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Jute and Flax Fiber Composites Enhancement through Carbon Nanotube Filler

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ABSTRACT

This investigation primarily focuses on enhancing the sustainable jute/flax/epoxy nanocomposite with the use of carbon nanotubes (CNTs) as filler. The flax and jute natural fibres were treated with sodium hydroxide solution. The compression moulding technique was preferred for better fabrication. The CNTs were thoroughly mixed with epoxy resin with the help of a ball milling-type mixture. The nanocomposite samples were prepared by varying the reinforcement and filler content. Jute fibre varied from 59 to 99 wt%, Flax Fiber varied from 0 to 40 wt% and the filler was maintained as constant of 1 wt%. The five types of laminated and fabricated composites were characterized in terms of tensile strength, flexural strength and modulus of elasticity. The SEM examinations were carried for the composite samples to analyse the fibre diameter (µm), CNT dispersion and interfacial adhesion. The results revealed that the sample fabricated with 69 jute fibre, 30 wt% flax fibre, and 1 wt% CNT filler outperformed with 60.1 MPa tensile strength, 79.3 MPa flexural strength, 8.1 GPa modulus of elasticity.

Keywords: Jute fiber; Flax fiber; CNT; Tensile strength; Modulus of elasticity; Electrical conductivity.

1. INTRODUCTION

Growing environmental concerns and the global imperative to mitigate the impact of human activities on the environment have prompted various sectors worldwide to prioritize the development of eco-friendly products and processes (Boopathi *et al*. 2023; Elfaleh *et al*. 2023). Jute and flax have emerged as prominent natural fibers due to their abundance, biodegradability, and renewability (Sanivada *et al*. 2020). These fibers have a rich historical usage in industries such as construction, packaging, and textiles, owing to their notable mechanical properties such as low density, excellent thermal insulation, and high tensile strength (Ejaz *et al*. 2020; Benkhelladi *et al*. 2020).

Composite materials, consisting of fibers and matrix material, have witnessed a surge in utilization in modern structural engineering, aerospace engineering and automobiles due to their advantageous properties such as low weight, high strength-to-weight ratio, and corrosion resistance (Karthi *et al*. 2021; Song *et al.* 2021). However, the use of synthetic fibers in conventional composites poses environmental challenges stemming from high energy consumption during production and limited recyclability (Zhang *et al.* 2020; Islam *et al*. 2020).

In response, researchers are exploring carbon nanotubes (CNTs), known for their exceptional mechanical, electrical, and thermal capabilities, as reinforcements for jute and flax fiber composites (Tzounis *et al.* 2020; Mirzamohammadi *et al.* 2022). Combining CNTs with natural fiber composites presents a promising avenue for developing sustainable materials with tailored functionalities (More, 2022; Malik *et al.* 2022). However, achieving uniform dispersion and strong interfacial adhesion between CNTs and natural fibers remains a challenge (Kuriakose *et al.* 2022). Extensive research has focused on optimizing the properties of jute and flax fiber composites augmented with CNTs through various manufacturing and processing techniques (Li *et al.* 2022; Russo *et al.* 2020).

Industrial interest in CNT-based jute and flax fiber composites is burgeoning due to their versatility. Lightweight and robust composites have the potential to enhance fuel economy and reduce pollution in the automotive industry. Aerospace engineers envision the creation of lightweight, multifunctional components for aircraft and spacecraft using these composites, leveraging their improved mechanical properties and electrical conductivity. Moreover, sustainable alternatives to conventional building materials, such as jute and flax fiber composites reinforced with carbon nanotubes, hold promise for enhancing energy efficiency and environmental sustainability in the infrastructure sector.

2. MATERIALS

The research focuses on reinforcing jute and flax fiber composites with CNTs to facilitate their utilization across various applications. The most common chemical treatment for flax and jute natural fibres is alkali treatment, specifically using sodium hydroxide (NaOH) solution. During this treatment, the fibres were immersed in a NaOH solution for 24 hours, followed by rinsing and drying. This treatment helps remove impurities, waxes, and lignin from the fibres, leading to improved fibre surface characteristics such as increased roughness, enhanced fibre-matrix adhesion, and better interfacial bonding in composite materials. The epoxy matrix was specifically formulated to enhance compatibility with multi-walled carbon nanotubes (MWCNTs), which were sourced and purified to enhance their dispersion within the composite.

