Mechanical and morphological evaluation of jute fiber reinforced epoxy composites for sustainable structural and automotive applications

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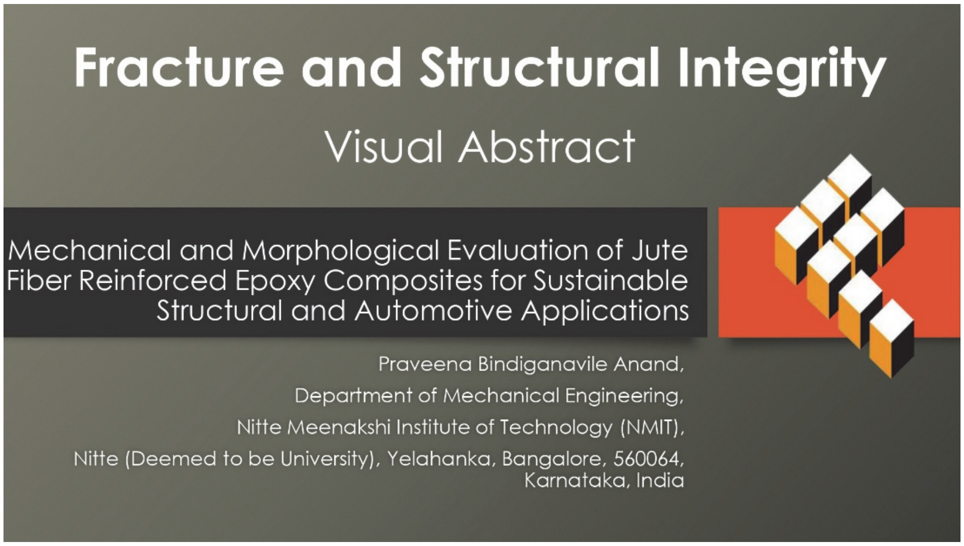

Fracture and Structural Integrity

Visual Abstract

Mechanical and Morphological Evaluation of Jute Fiber Reinforced Epoxy Composites for Sustainable Structural and Automotive Applications

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INTRODUCTION

The trend towards sustainability, resource conservation and environmentally friendly technologies in the world has increased the curiosity in natural fibre reinforced polymer composites (NFRPCs) in the current years. The common synthetic fibers including glass, carbon, and aramid that are being traditionally used have outstanding mechanical characteristics but have significant weaknesses like expensive, non-biodegradable, energy-consuming manufacturing process and detrimental effects on the environment during production and disposal. These shortcomings have prompted academic and industry researchers to consider natural fibers more often as a potential polymer matrix reinforcement [1]. Jute is one of these natural fibers that have been the focus of much attention because of its merits in terms of mechanical performance, economic growth, biodegradability, and all-around availability in South Asia and southeast Asia [2]. The fiber of jute is mostly a mixture of cellulose, hemicellulose, lignin, pectin and waxes where cellulose content is the source of strength and stiffness. It is relatively low density, high aspect ratio, and moderate tensile strength material that is used in a variety of low-to-moderate loading applications. Furthermore, jute fibers need very low energy to be manufactured than synthetic fibers, thus less carbon footprint of manufacturing as well as disposing [3]. Such aspects make jute a very promising raw material in the development of composite materials that are eco-friendly. The utilization of jute fiber also reflects the trends in the world toward the moralities of the round reduced, sustainable production, and the use of renewable resources in the automotive, construction, aerospace interiors, packaging, and customer goods industry [4]. While chemical or physical treatments of natural fibres can enhance interfacial bonding and mechanical performance, this study focuses on untreated jute fibres to establish a baseline understanding of their behaviour in epoxy composites.

In the design of polymer composites, the selection of the matrix material is at the centre of control of both thermal and thermal features of the composite. One of the most general-purpose matrices is epoxy resin which has the best mechanical strength, dimensional stability, low shrinkage, good chemical resistance and good bonding with natural fibers [5]. The most significant effect is the epoxy fiber interactions that define the efficiency of load transfer and performance of the structure in general. In the case of such natural fibers as jute, it is essential to obtain the necessary interfacial union between the fibres and the epoxy matrix since untreated fibres tend to be covered with surface impurities and be hydrophilic, which prevents bonding. The literature has indicated several surface modification methods such as alkaline treatment, silane treatment, and chemical compatibilizers to solve this problem [6]. Nonetheless, optimized fabrication techniques like vacuum-bag molding can be used to achieve an impressive level of wetting, a decrease in the number of voids, and a optimistic consequence on the quality of composites even without any chemical treatment [7].

One of the manufacturing methods that are widely adopted in the creation of polymer composites is the vacuum-bag molding method, which has been known to produce laminates with enhanced fiber dispersion, lower porosity and uniformity of fiber orientation [8-9]. The technique consists of loading fiber mats into a mold, pouring resin onto the mats, putting a vacuum bag over the assembly, and vacuuming air out of the assembly to cause the materials to consolidate at atmospheric pressure. This guarantees greater resin flow, even impregnation, improved consolidation, and high-quality mechanical properties as opposed to hand lay-up process [10-11]. Since natural fibers tend to create pores and non-even processes of wetting because they are hydrophilic, the vacuum-bag technique is useful in averting such problems by providing a controlled processing environment [12-13]. The latter renders the method efficient and scalable to be applicable to the industrial setting, in which the repeatability and quality control are crucial factors [14-15]. The mechanical characterization of jute fiber composites is the basis on which the composites can be substituted to take the place of traditional materials in the engineering processes. The tensile strength, tensile modulus, flexural strength, flexural modulus and surface hardness are the most researched properties. Tensile behavior gives information on how the composite can resist uniaxial loading and measure the transfer of fiber load to the matrix.

Flexural performance is essential to the components that are exposed to bending loads, especially in automotive interior parts, door trims, roof liners, floor panels and structural boards. Hardness testing is used to check the surface resistant to indentation and abrasion which is fundamental to applications with wear-resistance like interior automotive parts, casing enclosures and protective surfaces [16-17]. Fiber weight fraction, fiber length, fiber distribution and fiber matrix bonding efficiency have a important impression on these mechanical properties. Thus, the research of composites in various combinations of fibers is useful to determine the best reinforcement levels in various applications [18]. The morphological analysis is necessary as supporting evidence to extract mechanical properties. Fractured surface investigation of the composites can be used to study the internal physical properties of the composites such as fiber dispersion quality, matrix continuity, fiber pull-out, crack propagation patterns, and voids as well as fibre, matrix interfacial bonding [19]. Inadequate adhesion is usually indicated by fiber pull-out whereas cleanly fractured fibers are indicative of good bonding and effective load transfer. Weakness of mechanical performance because of poor impregnation or resin starvation areas may reduce over-fiber content. Morphological analysis at the optical level has been found to be especially helpful in the interpretation of the effects of fabrication variables and fiber loading and resin viscosity on composite microstructure. These structure property relationships are useful in streamlining fabrication processes, enhancing choice of materials, and service-life prediction.

The last ten years have seen a lot of investigation into the use of natural fibres as reinforcement of composites. Nonetheless, jute fiber composites still have a few gaps. To begin with, most studies are on surface treatments but there are no comparative studies of multiple fiber loadings with uniform processing conditions [20]. Second, mechanical properties and morphological aspects do not always correlate, and therefore, it is challenging to determine the behavior of the composites under actual structural situations in the real world. Third, there is limited literature on the industrial applicability of jute epoxy composites to the automotive or structural sectors. Secondly, past research studies have used hand lay-up fabrication, which brings about inconsistencies like high void content, differences in thickness and random fabric alignment. The following gaps demonstrate the necessity of systematic research involving optimized fabrication, mechanical testing, and morphological study, especially in the case of more than one type of jute fiber [21]. The automotive engineering needs on sustainability have pushed manufacturers to find lightweight, renewable, materials that are alternatives to conventional ones. The natural fiber reinforced composites can provide a strong reduction of up to 30 to 40 % of weight relative to the glass fiber systems without extensive reduction of mechanical strength [22]. Jute fiber composite also offers better noise absorption, vibration damping, thermal insulation and better safety as there is less tendency of splintering when it fails. Natural fiber composites are already finding applications in several automotive global brands in components that include door pads, parcel shelves, trunk liners, dashboards, seat backs, and headliners. They must, however, be widely accepted through good engineering information on predictable and consistent performances. This supports the sensitivity of tensile, flexural and hardness assessment at a series of fiber loadings under homogenizing circumstances [23].

