

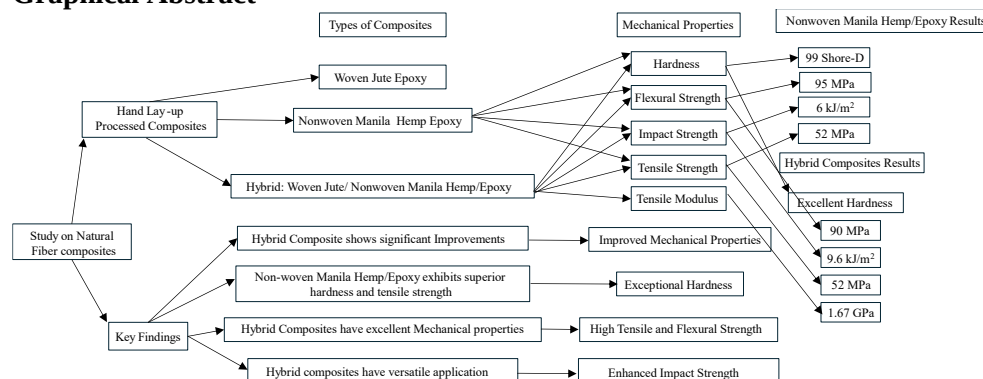
Mechanical and Morphological Analysis of Jute/Manila Hemp Hybrid Composites for Enhanced Structural Performance

Mukesh Kumar NAG^{1,*}, Parmanand Kumar²

Abstract

Natural fiber composites are renowned for their lightweight, strength, corrosion resistance, and high strength-to-weight ratio, often surpassing traditional metals. Despite challenges such as poor fiber-matrix adhesion and moisture susceptibility, hybridizing composites present a viable solution by enabling tailored properties for optimal performance. This study investigates hand-lay-up processed natural fiber composites, specifically woven jute/epoxy, non-woven manila hemp/epoxy, and their hybrid variants. Extensive testing was conducted on mechanical properties including hardness, flexural strength, impact strength, and tensile strength. The non-woven manila hemp/epoxy composite exhibited superior hardness (99 Shore-D) and tensile strength of 52 MPa. It also demonstrated exceptional flexural strength (95 MPa), although it had a lower impact strength (6 kJ/m²). Hybrid composites showed significant improvements over conventional ones. The woven jute/non-woven manila hemp/epoxy hybrid composite displayed excellent mechanical properties, with a maximum tensile strength of 52 MPa, a tensile modulus of 1.67 GPa, an impact strength of 9.6 kJ/m², and a flexural strength of 90 MPa. These findings highlight the exceptional performance and versatile applications of composite materials, particularly those incorporating woven jute and non-woven manila hemp natural fibers.

Graphical Abstract



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Keywords: Natural Fibers, Hybridization, Ecofriendly, lightweight, Fractures Surface, Mechanical Properties, Scanning Electron Microscope (SEM).

INTRODUCTION

There is a growing trend towards using natural fibers in polymer bio-composites to combat non-biodegradable synthetic waste, particularly in response to the pervasive problem of plastic pollution. This shift reflects a pressing need to find sustainable alternatives and reduce the

environmental impact of plastic waste [1–3]. Various studies contribute to the advancement of materials science by investigating innovative approaches to improve the performance and sustainability of engineered materials [4, 5]. Natural fibers, driven by increasing environmental consciousness, are emerging as robust alternatives to synthetic fibers like glass, carbon, and metals [6, 7]. Their unique molecular structure and low density characteristics contribute to outstanding acoustic and thermal insulation properties. These behaviors collectively enhance our comprehension of composite material behavior and offer insights for optimizing their mechanical performance across various applications [8–10]. Natural fiber-reinforced polymer composites have become more popular recently for the production of structural and non-structural components, including parts for automobiles [11, 12]. Polymer composites reinforced with natural fibers are known as natural fiber-based polymer composites, where the fibers are thoroughly embedded in the polymer matrix to form a strong bond. These fibers are tightly encapsulated in the polymer matrix, which can be either thermoset plastic or thermoplastic. This yields a composite material with ample strength to withstand targeted loading conditions [13].