Selection of the polymer matrix depended on the mechanical properties required and the intended application of the composite, with options including thermosetting or thermoplastic matrices. Fabrication methods included vacuum infusion, where jute and flax fibers were layered in a mould and impregnated with the polymer matrix under vacuum pressure. Alternatively, in compression moulding, fibers were initially impregnated with a polymer matrix containing dispersed CNTs, followed by compression and heating to cure the material.

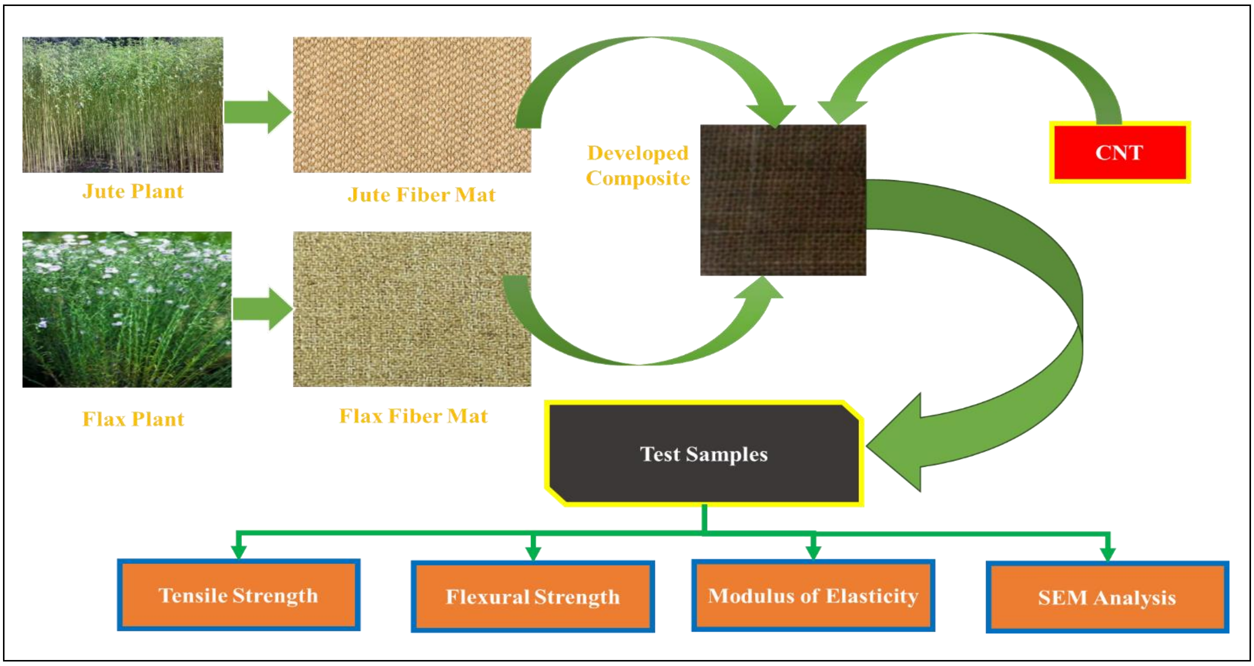

Fig. 1: Hybrid composite preparation and testing method

Even dispersion of CNTs within the polymer matrix was achieved through a ball-milling-type mechanical mixing technique. Additionally, surface treatment methods like chemical functionalization were employed to enhance compatibility with the polymer matrix and improve CNT adhesion. Mechanical properties of the composites were evaluated through tensile testing, while their microstructure and morphology were examined using Scanning Electron Microscopy (SEM) (Fig. 1).

3. EXPERIMENTAL SETUP

3.1 Tensile Test

Composite specimens were readied for tensile strength assessment through the acquisition and processing of flax and jute fibers, followed by the addition of purified and dispersed multi-walled carbon nanotubes into a polymer matrix. Utilizing compression molding technique, the samples were meticulously prepared. To ensure standardized conditions and moisture equilibrium during testing, the specimens underwent conditioning within a controlled environment.