Having the capability to design jute epoxy composite that has predictable structural performance may greatly increase their application diversities in structural and semi-structural industries. Moreover, the trend of making bio-based materials worldwide is enabled by the policies in Europe, Japan and the US which promote the use of recyclable and biodegradable products in cars and construction materials. Jute-fibre-reinforced epoxy composites match maximum of these regulatory demands due to their low ecological impact, minimal toxic fume emission and disposal [24]. Social sustainability is also supported by natural fibers in the composites as it will improve the demand of natural fiber production and encourage economic growth in rural areas. Such socio-economic advantages make it even more meaningful to consider jute based composite materials in terms of systematic mechanical and morphological research. In view of this, the current research paper is devoted to designing as well as the characterization of jute fibre reinforced epoxy composites when using five fiber compositions fabricated by vacuum-bag moulding. Tests that have been done are mechanical tests such as tensile, flexural and hardness tests. Fractured samples are morphologically analyzed to match mechanical performance, failure and fiber matrix interaction. The paper tries to find an ideal fiber content that provides optimum strength, stiffening, and durability to engineering purposes [25].

MATERIALS AND METHODS

Jute fiber

The reinforcement used in this paper is the jute fiber, which is a naturally available lignocellulosic fiber or material, because of its renewability, low cost, biodegradability and the exceptional specific mechanical strength [1]. Jute fibre purchased is made of certified supplier in Bangalore, India. When it was delivered, the fibers were cast aside and had leftover plant remnants, dust, and pith. To maintain uniformity, quality and to control the length to be reinforced during random-mat polymer composite, the fibers were separated, combed and cut by hand to the required lengths (25-30 mm). The fibres were also dry in an oven at 50 ^{0}C at 24 hours before being incorporated into the resin to remove any moisture content which is known to negatively influence the interface between fibres and the fibre matrix as well as mechanical performance. Tensile strength, Youngs modulus, cellulose content and moisture absorption are mechanical properties of jute fibers; each of them substantially affects overall behavior of the composite as illustrated in Tab. 1. A high percentage of cellulose helps with tensile stiffness and strength, and the lignin helps in giving rigidity and thermal stability. Hemicellulose, despite being an additive that improves flexibility, causes a loss of interfacial adhesion when it becomes moisture-sensitive and is not managed. Fig. 1. Displays the Jute fiber and epoxy resin.

Figure 1: Jute fibre and epoxy resin.

The polymer material employed in this experiment was an epoxy resin (LY-series) based on bisphenol-A and cured with an amine-based hardener (HY-series), which possesses high mechanical, chemical and dimensional stability [4]. Epoxy resins find extensive application in natural fiber composites due to their ability to promote consistent wetting of fibers, reduction in void formation, and high interfacial bonding, which are important in ensuring maximum performance of the composite in terms of mechanical performance. They were stirred mixed thoroughly to create a homogenous mixture that has a high ratio of resin and hardener (100:10) suggested by the manufacturer and has few bubbles. Correct wetting of fibers will guarantee that stress transmission between the matrix and reinforcement takes place, and this directly impacts flexural modulus, tensile strength and impact resistance of the composite. Tab. 2 summarizes the key mechanical and physical properties of the epoxy system including density, viscosity, tensile and flexural strength, Youngs modulus and glass transition temperature. The chosen system of jute fibers and epoxy resin offers a sustainable, lightweight, and mechanically strong platform to create polymer composites that can be used in structural and automotive work. Tab. 1. Shows the Typical Physical and Mechanical Properties of Jute Fibre.

Property	Value (Typical Range)
Density (g/cm³)	1.30–1.48
Cellulose content (%)	60–70
Hemicellulose (%)	20–25
Lignin (%)	10–15
Tensile strength (MPa)	350–800
Tensile modulus (GPa)	20–55
Elongation at break (%)	1.5–2.5
Moisture absorption (%)	8–12

Table 1: Typical physical and mechanical properties of jute fibre.

Epoxy resin

The polymer backbone used in this experiment was one of the commercially available bisphenol-A based epoxy resin (LY-series) mixed with an amine-type hardener (HY-series). Epoxy resins have been extensively used in natural fiber reinforced composites because of high mechanical strength, resistance to chemicals, retention of dimensions and high adhesion to cellulose-based fibers. As recommended by the manufacturer, the resin and hardener were mixed in the 100:10 weight ratio to give full crosslinking and highest mechanical properties. The mixture was gently swirled to attain homogeneity with minimal entrapment of the air that might otherwise create voids and lower the performance of the composites. Tab. 2. Shows the Physical and Mechanical Properties of Epoxy Resin.

This epoxy system has been selected due to its low viscosity that allows the full impregnation of the jute fibers as well as homogeneous stress transfer during mechanical loading. The tensile and flexural strength, Youngs modulus, and the glass transition temperature make it quite stiff, which, combined with load-bearing, and thermal stability, make up the composites with it. Moreover, the low rate of curing of the epoxy avoids internal stresses that will undermine fiber matrix adhesion. The set of these characteristics enables the system to be a good choice in creating sustainable, lightweight, and structural stable composites with jute fiber reinforcement to be used in the automotive and building industries.

Property	Value (Typical Range)
Density (g/cm³)	1.15–1.20
Viscosity at 25°C (Pa·s)	10–12
Tensile strength (MPa)	65–85
Flexural strength (MPa)	100–120
Young's modulus (GPa)	2.5–3.2
Glass transition temperature, Tg (°C)	70–85
Curing shrinkage (%)	< 1
Pot life (min)	25–35

Table 2: Physical and mechanical properties of epoxy resin.

Fiber preparation

Before composite fabrication, those fibers of jute were subjected to controlled drying to remove the moisture that has been absorbed in the fibers, and this is known to negatively affect the fiber matrix adhesion performance and mechanical behavior of natural fiber composites. The fibers were laid flat in a laboratory oven and left at 50 ^{0}C in 24 hours. This was to guarantee the elimination of free and bound moisture besides avoiding thermal decay of the cellulose and lignin components. No chemical surface treatment, alkaline, silane, or acetylation of the various surfaces was done in this study. It was aimed at assessing the level of natural compatibility among untreated jute fibres with the epoxy matrix and investigating the impact of fibre contented on mechanical and morphological performance in the absence of external alteration. After drying, fibers were cut into 20-25 mm lengths which is regarded as being the best length to be used in random-mat reinforcement and, randomly dispersed in the matrix. The homogeneity in the size of the fibre minimizes the stress concentration sites and enhances uniform mechanical action throughout the composite [3]. The study reports baseline mechanical and impact behaviour of untreated jute fibre reinforced epoxy composites, establishing reference performance for comparison with treated fibres reported in literature. The jute fibres used in this work were employed in their natural form, without any chemical or physical treatment.

Composite fabrication

The jute fibre reinforced epoxy composites were made by the vacuum bag method moulding which is a common technique of making natural fiber composites since it is simple, cheap and requires little equipment. This technique enables a good wetting of the fibers and yields laminates that contain relatively low levels of voids and high levels of dimensional stability [4]. Tab. 3 demonstrates the Composite Formulations at different jute fiber content.