Epoxy is widely used in thermoset polymer composites due to its outstanding mechanical properties and ease of processing, despite being non-biodegradable. These epoxy-based composites find applications in various industries [14, 15]. The use of natural fiber-reinforced epoxy composites has largely supplanted synthetic fiber composites [16]. Some natural fibers offer mechanical properties similar to synthetic ones, making these composites lighter than their glass fiber counterparts. Proper processing can help mitigate some of the marginal properties. The fibre-to-matrix adhesion of polymer composites containing natural fibers plays a crucial role in determining their mechanical strength, which is, in turn, affected by variables including the kind of natural fiber and processing techniques. Additionally, moisture can have a substantial impact on the interface between natural fibers and the matrix [17, 18]. Several studies have demonstrated that natural fiber-reinforced thermoset resins exhibit improved mechanical properties. Utilizing natural fiber-based hybrid composites within a concurrent engineering framework enhances product development processes by leveraging the synergistic benefits of both materials and methodologies [19]. Du et al. [20] observed a substantial improvement in the mechanical properties of thermoset resin when incorporated with pulp fibers, compared to neat resin without fibers.

This study aims to assess the mechanical properties of epoxy composites reinforced with natural fibers, specifically nonwoven hemp mats and woven jute mats. Despite the extensive literature on natural fiber composites, limited research has explored the hybridization of these particular fibers in epoxy composites. By investigating this novel combination, the study seeks to elucidate the impact of hybridization on the mechanical behavior of natural fiber-reinforced epoxy composites. Additionally, scanning electron microscopy (SEM) analysis is employed to examine fractured surfaces, providing insights into the microstructural aspects influencing the mechanical properties.

MATERIALS AND METHODS

Materials

Herenba Instruments and Engineers in Ambattur, Chennai, India, supplied the liquid thermoset epoxy resin (Grade 555R) and the transparent hardener (555H) used in this experiment. The jute woven sheet fiber came from Dharmapuri district, Tamil Nadu, India, and the nonwoven manila fiber sheet from K.G Enterprises in Bhiwadi, Rajasthan, India. Both fibers are depicted in Figure 1.

Formation of Composite Laminates

As illustrated in Table 1, the composite laminate utilized in the experiment comprised 75% by weight of matrix material, combined with a composition of woven jute fibers and nonwoven hemp fibers constituting 25% by weight.

Processing

The fabrication had been performed in steel mold frame with hand lay-up techniques. Three different combinations of fibers and matrix materials were utilized, each with a consistent 25% weight of fibers. For instance, in the woven jute/nonwoven manila hemp/epoxy composite, woven jute contributed 15%

by weight, and nonwoven manila hemp contributed 10% by weight, with the remaining 75% being epoxy. We applied a silica release gel to the mold surface to prevent resin adhesion. Next, epoxy resin was brushed evenly onto the mold's surface, and a fiber mat was layered on top, repeating as needed to achieve the desired fiber-to-matrix ratio for each composite. A metallic roller was used during each lay-up to ensure even distribution of epoxy and to remove trapped bubbles and gases. After completing the lay-up, the mold was sealed, and cured for a days at room temperature for better fabrication. After opening of mould, the prepared composite sheet is then cut as per ASTM for sample testing. Figure 2(a) shows woven jute/epoxy and nonwoven manila hemp/epoxy composite samples. Figure 2(b) displays a successfully fabricated hybrid composite (woven jute/nonwoven manila hemp/epoxy).

