieved by incorporating ZnO nanofiller into natural composites.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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