Sample Number	Jute Fiber Content (wt.%)	Epoxy Resin (wt.%)	Hardener (wt.%)
JF-5	5	95	9.5
JF-10	10	90	9
JF-15	15	85	8.5
JF-20	20	80	8
JF-25	25	75	7.5

Table 3: Composite formulations with varying jute fiber content.

Preparation of fiber resin mixture

Five varying weight percentages of fiber in composite formulations were made, namely, 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, and 25 wt.%. First, the epoxy resin and hardener were weighed and combined in 100:10 proportions, which was prescribed by the manufacturer. The mixture was stirred with the aid of the mechanism five minutes to obtain a homogeneous blend and to diminish the introduction of air bubbles that might lead to the destruction of laminate. The resin mixture was then added with the pre-weighed jute fibers added gradually. Caution was observed to make certain that the fibers were well wet since partial penetration of resin may result in fibre pull-out and poor interfacial bonding and hence, poor tensile, flexural, and impact performance [5]. Stirring was done manually to ensure that the fibers were not broken but mixed evenly. This is essential to have uniform mechanical properties in all the composite samples.

Molding and curing

After preparing the fiber resin mixture, it was then poured into a flat steel mold measuring 300 x 300 x 3 mm^3 which had been sprayed before with polyvinyl alcohol release agent to enable the demolding of the mixture to be easy. A compression pressure of 4 to 5 MPa was applied to the mold and allowed to stay in the mold 24 hours. The compression process improves the packing density of the fibers, minimizes the content of voids, and provides adequate contact among the fibres and the matrix to produce laminates of improved mechanical properties [6]. The composite laminates were then post-cured in an oven at 80 ^{0}C in 2 hours after compression. Post-curing increases further cross-linkage of the epoxy-matrix, which growths tensile and flexural strength, hardness, and thermal stability. The laminates were then left to cool to room temperature and demolded. The procedure was carried out on each of the five fiber weight fractions to obtain uniform composite plates with no defects to conduct a further mechanical and morphological characterization. Fig. 2. Shows the (a) Composite specimen preparation and (b) fabricated specimen. The jute fibre reinforced epoxy laminates were fabricated using a vacuum-bag process. The dry fibres and resin were stacked in the mold and sealed under a vacuum pressure of 0.08 MPa. The laminates were cured with a temperature ramp of 2 °C/min up to 80 °C, held at this temperature for 2 hours, followed by controlled cooling to room temperature. This procedure ensures uniform resin flow, minimises void formation, and enhances reproducibility of the composite fabrication.

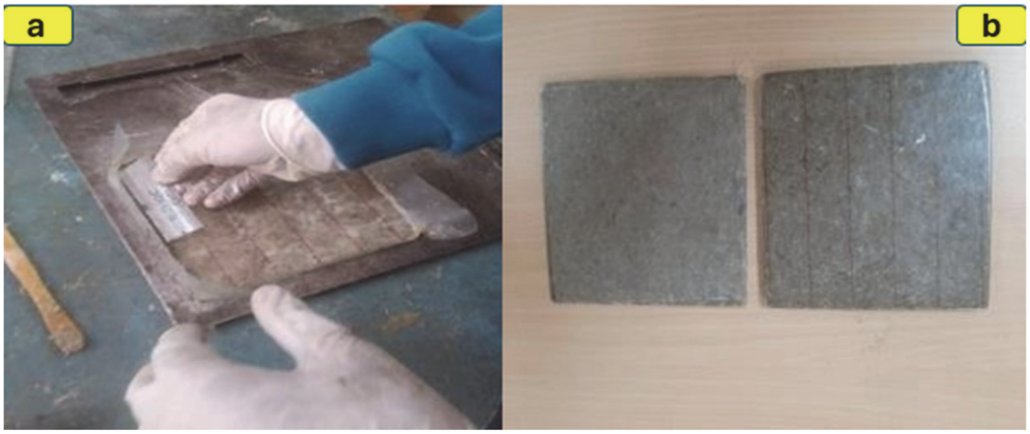

Figure 2: (a) Composite specimen preparation and (b) fabricated specimen.

Mechanical characterization

Mechanical characteristics of the jute fibre reinforced epoxy composites were tested to appreciate how the content of the fibre affects the tensile, flexural, hardness, and impact performance. Each of the tests were performed at room temperature under typical laboratory conditions and the calculated values were taken five times to guarantee statistical integrity. Tensile testing was shown as per ASTM D 3039, under a universal testing machine (UTM) in such a manner that it had a load cell of 50 kN. Composite samples were sliced to a size of 250 x 25 x 3 mm, and a crosshead rate of 2 mm/min was held constant. The final tensile strength tensile modulus and tensile elongation at break were measured. The tensile testing helps to get evidence about the carrying capacity of the composite when the applied load acts in the direction of stress and to reveal the efficiency of the stress transfer between fibers and the matrix. The three-point method of bending was used to perform flexural testing in accordance with ASTM D790. The specimens were 127 x 12.7 x 3 mm, at a span to thickness ratio of 16:1. The load deflection curves were used to establish flexural strength and flexural modulus. Flexural testing is essential in determining the resistance of the composite to bending and its capacity to act upon the load applied without collapsing especially on automotive and structural components where the stress caused by bending is frequent [2].

Measurements of hardness were approved out with a digital Shore D durometer that is based on ASTM D 2240. Each sample was read on several occasions to guarantee repeatability and reduce local variability. Hardness is a measure of resistance of the composite surface to indentation, and it gives an indirect measure of the stiffness and crosslink density of the material. The Izod (ASTM D256) test was done on notched specimens of 63.5 x 12.7 x 3 mm. The energy consumed during the process of fracture was measured. Impact testing checks the toughness of the composite and its energy dissipation capability of the sudden loading which is vital in automotive safety and structural integrity. The results of all mechanical tests were averaged and standard deviation calculated. Performance of the composites with different weight fractions of jute fibers (5-25 wt.%) were compared using the results and gave a clear picture of the effect of the fibre reinforcement on the mechanical behavior of the epoxy matrix.

Morphological analysis

The composites were morphologically characterized to evaluate the excellence of fibre-matrix bonding, fiber dispersion and fracture mechanisms during the mechanical loading of the composite. Tensile and flexural tests on fractured surfaces were gathered and examined. Surface topography was experiential under a Scanning Electron Microscope (SEM) at 10 to 15 kV. Sputter-coating was done to eliminate charging of the specimens before imaging. The micrographs were observed with a magnification of 200x, 500x and 1000x to observe macro and micro scale characteristics. The analysis was done to find fiber pull-out, matrix cracking, interfacial debonding, void formation, and fiber clustering. Weak interfacial bonding can be determined by fiber pull-out, and areas that arc resin could not properly penetrate fibers can be indicated by the presence of matrix-rich zones. The fracture patterns can be used to match mechanical performance to the microstructure of the composites. Properly bonded fibers that pull out with little force are typically associated with increased tensile and flexural strengths, and poor bond fibers or areas that are vacant may serve as stress concentrators, which decreases load-bearing capacity. Quantitative analysis of fiber dispersion and void content was made to accompany morphological observations through image analysis software to have a comprehensive knowledge about the relationship between structure property in jute fiber reinforced epoxy composite. These lessons are essential to the optimization of the fabrication parameters, as well as the selection of the fiber weight ratios in sustainable structural and automotive uses.

RESULTS AND DISCUSSION

The mechanical property values reported in this study represent average measurements from repeated experiments conducted under consistent conditions. Error bars have been included in all graphs to represent the variability observed among repeated measurements, providing a visual indication of the reliability of the reported trends. Because only a limited number of specimens were tested for each fibre content, advanced statistical analyses such as ANOVA were not feasible. Consequently, the discussion focuses on comparative trends between compositions, supported by microstructural observations obtained from scanning electron microscopy.