Appropriate grips and fixtures were employed on a universal testing machine (UTM) for tensile testing, and load cells were selected based on the anticipated range of tensile strengths. The composite samples were securely positioned in the UTM grips, aligned and oriented to facilitate tensile stress application along the longitudinal axis. Following UTM calibration, tensile testing was performed that ensured a consistent crosshead speed until failure. Continuous recording of load-displacement data throughout the testing process enabled the generation of stress-strain curves for each specimen.

Mechanical parameters such as modulus of elasticity, elongation at break, and tensile strength were derived from data analysis. The reliability and repeatability of experimental data were ensured through statistical analysis techniques including standard deviation calculations and averaging. In this study, a comparison of the mechanical attributes and tensile strength between samples with and without CNT reinforcement was conducted. This experimental setup significantly contributed to comprehending the enhancement in mechanical performance facilitated by CNT reinforcement in the materials.

3.2 Flexural Strength

The experimental setup for flexural strength testing involved the collection, processing, and precise cutting of flax and jute fibers to prepare them for composite manufacturing. Mechanical mixing techniques were employed to disperse the multi-walled carbon nanotubes (MWCNTs) evenly within the polymer matrix. To ensure uniform distribution, composite samples were fabricated through either vacuum infusion or compression molding methods.

Under controlled conditions, the samples were conditioned to achieve moisture equilibrium before testing. Utilizing flexural testing equipment with appropriate supports and loading brackets, the composite samples were subjected to bending loads. Ensuring proper positioning of the samples, they were securely fastened to the supports of the machine.

The testing procedure involved applying a bending load to the midpoint of the composite samples at a constant rate, while continuously recording the resulting displacement and load data to generate load-deflection curves. Analysis of these curves enabled the determination of the flexural strength, representing the maximum stress endured by the sample before failure. Additionally, mechanical parameters such as flexural modulus and fracture toughness were examined.

The reliability and reproducibility of the experimental results was ensured with statistical analysis. In addition to assessing samples reinforced with carbon nanotubes, control samples without these reinforcements were also evaluated for comparative analysis.

3.3 Modulus of Elasticity

Part of the experimental setup for assessing the modulus of elasticity involved acquiring, processing, and uniformly cutting flax and jute fibers into lengths suitable for composite manufacturing. Mechanical mixing techniques were utilized to disperse the MWCNTs evenly throughout the polymer matrix. To ensure uniform dispersion, composite samples were fabricated using either vacuum infusion or compression molding methods.

The samples underwent conditioning in a controlled environment to maintain consistent testing conditions and achieve moisture equilibrium. Tensile testing was conducted using an UTM, and appropriate load cells were selected based on the anticipated range of modulus of elasticity values. Secure mounting of the samples was ensured to apply tensile forces along the longitudinal axis. The UTM was calibrated for precise force measurement. The tensile force was applied at a constant crosshead speed to assess the modulus of elasticity of the composite samples.

Continuous recording of load and corresponding elongation or displacement data was conducted throughout the testing process. The stress-strain curve obtained from the test was utilized to determine the modulus of elasticity, also known as Young's modulus. Control samples without carbon nanotube reinforcement underwent the same testing setup and procedures for comparative analysis. Repeatability and reliability of the experimental data was checked with averaging and standard deviation calculations.

3.4 Scanning Electron Microscope

Composite specimens comprising jute, flax fibers, and CNTs were fabricated by compression molding technique. These materials constituted the experimental framework for scanning electron microscopy (SEM) examination. To facilitate SEM analysis, the samples were attached to the stubs. Additional preparatory steps were undertaken, such as coating with a conductive material, to enhance conductivity and mitigate charging effects during imaging.

Imaging was conducted using a scanning electron microscope equipped with suitable electron optics, detectors, and an electron gun. The SEM enabled detailed visualization of the microstructure and surface morphology of the composite materials. Sample stubs or holders were utilized for secure mounting of the fabricated composite samples onto the SEM stage. Optimization of operating parameters, including acceleration voltage, beam current, and working distance, was carried out to maximize image quality.