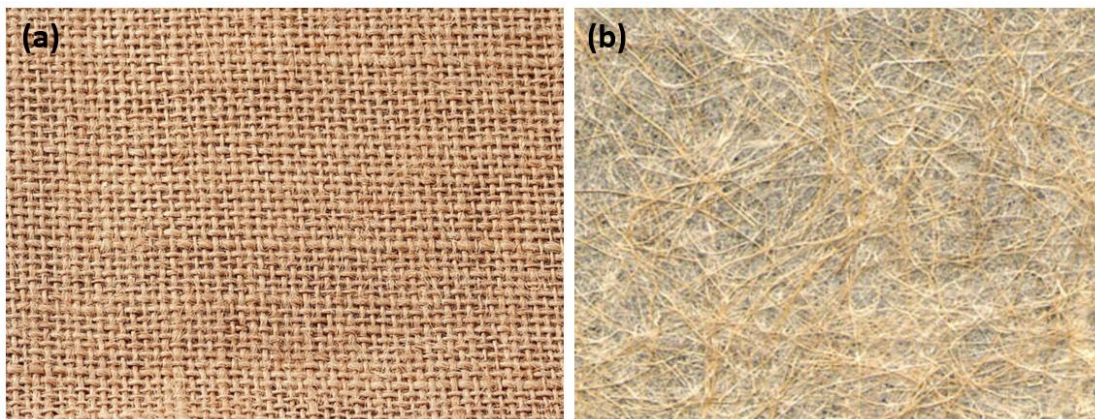


Figure 1. Used Fibers (a) woven Jute sheet (b) Nonwoven Manila Hemp fibers sheet.

Table 1. Natural frequencies Analytical and Experimental.

S.N.	Woven Jute Fiber		Non-Woven Manila Fiber		Epoxy Resin	
	(%)	(grams)	(%)	(grams)	(%)	(grams)
1.	25%	18	0%	0	75%	54
2.	0%	0	25%	18	75%	54
3.	15%	10.8	10%	7.2	75%	54

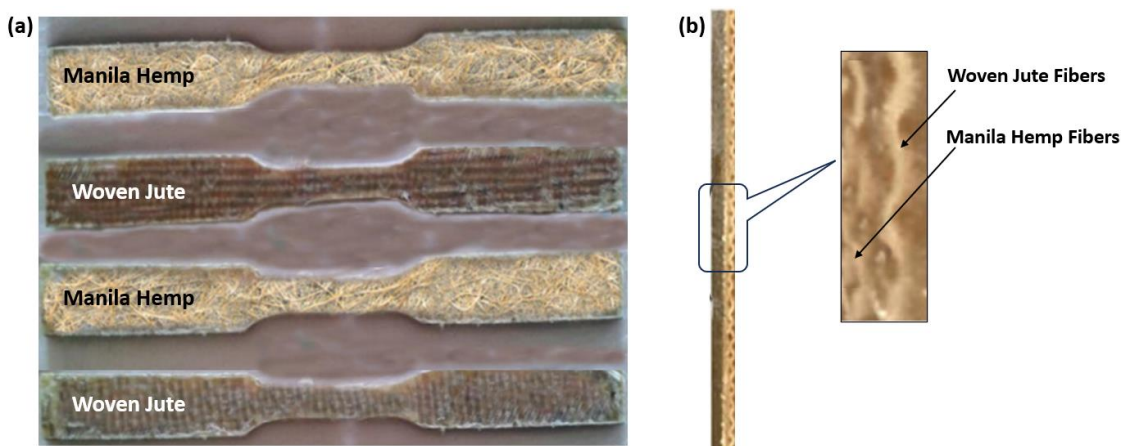


Figure 2. (a) Tensile test specimen as per ASTM standard (b) Hybrid laminate: Jute/Manila Hemp/Epoxy composite.

Density Calculation

In order to determine the density of the bio-composites and hybrid composites, the Archimedes' principle water immersion method was employed. Using the following equation, Agarwal and Broutman calculated the Ideal density of bio-composites in 1990:

$$\frac{1}{\rho_T} = \frac{W_M}{\rho_M} + \frac{W_R}{\rho_R} \quad (1)$$

The fractions of the composite matrix and reinforcement are denoted as w_M and w_R , with ρ_R and ρ_M representing the densities of the reinforcement and matrix materials. For composites with more than two constituents, adjustments can be made accordingly. The equation for the Woven jute/Nonwoven manila hemp/Epoxy composite can be expressed as follows:

$$\frac{1}{\rho_T} = \frac{W_J}{\rho_J} + \frac{W_H}{\rho_H} + \frac{W_M}{\rho_M} \quad (2)$$