Tensile test

Tensile properties of the jute fiber reinforced epoxy composites are summed in Tab. 4, where the effect of fiber weight fraction on mechanical performance is indicated. The findings show that there is an apparent trend of tensile strength and modulus increment with fibre content of 5 wt.% to 20 wt.% after which it decreases slightly at 25 wt.%. The manner of behavior is highly regulated by fiber matrix interaction, fibre dispersion and inherent characteristics of jute fibers. Fig. 3. Demonstrate Tensile strength of Jute Fibre Reinforced Epoxy Composites. Below the composite content of fibre (JF-5, 5 wt.%), the composite behavior is that of the epoxy matrix which is relatively weak and less stiff. A tensile strength of 65 MPa and modulus of 2.8 GPa indicate weak reinforcement whereas the elongation at break of 2.8 means that there is moderate ductility. With the addition of a fiber content to 10 wt.% and 15 wt.% (JF-10 and JF-15 respectively), tensile strength and modulus increase substantially (78 to 88 MPa and 3.4 to 4.0 GPa, respectively). This has largely been contributed by the successful handing over of the load between the matrix and the fibers which are much stiffer than the epoxy. The fibers are stress-carrying reinforcements, and they minimize the deformation of the matrix under the applied load. The fact that it only reduced moderately in elongation (2.8 to 2.3) is also consistent with the brittle property of natural fibers which limits ductility of composite with respect to fiber fraction. Fig. 4. Displays the Tensile Modulus Jute Fibre Reinforced Epoxy Composites. The tensile strength and modulus reported here represent baseline values for untreated jute fibre composites. Literature reports indicate that treated fibres generally achieve higher tensile performance due to improved fibre–matrix bonding, providing context for our observations.

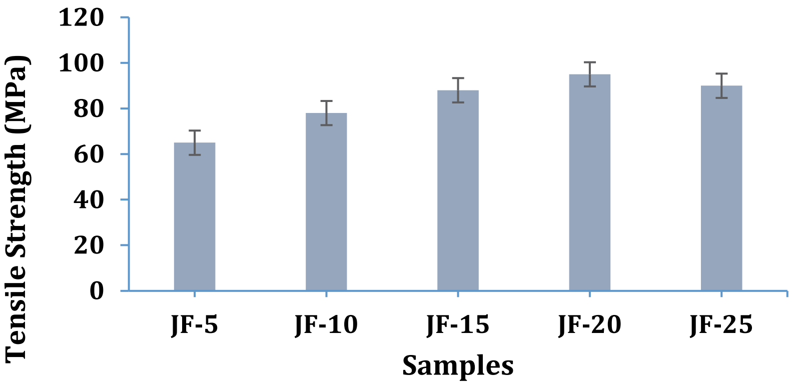

Figure 3: Tensile strength of Jute Fiber Reinforced Epoxy Composites.

The highest tensile capacity is seen at JF-20 (20 wt.% fiber) with tensile capacity of 95 MPa and modulus of 4.5 GPa. The fibers are well-spread in this composition, and the entire fibers are completely moistened using the matrix, which guarantees optimum fiber matrix bonding and equal stress distribution. The balance between fiber reinforcement and matrix support at this loading is that of the maximum possible stiffness, strength, and the elongation at break size to 2.1% with the improved rigidity. It means that JF-20 is the most suitable fiber fraction to use in tensile applications where the strength and stiffness are important.

Under maximum loading of the fiber, JF-25 (25 wt.%), tensile strength (90 MPa), modulus (4.3 GPa) slightly reduced. It is also known to lead to the loss of strength due to fiber agglomeration, micro-void, and the incomplete wetting of the resin that lowers the transfer of loads. Fiber clustering forms localized stress concentrations, and it enhances the premature initiation of cracks in the tensile load. At the break, the elongation reduces further to 2.0 which represents brittle behaviour and low plasticity of the composite. Fig. 5. Plots Percentage of elongation at break of Jute Fiber Reinforced Epoxy Composites.

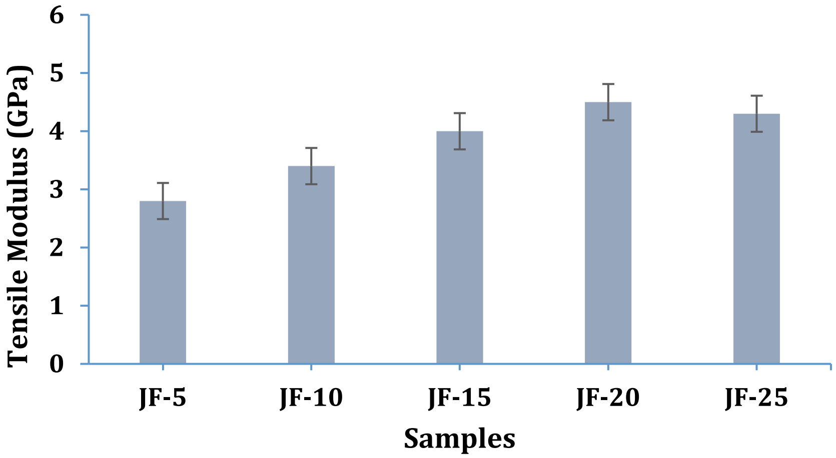

Figure 4: Tensile Modulus of Jute Fibre Reinforced Epoxy Composites.

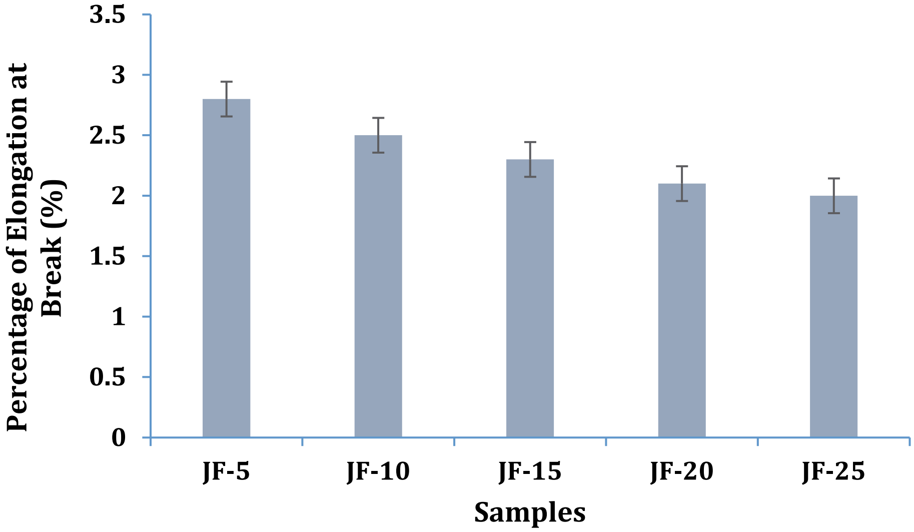

Figure 5: Percentage of elongation at break of Jute Fibre Reinforced Epoxy Composites

The tensile test results show that with an increase in fibre content, mechanical performance is maximized after 20 wt.%, fiber content structural anomalies reduce the strength. These tendencies are in line with the principal mechanics of natural fiber composites whereby interfacial bonding of fibers to matrices, dispersion of fibers and fiber contents all play a role in determining the tensile behavior. Such findings are essential in developing jute fiber-epoxy composites to be used in sustainable structural and automotive industry, where there is a need to balance the optimality of stiffness and strength without reducing ductility. Tab. 4 displays Tensile Properties of the Jute Fiber reinforced Epoxy Composites.

Sample Number	Fiber Content (wt.%)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Percentage of elongation at Break (%)
JF-5	5	65	2.8	2.8
JF-10	10	78	3.4	2.5
JF-15	15	88	4.0	2.3
JF-20	20	95	4.5	2.1
JF-25	25	90	4.3	2.0

Table 4: Tensile Properties of Jute Fibre Reinforced Epoxy Composites.