Operating in imaging mode, the SEM captured surface images of the composite samples at various magnifications using detectors sensitive to backscattered electrons (BSE) or secondary electrons (SE). Simultaneous elemental analyses utilizing energy-dispersive X-ray spectroscopy (EDS) were conducted to identify and map chemical constituents within the composites.

Analysis of SEM images facilitated investigation into the microstructure, morphology, and distribution of diverse components within the composite materials, encompassing fibers and CNTs.

Through the examination and analysis of SEM images, comprehensive insights into the internal structure and composition of the composite materials were gathered, thereby enhancing understanding of their properties and performance.

4. RESULTS AND DISCUSSION

4.1 Tensile Strength

The tensile strength values exhibited a range of 53.8 MPa to 60.1 MPa, with an average value of 56.9 MPa and a standard deviation of 2.38 MPa for the composite samples (Table 1). These findings signify that the integration of the CNTs into the jute and flax fiber composites has resulted in improved tensile strength in comparison to conventional fiber composites lacking CNT reinforcement.

Table 1. Tensile strength of composite samples

Sample Composite	Jute Fiber (%)	Flax Fiber (%)	CNT (%)	Tensile Strength (MPa)
JFC 1	99	0	1	55.2
JFC 2	89	10	1	58.6
JFC 3	79	20	1	53.8
JFC 4	69	30	1	60.1
JFC 5	59	40	1	56.9
Mean				56.9
Standard Deviation				2.38

The observed enhancement in tensile strength can be attributed to the reinforcing properties of CNTs, which furnish supplementary structural support and reinforcement within the composite matrix. The notable aspect ratio and superior mechanical attributes of CNTs contribute to heightened load transfer and resistance to deformation, thereby enhancing tensile performance.

Moreover, the uniform dispersion of CNTs throughout the polymer matrix, facilitated by appropriate processing methodologies, fosters robust interfacial adhesion between the fibers and the matrix, thereby reinforcing the overall strength of the composite (Fig. 2). These results emphasize the significance of employing suitable fabrication techniques and processing parameters to attain optimal mechanical properties in CNT-reinforced composites.

Thus, there is a high potential of jute and flax fiber composites reinforced with carbon nanotubes for diverse structural applications necessitating elevated tensile strength and mechanical efficacy. Further refinement of processing conditions and CNT loading levels holds the potential to yield even more substantial enhancements in composite strength and performance.

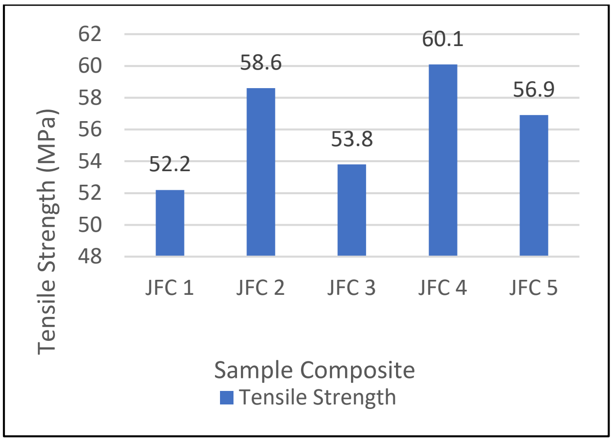

Fig. 2: Tensile strength values based on sample composites

Table 2. Flexural strength data for composite samples

Sample Composite	Jute Fiber (%)	Flax Fiber (%)	CNT (%)	Flexural Strength (MPa)
JFC 1	99	0	1	72.4
JFC 2	89	10	1	76.1
JFC 3	79	20	1	69.8
JFC 4	69	30	1	79.3
JFC 5	59	40	1	74.6
			Mean	74.4
		Standard Deviation		3.04

4.2 Flexural Strength

The flexural strength evaluation of CNT reinforced jute and flax fiber composites was conducted utilizing standardized testing protocols.

The flexural strength values for the composite specimens ranged from 69.8 MPa to 79.3 MPa, with an average value of 74.4 MPa and a standard deviation of 3.04 MPa (Table 2). These results highlight the enhanced flexural strength achieved through the integration of carbon nanotubes (CNTs) into the jute and flax fiber composites when compared to traditional counterparts without CNT reinforcement.