Where, w_J , w_H , and w_M represent the weight fractions of woven jute, nonwoven manila hemp fibers, and epoxy matrix respectively. Similarly, ρ_J , ρ_H , and ρ_M denote the densities of woven jute, nonwoven manila hemp fibers, and epoxy matrix. The equation used to calculate the percentage change in density (% ΔD) for each composite is as follows:

$$\% \Delta D = \frac{\text{Theoretical Density} - \text{Actual Density}}{\text{Theoretical Density}} \times 100 \quad (3)$$

MECHANICAL CHARACTERIZATION

Hardness

Composite laminate hardness was measured with a Shore-D Hardness tester. This tester features a rigid steel rod indenter foot with a diameter ranging from 1.1 mm to 1.4 mm. The indenter has a tip radius of 0.1 mm and a conical point with a 30° angle. It applies a force of about 44.64 N to the specimen.

Tensile Testing

The specimens were subjected to tensile testing on an Instron 3369 machine with a cross-head speed of 2 mm/min, following the procedures outlined in ASTM Standard D638-14 [21]. Figure 3(a) shows the stress-strain properties of the composite made from woven jute, nonwoven manila hemp, and epoxy.

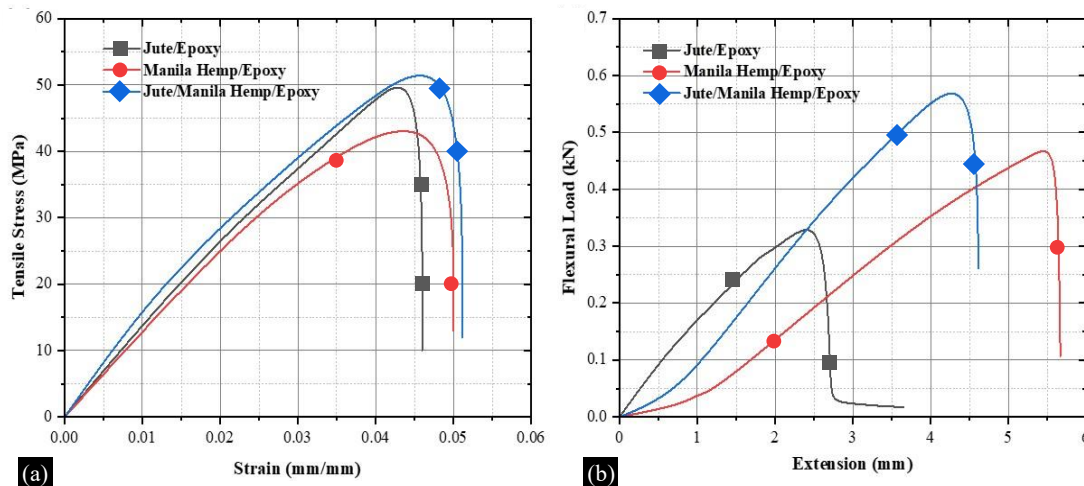


Figure 3. (a) Stress Vs strain curve and (b) Load Vs extension curve of fabricated composites.

Flexural Testing

As per ASTM D790 [22], flexural specimens were prepared and tested on an Instron 3369 universal testing machine at 2.5 mm/min crosshead speed. Figure 3(b) shows the load-extension curve for the woven jute/nonwoven manila hemp/epoxy composite in flexural testing.

Impact Testing

A Charpy impact tester (TFIT-300EN, ISO 148) manufactured by Fine Testing Instruments in India was used for the purpose of evaluating impact energy. The impact strength of the manufactured hybrid

composites was ascertained by means of the Charpy test. The IT-30 digital Charpy pendulum impact tester was used to construct the sample in accordance with the ASTM D256 standard [23].

Morphological Analysis

SEM (S-3700 Ultra Large VP-SEM) was used to analyze fiber/matrix interface morphology in composite laminates. Specimens were gold-coated to improve their conductivity before capturing micrographs.

RESULTS AND DISCUSSIONS

Density

Table 2 lists all the composites and hybrid composites. Percentage density changes indicate porosity in the composite due to the fabrication process. Despite some air entrapment, the processing technique was high-quality, with minimal density variation. To prevent trapped air or gas between the fiber mat and epoxy, thorough rolling is essential after each epoxy layer is applied.