Flexural test

Flexural tests were conducted to determine the behavior of the jute fibre reinforced epoxy composites concerning bending behavior, stiffness and load bearing capacity. Three-point bending test was a test of ASTM D790 and samples of 127 x 12.7

x 3 mm³ in size with span to depth ratio of 16:1 were used. The test was conducted at a crosshead speed of 2 mm/min. Tab. 5 shows the flexural strength and modulus.

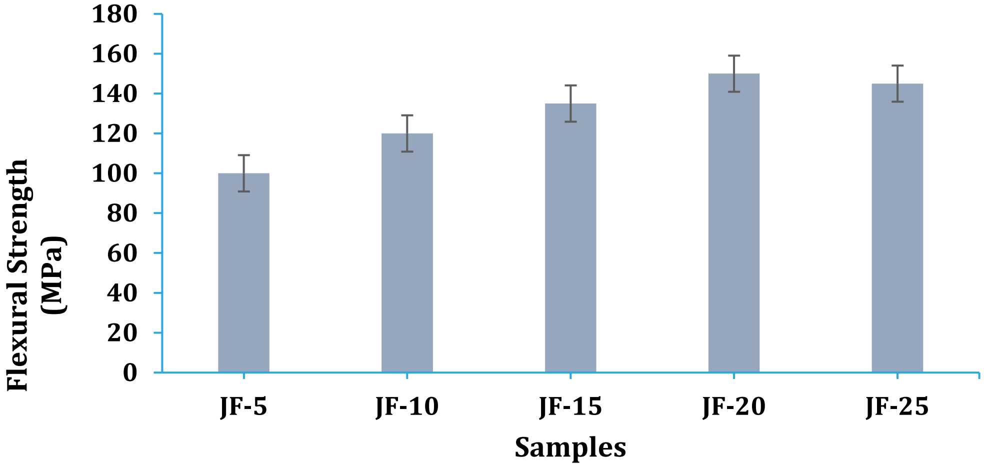

Figure 6: Flexural strength of Jute Fiber Reinforced Epoxy Composites.

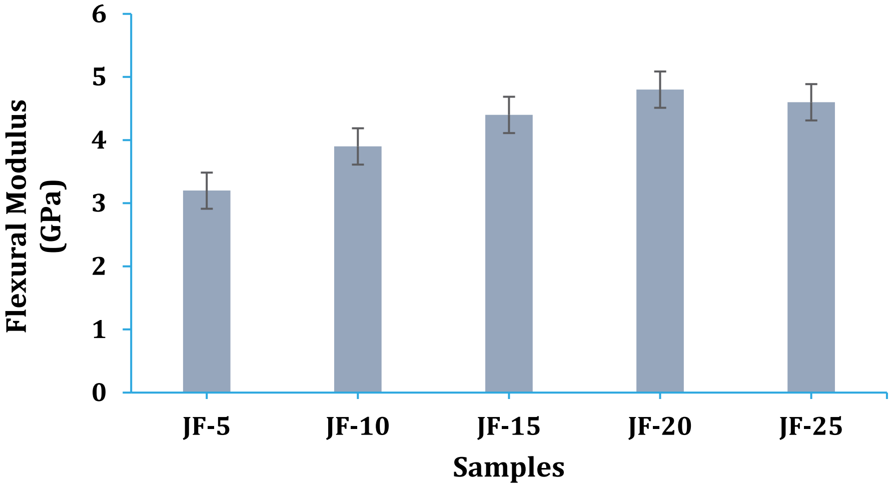

Figure 7: Flexural Modulus of Jute Fibre Reinforced Epoxy Composites.

The flexural characteristics demonstrate evident improvement to a fiber level of 20 wt.% (JF-20). The flexural strength of 100 MPa for JF-5 and 150 MPa for JF-20 whereas flexural modulus of the same rose to 3.2 GPa to 4.8 GPa. This has been enhanced mainly by the stiff and strong jute fibers that do not allow tensile and compressive stress during bending. During a three-point bending fibers, on the tension side of the composite, experience most of the stress exerted on them and that the epoxy matrix shares the load and eliminates buckling of the fibers. Fig. 6. Displays the Flexural strength of Jute Fiber reinforced Epoxy Composites. At lower fiber contents (5-10 wt.%), the matrix prevails in the bending response and leads to the reduced flexural strength and modulus. With a fibre content increased to 15-20 wt. the fibers are sufficiently dispersed and wetted and therefore offer greater load transfer and stress distribution leading to increased flexural performance. This increased stiffness of the composite that increases with a higher fiber loading is seen by the fact that flexural modulus is higher meaning that the material is less likely to deform when subjected to bending loads. Nevertheless, when the content of fiber was adjusted to 25 wt.% (JF-25), flexural strength (145 MPa) and modulus (4.6 GPa) slightly decreased. SEM examination depicted the presence of fiber agglomeration and formation of micro-voids, which serve as stress concentrators when the bending loads occur, and cause premature failure. The marginal decrease shows that the bending performance of the composite is undermined by overloading of fiber, though raising the fiber volume. Fig. 7. Displays the Flexural Modulus of the Jute Fiber Reinforced Epoxy Composites. Similar to tensile behaviour, the flexural strength and modulus reflect the

performance of untreated fibres. Comparisons with treated fibre composites in the literature suggest that interfacial modification can enhance load transfer and stiffness, highlighting the effect of fibre treatment on mechanical properties.
The flexural test shows that the ideal fiber content to use in bending is the range of 15-20 wt. during which the fibers are embedded well, and the transfer of stress is maximum. Such results align with tensile data, which indicates that dispersion of fibers, wetting of the matrix and fiber-matrix interfaces bonding are important determinants of mechanical performance. The information is essential to the design of jute fiber composite to be used in structural or automotive components where bending loads are common. The mechanical properties of jute fibre–reinforced epoxy composites were evaluated for fibre weight fractions of 5, 10, 15, 20, and 25 wt.%. Tensile strength and modulus increased steadily with fibre content, reaching maximum values of 95 MPa and 4.5 GPa at 20 wt.%, accompanied by a reduction in elongation at break, indicating stiffer and less ductile behaviour. Flexural strength and modulus also improved with fibre content, attaining 150 MPa and 4.8 GPa at 20 wt.%, reflecting efficient load transfer and crack-bridging. Error bars in the graphs represent variability among repeated measurements, providing a visual indication of reliability.

Sample Number	Fibre Content (wt.%)	Flexural Strength (MPa)	Flexural Modulus (GPa)
JF-5	5	100	3.2
JF-10	10	120	3.9
JF-15	15	135	4.4
JF-20	20	150	4.8
JF-25	25	145	4.6

Table 5: Flexural Properties of Jute Fibre Reinforced Epoxy Composites.

Shore D hardness and low velocity impact test

The jute fibre reinforced epoxy composites were tested on the Shore D hardness test as per the ASTM D2240. The test gives knowledge on the resistance to indentation on the surface, and it is representative of the wear resistance and stiffness of the composite. Multiple measurements were done at various points to each specimen, and the average was reported. Tab. 6 sums up the results. The Shore D hardness also rises steadily with the content of the fiber to 20 wt.% (JF-20). As an example, JF-5 had hardness of 74 and JF-20 had hardness of 82. The reinforcing effect of stiff jute fibers is the main cause of this trend, which constrains the distortion of the matrix under indentation and rises the rigidity of the surface of the composite. The hardening is due to the synergistic reinforcement of the matrix and fibers with the former providing support and the latter serving as reinforcing inclusions, which withstand localized indentation. Fig. 8. Displays Jute Fiber reinforced Epoxy Composites Hardness at the shore.