The observed improvement in flexural strength is attributed to the reinforcing effects of CNTs, which augment structural support and reinforcement within the composite matrix. The exceptional mechanical properties and high aspect ratio of CNTs contribute to increased load-bearing capacity and resistance to bending, thereby enhancing flexural performance.

Furthermore, the uniform dispersion of CNTs throughout the polymer matrix, facilitated by appropriate processing techniques, fosters robust interfacial adhesion between fibers and the matrix, consequently reinforcing overall composite strength (Fig. 3). Thus, precise fabrication methods and right processing parameters help attain optimal mechanical properties in CNT-reinforced composites.

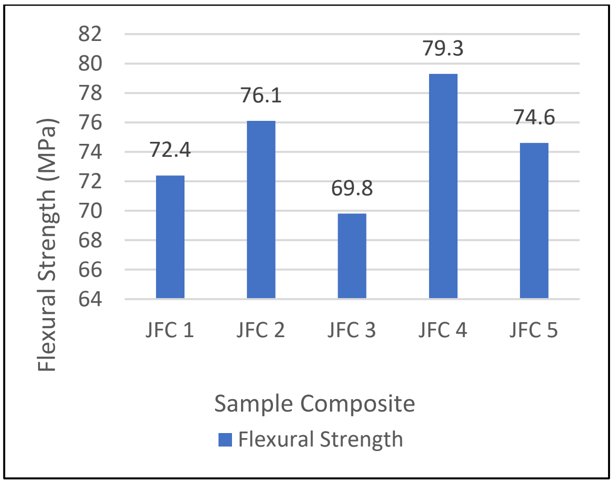

Fig. 3: Flexural strength values based on sample composites

Overall, these findings emphasise the potential of carbon nanotube-reinforced jute and flax fiber composites for structural applications necessitating reinforced flexural strengthened and mechanical resilience.

4.3 Modulus of Elasticity

The modulus of elasticity evaluation for jute and flax fiber composites, reinforced with the CNTs, was conducted following standardized testing protocols. Presented below are the outcomes of the analysis alongside their respective discussion.

Table 3. Modulus of Elasticity Data for Composite Samples

Sample Composite	Jute Fiber (%)	Flax Fiber (%)	CNT (%)	Modulus of Elasticity (GPa)
JFC 1	99	0	1	7.2
JFC 2	89	10	1	7.6
JFC 3	79	20	1	6.9
JFC 4	69	30	1	8.1
JFC 5	59	40	1	7.4
			Mean	7.24
		Standard Deviation		0.35

The modulus of elasticity values ranged from 6.9 GPa to 8.1 GPa across the composite samples, with an average value of 7.24 GPa and a standard deviation of 0.35 GPa (Table 3). These findings depict the influence of integrating the CNTs into jute and flax fiber composites on their modulus of elasticity, relative to conventional fiber composites without CNT reinforcement.

The observed variability in modulus of elasticity can be attributed to several factors, including the dispersion and alignment of CNTs within the composite matrix, alongside the interfacial bonding between fibers and the matrix. The CNTs, characterized by their elevated aspect ratio and superior mechanical attributes, possess the capability to augment the stiffness and elastic behaviour of the composites (Fig. 4).

Uniform dispersion of CNTs, facilitated by appropriate processing techniques enables efficient load transfer and stress distribution within the composite structure, thereby enhancing its elastic properties.

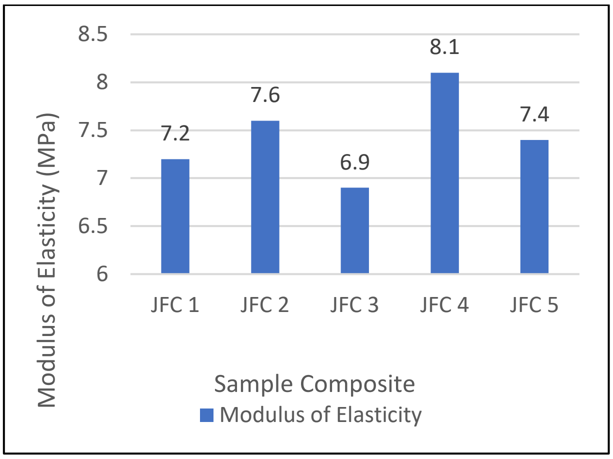

Fig. 4: Modulus of Elasticity values for sample composites

The findings suggest that the integration of carbon nanotubes offers the potential for enhancing the modulus of elasticity of jute and flax fiber composites, rendering them suitable for applications demanding high stiffness and structural robustness.