Table 2. Experimental and theoretical composite densities

Fabricated Composites	Measured Density (g/cm ³)	Ideal Density (g/cm ³)	% ΔD (%Porosity)
Woven Jute/Epoxy	1.082	1.162	6.884
Nonwoven Manila Hemp/Epoxy	1.104	1.169	5.560
Jute/Manila Hemp/Epoxy	1.101	1.172	6.058

Hardness Evaluation

Figure 4(a) presents the hardness characteristics of woven jute and nonwoven manila hemp fiber-reinforced composites, as well as hybrid composites. Composites made from jute/manila hemp/epoxy showed peak Shore-D hardness values of approximately 99, while nonwoven manila/epoxy composites and woven jute/epoxy hybrid composites had lower values. Notably, nonwoven manila/epoxy composites exhibited the lowest hardness, approximately 90 Shore-D. Hybridizing different layers of natural fiber woven mats enhanced composite hardness, influenced by factors like reinforcement properties, adhesion, and fiber loading. A previous study (Kumar et al., 2021) found that adding kenaf fiber to phenol-formaldehyde composites linearly increased their hardness, and hybrid composites showed a continuous hardness improvement with nonwoven manila hemp fiber addition [24].

Tensile Testing

Figures 4(a) and 4(b) show the results of tensile tests performed on hybrid and natural fiber-reinforced composite materials. We measured elongation percentage and tensile modulus with the help of universal testing machine Instron 3369. Different combinations of natural fibers woven mats were used for reinforcement within the epoxy matrix to enhance tensile strength. The composites exhibited enhanced tensile strength, surpassing the pure epoxy resin (approximately 30 MPa, as depicted in Figure 4(a). 52 MPa was the highest average tensile strength achieved by the woven jute/nonwoven manila hemp/epoxy composite. In comparison, the woven jute/epoxy and nonwoven manila/epoxy composites recorded strengths of 48.93 MPa and 41.64 MPa, respectively. Integrating natural fiber reinforcement into hybrid and composite structures leads to an elevated Young's modulus compared to that of pure epoxy resin. To be more precise, the composite made of Jute, Manila Hemp, and Epoxy showed the highest average Young's modulus at 2.0 GPa (refer to Figure 4(b)). The manila hemp/epoxy and jute/epoxy composites both displayed comparatively low average tensile moduli, coming in at 1.70 GPa and 1.73 GPa, respectively. The jute/epoxy composite, on the other hand, had the lowest average Young's modulus, measuring 1.70 GPa. Although, the tensile modulus consistently surpassed that of pure epoxy resin (1.1 GPa), underscoring variations in Young's modulus among the composite materials due to the specific natural fiber type and its interaction with epoxy. Diverse natural fibers, each with varying surface characteristics and stiffness in their mats when combined with epoxy resin, affect the resulting tensile modulus in hybrid composites. These effects stem from differences in adhesion levels, resulting in

distinct properties. The inclusion of natural fibers enhances the stiffness of the fabricated composite. The aspect ratio, orientation, and fiber characteristics have the biggest effects on a composite laminate's tensile modulus [25].

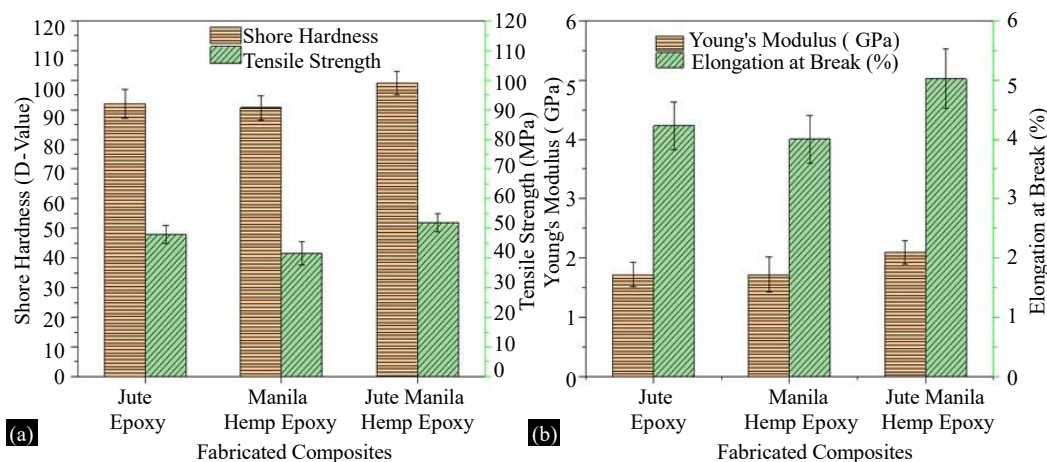


Figure 4. (a) Shore hardness Vs Tensile strength and (b) Young's modulus Vs Elongation percentage of fabricated composites.