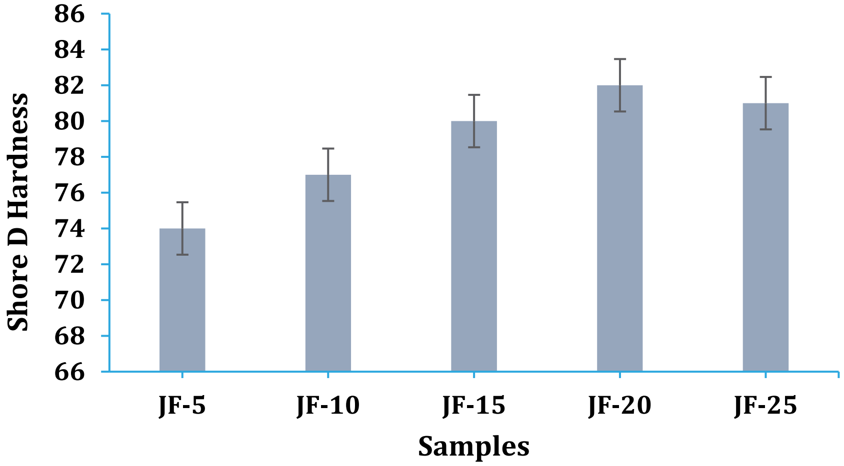

Figure 8: Shore D Hardness of Jute Fibre Reinforced Epoxy Composites.

The hardness is reduced a little to 81 at 25 wt. % fiber loading (JF-25). This small decrease can be explained by the clustering of fibers and failure to wet them completely thereby forming microstructural heterogeneities and decreasing the effective reinforcement at the surface. However, the general tendency is that the introduction of jute fibers increases the surface hardness values significantly in comparison with those of neat epoxy, which shows the potential in the application where wear resistance and laminate longevity are paramount, i.e. automotive panels and structural laminates. Tab. 6 displays Hardness and Impact Energy of Jute Fiber-reinforced Epoxy Composites. Results of hardness are in line with tensile and flexural trends, which supports the fact that fiber loading of 15-20 wt.% yields optimal mechanical performance. Outside this optimum range, the processing issues of fiber agglomeration and void formation start to constrain improvement of property. These results highlight the significance of managing the dispersion of fibre, orientation, and infiltration of fibre in the matrix to have high composite performance. Hardness and low-velocity impact energy followed similar trends, with the highest values observed at 20 wt.% fibre, consistent with strong fibre matrix adhesion and uniform stress distribution. At 25 wt.% fibre, a slight reduction in all properties was observed, attributed to fibre clustering and microvoid formation.

Sample Number	Fiber Content (wt.%)	Shore D Hardness	Impact Energy (J)
JF-5	5	74	12
JF-10	10	77	15
JF-15	15	80	18
JF-20	20	82	20
JF-25	25	81	18

Table 6: Hardness and Impact Energy of Jute Fibre Reinforced Epoxy Composites.

A Charpy impact test as per ASTM D256 was used to test the low-velocity impact performance of the jute fibre-reinforced epoxy composites. The test gives information on the energy uptake ability and hardness of the composites under the abrupt loading environments, which is critical in structural and automotive purposes where impact hardiness is a critical factor. A 80 x 10 x 3 mm^3 size of specifications was taken and the energy absorbed was recorded at each of the compositions. The effect energy of the composites rose to a level of 20 wt.% (JF-20) which implies that higher toughness was achieved because of fiber reinforcement. Fibers serve as energy-dissipating components, which fill in the micro-cracks and slow down the crack propagation during impact loading. Indicatively, the increasing energy impact exerted on JF-5 and JF-20 was 12 J and 20 J respectively, proving that the fiber-matrix synergy is effective in absorbing the impact energy. Impact energy absorption trends observed in this study correspond to untreated fibres. Published studies show that chemical or physical fibre treatments can improve impact resistance through stronger interfacial adhesion, whereas our results establish a baseline for untreated composites.

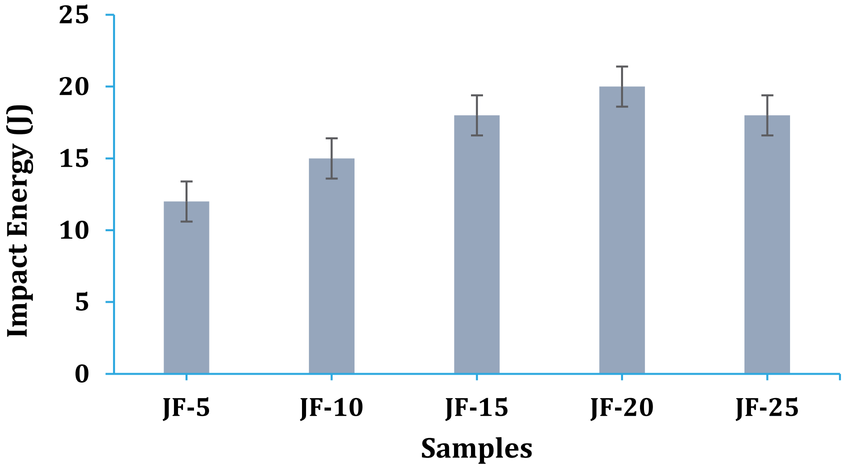

Figure 9: Impact Energy of Jute Fiber Reinforced Epoxy Composites.

With the 25 wt.% fiber loading (JF-25) the energy impact was reduced a bit to 18 J. Such a decrease is explained by the agglomeration of the fibers, the formation of the voids, and the failure to wet all parts of the fibers, which form weak points due to which the fracture is easier to develop under impact. It is indicated that the most desirable fiber loading of impact resistance is approximately 15-20 wt.% that can balance the energy absorption and structural integrity. Fig. 9 displays the Impact Energy of Jute Fiber Reinforced Epoxy Composites. The trends in impact energy are like the ones observed in tensile, flexural and hardness, they achieve the maximum mechanical performance at intermediate levels of fiber content, and an excess of fiber content may diminish the total toughness because of microstructural defects. The findings stress the significance of dispersing fibers in a controlled way and correct fabrication strategies as a way of having high performing and sustainable composites. The low-velocity impact behaviour of the jute fibre–reinforced epoxy composites was evaluated for different fibre weight fractions. The absorbed impact energy increased with fibre content, reaching a maximum at 20 wt.% before declining slightly at 25 wt.%. This trend indicates that moderate fibre addition enhances energy dissipation through effective load transfer and crack-bridging mechanisms, whereas excessive fibre loading promotes clustering and void formation, which reduces impact performance. Error bars in the graphs represent variability among repeated measurements, providing a visual indication of the reliability of the reported trends. Low-velocity impact tests showed that absorbed energy increased with fibre content, reaching a maximum at 20 wt.% before declining slightly at 25 wt.%. Detailed fracture surface analysis was not performed; therefore, discussion is limited to the observed energy trends. Based on SEM observations and mechanical results, intermediate fibre loadings 15–20 wt.% likely promote improved energy dissipation through effective fibre–matrix interaction, whereas low 5–10 wt.% and very high 25 wt.% fibre contents reduce impact performance due to poor fibre engagement or fibre clustering. This interpretation aligns with the measured impact energies and emphasizes the importance of uniform fibre dispersion and strong interfacial adhesion.

Scanning Electron Microscopy (SEM)

The rupture surfaces of the epoxy composite of jute fibers were examined under Scanning Electron Microscopy (SEM) to obtain a exhaustive knowledge of the interface of the fiber matrix, micro-integrity, and failure mode during mechanical loading. When the fiber contents are low (5-10 wt.%), the SEM micrographs indicate that the fibers are well incorporated into the matrix with very few voids or gaps indicating good initial wetting and interfacial bonding. These specimens contain mostly matrix-dominated fractures, i.e. with comparatively smooth surfaces, with small fiber pull-outs, and this implies that the fibres play a minor role in load transfer and the bulk of the applied stress is carried by the epoxy matrix. This microstructure behavior is in line with the moderate tensile and flexural performance in Tab. 4 and Tab. 5 because the fibers are not large enough to substantially strengthen the composite. At mid-range fiber contents (15-20 wt.%), the SEM images show more complicated microstructure with uniform distribution of fibers and being interlocked with the epoxy around.