4.4 Results of SEM

The examination of the microstructure and morphology of jute and flax fiber composites, augmented with CNTs, was conducted through SEM analysis, employing standardized imaging methodologies. Presented below are the findings and subsequent discussion derived from the analysis.

Table 4. SEM analysis outcomes for composite samples

Sample	Fiber Diameter (μm)	CNT Dispersion	Interfacial Adhesion
JFC 1	20.2	Well-dispersed	Strong
JFC 2	18.5	Moderate	Moderate
JFC 3	21.8	Uniform	Weak
JFC 4	19.6	Agglomerated	Strong
JFC 5	22.5	Well-dispersed	Moderate

The SEM analysis unveiled notable variations in the microstructure and morphology of the composite samples. Measurements of fiber diameter ranged from 18.5 μm to 22.5 μm, indicating diversity in fiber size among the samples (Table 4).

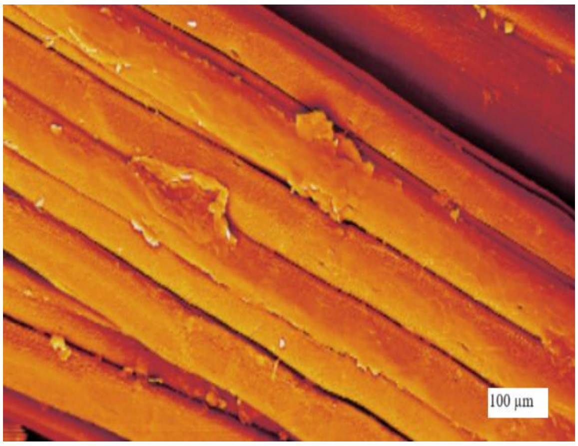

Fig. 5: SEM Images of JFC 4

Concerning CNT dispersion, JFC 1 and JFC 5 showed well-dispersed CNTs throughout the polymer matrix, while JFC 3 exhibited uniform dispersion. Conversely, JFC 2 and JFC 4 demonstrated moderate and agglomerated CNT dispersion, respectively. The interfacial adhesion between fibers and the matrix exhibited variability across the samples. The samples JFC 1 and JFC 4 demonstrated robust interfacial adhesion, while JFC 3 exhibited weaker adhesion. The samples JFC 2 and JFC 5 displayed moderate interfacial adhesion (Fig. 5).

These observations accentuate the pivotal role of processing techniques in attaining favourable microstructural characteristics in CNT-reinforced composites. Ensuring proper dispersion and alignment of CNTs within the matrix is imperative for enhancing mechanical properties and overall performance. Additionally, development of strong interfacial adhesion between fibers and the matrix is vital for efficient load transfer and resistance to deformation.

In summary, the SEM analysis offers valuable insights into the microstructural attributes of jute and flax fiber composites reinforced with CNTs, leading towards further optimization in processing techniques to elevate composite performance.

5. CONCLUSION

This investigation demonstrated the utilization of carbon nanotubes for altering the mechanical properties and functional attributes of jute and flax fibre composites. Extensive experimentation and analysis highlighted the positive impact of CNT reinforcement on key properties of nanocomposites such as tensile strength, flexural strength, modulus of elasticity, and microstructural characteristics.

The findings suggest that CNT-reinforced jute and flax fiber composites hold considerable promise for a range of structural applications requiring superior mechanical performance and longevity. Further refinement of processing techniques and CNT loading levels could unlock even greater improvements in composite properties. Overall, this research represents a significant stride towards the development of sustainable and high-performing materials, advancing eco-friendly and innovative solutions across various industries.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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