Tensile testing elongation reflects material behavior (brittle or ductile). Figure 4(b) shows % elongation for composites, hybrid composites, and pure epoxy, with the Jute/Manila Hemp/Epoxy composite reaching a maximum average elongation of 5% at fracture. Other fabricated composites, jute/epoxy and manila hemp/epoxy, had average elongation at break values of 4.2% and 4%, respectively. The Jute/Epoxy composite showed an elongation at break of 4.2%, nearly equal to the Manila Hemp/Epoxy composites. Manila Hemp/Epoxy composites had the lowest average elongation at break, which was 4% compared to other fabricated composites. Composites and hybrid variants exhibit increased ductility, comparing that of pure epoxy resin (3.2%), expanding their applications in automotive, aerospace, and naval sectors. Properties of the natural fibers used to make the composite are crucial in determining its final features. The fiber alignment (fibril orientation), chemical composition (such as the percentage of cellulose and wax), and physical attributes of natural fiber-reinforced composites determine their properties [26]. Composites reinforced with natural fibers improve modulus, elongation%, and tensile strength, according to previous research [27]. The scanning electron microscopy (SEM) analysis of the fracture surface was performed after the tensile test. Scanning electron micrographs (SEMs) shown in Figure 5 disclose the causes and processes of the composite and hybrid composite failures identified in the tensile test. These images reveal fiber fractures, fiber pullouts, matrix failures, and voids/porosity on the fracture surfaces of both composites and hybrids. The adhesion between natural fibers and the polymer matrix depends on the surface characteristics of the fibers [28]. Fibers characterized by the presence of excessive oily substances or an abundance of wax exhibit weakened adhesion with epoxy matrices attributable to inadequate wetting phenomena. To achieve optimal adhesion, fiber surfaces should be clean, free from oils, moderately dry, and have a rough texture. Several research studies have acknowledged improved tensile properties in thermoset polymers with natural fiber reinforcement, and SEM images have shed light on the governing failure mechanisms. Ramnath et al. (2013) used SEM to examine the surface characteristics of a composite made from abaca, jute, and epoxy during tensile testing [29]. Combining jute fiber with epoxy polymer significantly improves wettability, enhancing adhesion and preventing concerns about fiber pull-out, fracture, and debonding. Ozturk revealed through SEM micrographs of fractured specimens that finer fractures and fiber pull-out played a vital role in the composite's fracture mechanism during tensile testing [30]. Haameem et al. utilized SEM analysis to investigate the post-tensile testing failure of a napier/polyester composite. It was discovered through their investigation that fiber pull-out caused fiber extrusion, which in turn caused fiber debonding, matrix cracking, and fracture [31].

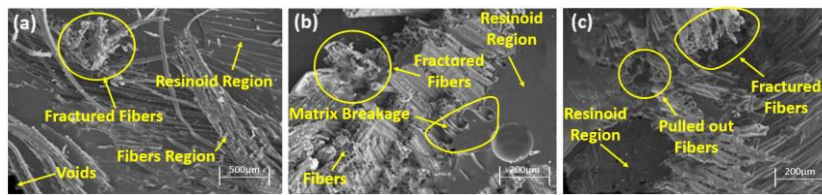


Figure 5. Fractured surface of tensile tested composites (a) Jute/Epoxy (b) Manila Hemp/Epoxy and (c) Jute/Manila Hemp/Epoxy composites.