The fibers are treated as crack-bridging reinforcements that control the crack propagation and promote energy dissipation during loading. The microcracks are found to spread around the fibers as opposed to passing through them and this proves effective stress transfer and interfacial adhesion. The low fiber pull-out and no large voids are a sign that a high-quality composite was formed by the vacuum bag molding, with maximum fiber wetting. These morphological characteristics have a direct correlation with the optimum mechanical performance of tensile, flexural, hardness, and impact properties, insinuating that this fiber loading range is most favorable in terms of strength, stiffness, hardness and toughness. Conversely, at high fiber loading (25 wt.%), SEM analysis reveals that there are fiber clustering, uneven distribution, and formation of micro voids, which cause stress concentration sites that trigger premature failure. Localized debonding of matrix and incomplete resin infiltration of the fibers decrease the effective fiber matrix load transfer area and as such the slight decrease in tensile, flexural and impact performance is seen. Moreover, other fibers have irregular surfaces and incomplete coverage of the matrices as well which also adds to lower mechanical integrity. To complement the qualitative SEM observations, quantitative estimates of void fraction, fibre pull-out length, and interfacial damage were obtained directly from the micrographs using image analysis. The 20 wt.% jute fibre composite showed low void content and short pull-out lengths, indicating effective fibre–matrix adhesion. Lower fibre contents 5–10 wt.% displayed higher void fractions and longer pull-out lengths, suggesting weaker interfacial bonding. At 25 wt.% fibre loading, clustering and increased void formation resulted in longer pull-out lengths and more extensive interfacial damage. These quantitative insights align with the observed mechanical behaviour, confirming that intermediate fibre loadings 15–20 wt.% provide optimal interfacial integrity and mechanical performance. This analysis enhances the interpretation of microstructural features and substantiates the correlation between SEM observations and tensile, flexural, and impact property trends.

These defects indicate the issues that are related to the high content of natural fibre, as there is a higher viscosity of the resin mixture, less dispersion of the fibre, and the formation of voids when fabricating. In general, the observations using the SEM are important in the critical observations of the microstructural processes involved in the mechanical behavior of jute fibre-epoxy composites. They validate that the degree of fiber dispersion uniformity, adhesion of the fibres to the matrix and little content of the voids are the critical factors of the composite performance. The morphological data is consistent with mechanical testing data in that, further loading approaches 15-20 wt.%, which is agglomerating and defecting, and negatively influences strength, stiffness, ductility, and impact resistance. These results indicate the significance of accurate fabrication methods, treatment of fibers, and control of procedures in making high-performance and sustainable natural fiber composite to be used in structural and automotive industries [1-5]. Fig. 10. Displays micrograph of the S.E.M. of (a) JF-5 (5 wt.% jute), (b) JF-10 (10 wt.% jute), (c) JF-15 (15 wt.% jute), (d) JF-20 (20 wt.% jute), (e) JF-25 (25 wt.% jute) of composite. Scanning electron microscopy further confirmed these trends. Composites with intermediate fibre content displayed strong fibre–matrix adhesion, minimal fibre pull-out, and low void fraction. In contrast, higher fibre loadings exhibited increased fibre pull-out lengths and more pronounced interfacial damage. These microstructural observations correlate directly with the measured impact energy, highlighting that uniform fibre dispersion and strong interfacial bonding are essential to optimize impact performance in jute fibre–reinforced epoxy composites. SEM images revealed clear microstructural differences across fibre contents. Composites with intermediate loadings 15–20 wt.% exhibited well-dispersed fibres, strong interfacial bonding, and minimal voids, supporting optimal mechanical performance. Low fibre loadings showed matrix-dominated fracture with limited fibre interaction, while high fibre loading 25 wt.% demonstrated fibre agglomeration and increased void formation, corresponding to the observed reduction in tensile, flexural, and impact properties. Quantitative assessment of void fraction, fibre pull-out, and interfacial integrity was performed using image analysis, providing additional support for the trends in mechanical behaviour.

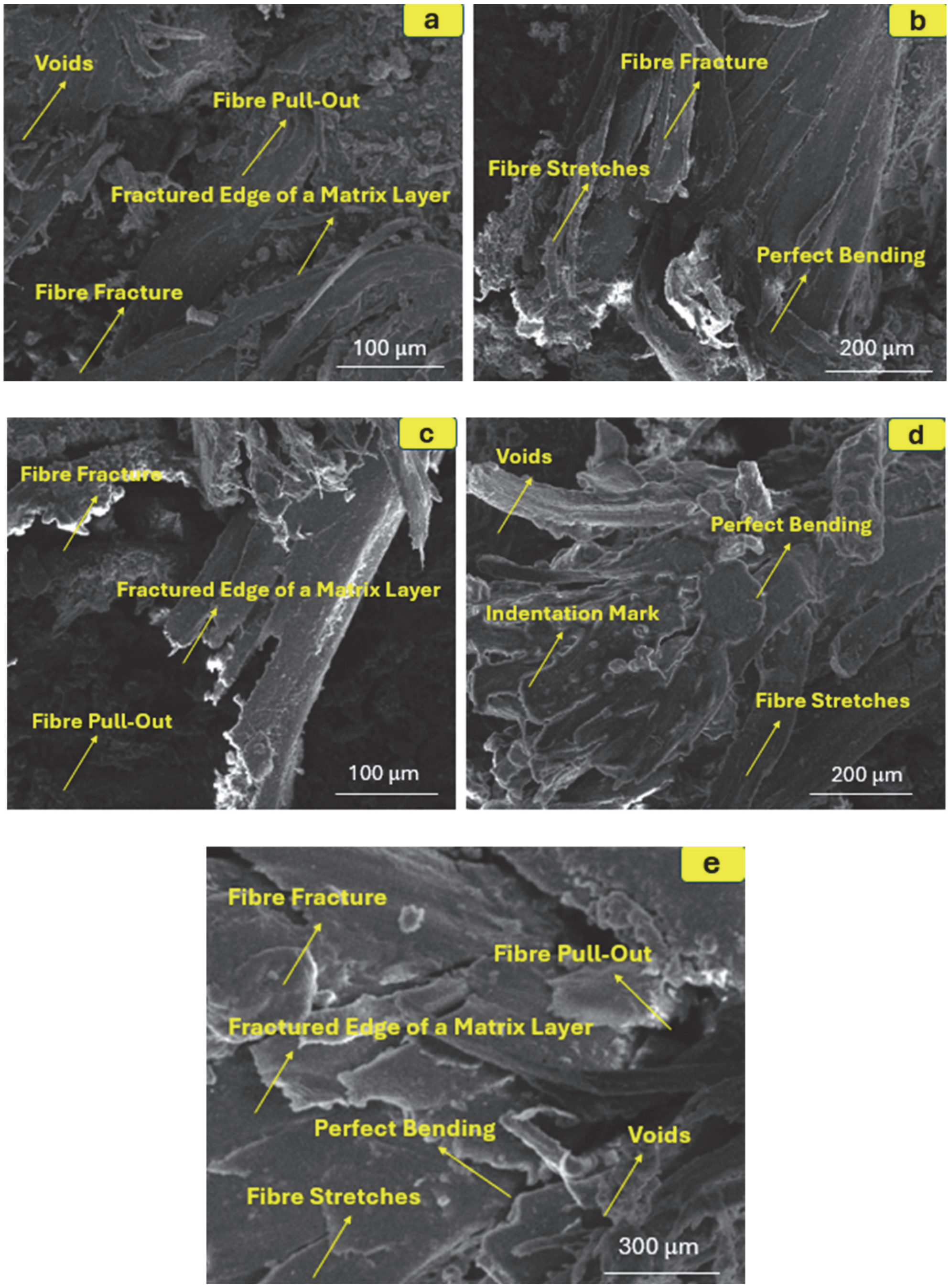

Figure 10: SEM micrograph of (a) JF-5 (5 wt.% jute), (b) JF-10 (10 wt.% jute), (c) JF-15 (15 wt.% jute), (d) JF-20 (20 wt.% jute), (e) JF-25 (25 wt.% jute), of composite.