Flexural Testing

Composites with different combination of natural fibers matting reinforcing with epoxy resin showed increased flexural characteristics in a three-point bending test. Figure 6(a) displays the average flexural modulus and flexural strength. In terms of flexural strength and flexural modulus, pure epoxy resin is 34.69 MPa and 0.6 GPa, respectively have been substantiated in previous work. Impressive flexural strengths of 90 MPa and 0.78 GPa, respectively, are shown by the Jute/Manila and Hemp/Epoxy hybrid composites. In comparison to the hybrid Jute/Manila Hemp/Epoxy composite, the flexural strength of the Jute/Epoxy and Manila Hemp/Epoxy composites is significantly lower. Jute/Epoxy composites had the lowest values for flexural modulus and flexural strength, measuring 0.94 GPa and 64.6 MPa, respectively. On the other hand, the Manila Hemp/Epoxy composite exhibited a substantially higher flexural modulus at 2.12 GPa with a flexural strength of 95 MPa, indicating a significant increase in modulus within these composites. Considerable factors impacting the flexural properties of polymer composites reinforced with natural fibers include the mechanical properties of the fibers themselves, the mat type (woven, unidirectional, bidirectional), and the state of the fiber surfaces. All of these things have a big role in how well the fibers stick to the matrix.

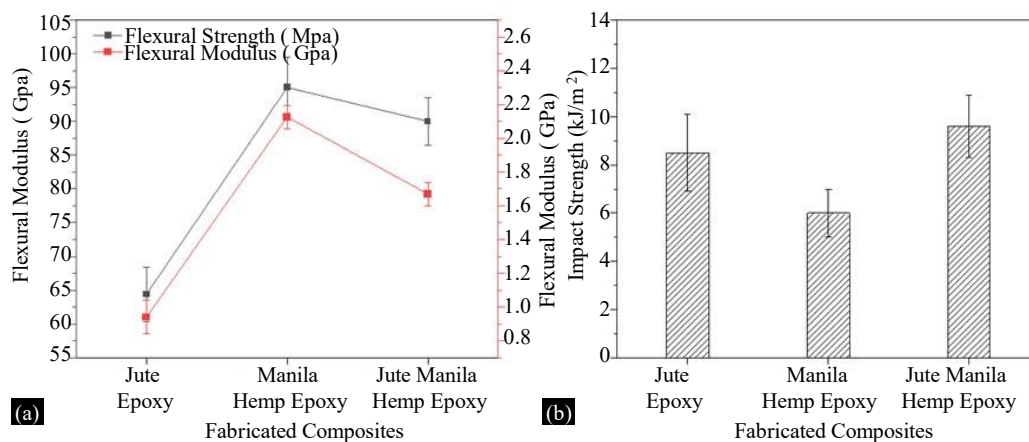


Figure 6. (a) Flexural strength Vs Flexural modulus (b) Impact strength of fabricated composites.

Scanning electron microscopy (SEM) analysis of composite fracture surfaces after flexural testing showed examples of sharp-edged matrix ruptures, fiber-matrix debonding, fiber fractures, and layer delamination (Figure 7). Surprisingly, the manila hemp/epoxy composite showed very little debonding of the fibers and matrix, indicating improved adhesion. Furthermore, the Jute/Epoxy and Jute/Manila Hemp/Epoxy composites were not as strong as the Manila Hemp/Epoxy hybrid composite in terms of flexural strength. This is because the rough surface, lack of moisture, and cleanliness of Manila hemp fibers all work together to improve the bonding of epoxy polymers. The interfacial adhesion between natural fibers and the matrix plays a crucial role in influencing the flexural strength of these composites. This aspect's importance is highlighted by Bajpai, Singh, and Madaan [28]. Similar improvements in flexural characteristics have been shown in previous studies of natural fiber-reinforced bio-composites, such as those by Balasubramanian, Kumar and Babu (2021). Yousif et al. remark that improved interfacial bonding reduces both fiber pull-out and debonding, consequently enhancing the adhesion at fiber/matrix interfaces [32].

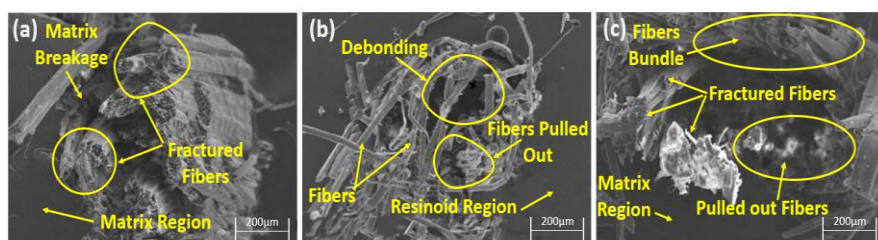


Figure 7. Fractured surface of flexural tested composites (a) Jute/Epoxy (b) Manila Hemp/Epoxy and (c) Jute/Manila Hemp/Epoxy composites.

Impact Testing

Figure 6(b) presents the results of Charpy impact testing, which was used to assess the impact strength of the manufactured composites. At 4 kJ/m^2 , the impact strength of pure epoxy was significantly lower than that of natural fiber-reinforced epoxy composites. At 10 kJ/m^2 , the hybrid composite made of manila hemp, jute, and epoxy showed the highest mean impact strength. The impact strengths of the Jute/Epoxy and Manila Hemp/Epoxy composites were 8.5 and 6 kJ/m^2 , respectively, which is rather good. A minimum impact strength of 6 kJ/m^2 is achieved using composites made of Manila hemp and epoxy. Diverse natural fiber matting' varying degrees of adherence to the epoxy matrix accounted for the observed range of impact strengths. Figure 8 displays SEM micrographs of the fractured composite specimen surfaces after impact testing. Debonding at the fiber-matrix interface, severe epoxy matrix rupture and cracking, fiber fracture, and complete fiber pull-out are all visible in the micrographs. These SEM images provide evidence of brittle laminate failure with a clear and clean matrix fracture. The impact characteristics of cellulose epoxy composites were investigated by Mader et al. based on fiber-matrix adhesion. According to the researchers, fiber pull-out in composites reduced impact strength, indicating weaker interfacial shear strength [33].

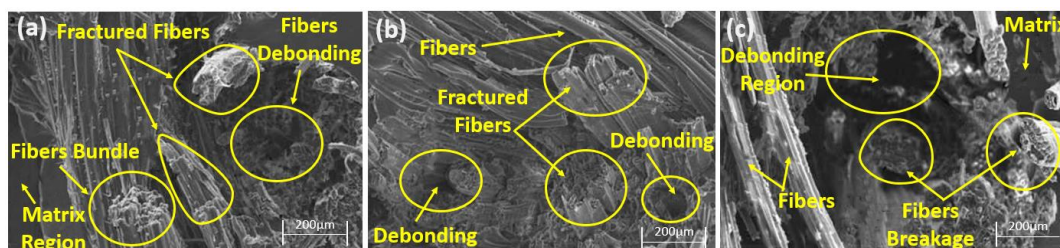


Figure 8. Examination of Fractured Surfaces in Impact-Tested Composites: (a) Jute/Epoxy (b) Manila Hemp/Epoxy and (c) Jute/Manila Hemp/Epoxy Composites.

Summary

In this study, three distinct combinations of natural fibers—woven jute, nonwoven manila hemp, and their hybrid—were fabricated using the hand lay-up technique. Mechanical properties and fiber adhesion to the epoxy matrix were analyzed through SEM micrographs, providing insights into the functionality of hybrid composites for various applications and future research. The conclusions drawn are as follows:

- The fabricated composites exhibit slight density variations from expected values, confirming the suitability of the manufacturing technique.
- Natural fiber-based bio-composites demonstrate superior strength compared to epoxy alone, with the jute/manila hemp/epoxy hybrid showing the strongest fiber-polymer bonding and highest mechanical properties.
- Manila hemp/epoxy composites display inferior mechanical properties due to insufficient adhesion between fibers and epoxy.
- Both the developed bio-composites and their hybrids exhibit enhanced flexural properties, with the manila hemp/epoxy composite demonstrating particularly cohesive behavior under flexural stress.

- (e) Impact strength is highest in the jute/manila hemp/epoxy hybrid, followed by the jute/epoxy composite, and lowest in the manila hemp/epoxy composite.
- (f) SEM analysis reveals the failure and damage mechanisms in natural fibers and the matrix under tensile, flexural, and impact loading.

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