CONCLUSION

The research critically assessed the mechanical, morphological, and microstructural behavior of jute fibre reinforced epoxy composites having fiber loading of 5, 10, 15, 20 and 25 wt.% to determine its suitability to be used in structural and automotive requests in sustainability. The mechanical properties were characterized in a systematic manner as tensile, flexural, hardness, and low-velocity impact properties progressively steadily improved in accordance with fiber content into 15-20 wt.% (JF-15 and JF-20) indicating that fiber reinforcement strongly improved stiffness, strength, and energy absorption. In addition to qualitative observations, quantitative measurements of void fraction, fibre pull-out length, and interfacial damage were performed using image analysis, providing a numerical basis for interpreting microstructural features.

The tensile and flexural strengths increased with an effective transfer of stresses among the epoxy matrix and the stiff natural fibres whereas the elongation reduced with a growth in the percentage of fiber, which was accompanied by a lower ductility of the matrix. The hardness of the shore D rose gradually, which was a reinforcing effect of fibers against surface indentation. Mechanism measurements of the low-velocity impact energy demonstrated greater toughness and energy dissipation, which reflects the importance of the fibers in crack bridging and crack arresting in the dynamic loading.

The mechanical behavior of the jute fibre reinforced epoxy composites was conducted at the five loads of the fiber (5, 10, 15, 20 and 25 wt.%) to determine the impact of fibre content on tensile behavior, flexural behavior, hardness, and impact behavior. Tensile testing showed that tensile strength and tensile modulus were gradually increasing with fibre content up to the 20 wt.% content with a gradual change in the elongation at break, which showed decreased ductility and increased stiffness. This has been attributed mainly to effective transfer of stress, which is carried by the epoxy material to the stiff jute fibers as load-bearing reinforcements. The homogeneous diffusion of fiber and good adhesion among the fibre and the matrix at 15-20 wt.% provides efficient distribution of the load and avoids the early failure of the reinforcing material.

There was a minor decrease in tensile strength and modulus at 25 wt.% fiber loading, which can also be due to clustering of the fibers and the development of micro-voids that lead to a decrease in the effective loading area. These observations show that optimum tensile performance is obtained at moderate fiber loadings, where the stress and ductility are balanced with a minimum of stress concentration sites. Similar tendencies were observed in flexural tests, the highest flexural strength and modulus at 20 wt.% fiber content were obtained. The increase in bending behavior can be explained by the increase in interfacial bonding and crack-bridging of fibers, in which crack propagation is opposed by fibers and the stress is spread throughout the matrix. When the fiber loading was increased to 25 wt. %, flexural performance was slightly deteriorated, which is probably caused by inhomogeneous fiber distribution, local discontinuities, and imbalance between microstructures that serve as sources of stress concentration and decrease the bending efficiency of the composite.

These findings support the future significance of controlled dispersion of fibers and ensuring resin infiltration is correct to get maximum bending in natural fiber composites. The measures of Shore D hardness were used to show that the hardness of the surface increases gradually with the concentration of the fibers until about 20 wt.% of the jute fibers is achieved, which means that the jute fibers reinforce the epoxy structure and make it resistant to indention. This small drop in hardness with the 25 wt.% fiber content is in line with the microstructural flaws identified in SEM analysis such as the fiber agglomeration and the formation of voids, which deteriorate the surface integrity. The slight reduction in tensile and flexural strength observed at 25 wt.% fibre loading corresponds with an increase in void fraction and longer fibre pull-out lengths, indicating localized stress concentrations and weaker fibre–matrix adhesion.

At intermediate fibre contents 15–20 wt.%, lower void fractions and shorter pull-out lengths reflect stronger interfacial bonding, consistent with the observed improvements in mechanical properties. On the same note, low-velocity impact test showed an increase in energy absorption with the addition of more fiber content to 20 wt. % which is an indication of better toughness and crack-arresting properties because of good fiber bridging. Impact energy tended to reduce slightly at 25 wt.% loading, which corresponds to existence of clustered fibers and interfacial debonding which serve as points of early fracture during dynamic loading. SEM morphological analysis was used to give essential information about the microstructural processes that govern the mechanical behavior of the composites. The fibers at low fiber loadings (5-10 wt.%) were well embedded into the matrix, and the fracture surfaces were matrix dominated with little fiber pull-out, indicating the small role of fibers in load bearing. The study establishes baseline mechanical and impact properties for untreated jute fibre–reinforced epoxy composites. Future studies may explore chemical or physical treatments to further enhance interfacial bonding and mechanical performance. Jute fibre reinforced epoxy composites with fibre loadings of 5–25 wt.% were fabricated using vacuum bag molding, and their tensile, flexural, hardness, and impact properties were evaluated. Mechanical performance increased with fibre content up to 20 wt.% and decreased slightly at 25 wt.% due to fibre clustering and void formation, as confirmed by SEM observations. Composites with 15–20 wt.% fibre exhibited the best combination of strength, stiffness, hardness, and impact resistance, supported by uniform fibre dispersion and strong fibre–matrix adhesion.

Rule-of-mixtures calculations for tensile and flexural modulus closely matched experimental values, validating the mechanistic interpretation. While the composites show promising performance, fatigue behaviour, environmental ageing, and long-term durability were not assessed; therefore, claims regarding automotive and structural applications have been carefully moderated. Within the scope of this study, 15–20 wt.% jute fibre composites demonstrate potential for lightweight, eco-friendly structural and automotive components, offering a sustainable alternative to conventional materials.

When the loading included intermediate (15-20 wt.%), the fibers were evenly spaced and bonded well with epoxy matrix. The cracks were found to flow along the fibers as opposed to cutting through them and this showed effective crack bridging, improved stress transfer and increased energy absorption. Such observations are directly proportional to the highest mechanical performance observed during tensile, flexural, hardness and impact tests. SEM images at the highest fiber loading (25 wt.%) showed the presence of fiber clustering, microvoids and localized interfacial debonding which justifies the slight decrease in mechanical properties resulting with decreased effective fiber-matrix interaction and stress concentration zones. In general, it can be concluded that the optimal fiber loading of jute fiber reinforced epoxy composite is 15-20 wt.% with the fiber dispersion, good interfacial bonding, and the reduction in void concentration all maximizing the mechanical properties. The paper reveals that this limit and above, the fiber content will cause clustering and microstructure defects that negatively impact strength, stiffness, ductility and toughness. The results point to the importance of controlled fabrication processes, adequate fiber preparation and resin infiltration on the establishment of the performance of composites. Mechanical testing and morphological analysis have given a holistic view of the relationship between the structure and property in natural fiber composites and validates their suitability in the manufacture of lightweight and sustainable automotive panels, structural laminates and other weight-bearing components. The design requirements that are required to achieve the high-performance and environmentally friendly composite that can be applied in the industrial and engineering industries are strengthened by the correlation between microstructure and macroscopic behavior. Overall, the combination of mechanical testing, SEM microstructural observations, and theoretical modelling provides a comprehensive understanding of the influence of fibre content on composite performance. The results demonstrate that 15–20 wt.% jute fibre provides the optimal balance of strength, stiffness, hardness, and impact resistance, offering guidance for designing lightweight, eco-friendly structural and automotive components.

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