Improving Mechanical Performance of Hybrid Polymer Composites: Incorporating Banana Stem Leaf and Jute Fibers with Tamarind Shell Powder

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Mechanical properties were evaluated for bio-natural fiber-reinforced epoxy hybrid composites made with varying amounts of jute, banana stem leaves (BSL), and tamarind shell powder (TSP). Each composite design had varying weight percentages of jute and BSL (5 to 25%) and a consistent mix of TSP (10%) and epoxy resin (60%). The tensile strength, flexural strength, interlaminar shear strength (ILSS), impact strength, hardness, and water absorption were examined. Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) were used to investigate chemical bonding and morphology. The findings indicated a relationship between fiber and filler content and mechanical properties of composites, with 20% jute fiber content resulting in the highest performance. The tensile strength of the composite increased by 24.6%, rising from 32.4 MPa for the 5% jute and 25% banana stem leaves (5J25BSL) composite to 40.4 MPa for the 20% jute and 10% banana stem leaves (20J10BSL) composite. Similarly, the flexural strength saw a 27.9% improvement, increasing from 67.2 MPa in the 5J25BSL composite to 86.0 MPa in the 20J10BSL composite. The impact strength also experienced a notable increase of 39.1%, moving from 2.56 J for the 5J25BSL composite to 3.56 J for the 20J10BSL composite. These results highlight significant improvements in all three properties, as the proportion of jute in the composite increased and the proportion of banana stem leaves decreased. This research influences material selection for engineering applications and informs the development of specialized composite materials.

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INTRODUCTION

Hybrid polymer composites represent a groundbreaking advancement in material science, offering a synergistic combination of different reinforcing components within a polymer matrix (Prashanth *et al*. 2017; Santulli *et al*. 2023; Gurusamy *et al*. 2024). By incorporating various reinforcements, such as fibers, particulates, or nanoparticles, hybrid polymer composites have the potential to achieve enhanced mechanical strength, improved toughness, superior thermal stability, and tailored electrical or magnetic properties. One of the key advantages of hybrid polymer composites lies in their versatility and adaptability to diverse application requirements. Different types of reinforcements can be selectively chosen and combined to achieve specific performance targets, making these composites highly customizable for various industries and engineering applications (Parbin *et al*. 2019). For instance, natural fibers like jute, banana stem leaf fibers, or sisal can be used alongside synthetic fibers such as glass or carbon to create composites with a unique balance of strength, stiffness, and sustainability. Fabrication techniques for hybrid polymer composites are equally diverse, ranging from conventional methods such as compression molding and resin transfer molding to advanced techniques such as additive manufacturing and in-situ polymerization (Sathishkumar *et al*. 2014; Kumar *et al*. 2023; Aruchamy *et al.* 2024). Each fabrication method offers its own set of advantages and challenges, allowing users to tailor the manufacturing process to suit the desired composite properties and production scale.

Mechanical properties are a key focus in the development of hybrid polymer composites. By combining different types of reinforcements, researchers aim to improve tensile strength, flexural strength, impact resistance, and fatigue performance compared to pure polymer matrices (Saba *et al*. 2016; Karthik *et al*. 2023c; Manickaraj *et al*. 2024a). Thermal stability is another important aspect of hybrid polymer composites, especially in high-temperature applications. The addition of certain reinforcements can improve the heat resistance of the composite, delaying thermal degradation and enhancing overall thermal conductivity (Karthik *et al*. 2023a). This is particularly relevant in industries such as aerospace, automotive, and electronics, where materials are exposed to elevated temperatures during operation.

These techniques provide valuable insights into the dispersion, distribution, and interfacial bonding between the polymer matrix and reinforcing components (Karuppiah *et al*. 2020). Understanding the microstructural features of the composite is essential for optimizing its mechanical, thermal, and electrical properties (Karthik *et al*. 2023b). This opens up opportunities for innovative applications in fields such as sensors, actuators, electromagnetic shielding, and sound absorption. Overall, hybrid polymer composites represent a frontier in material science, offering a diverse range of properties and applications. Continued research and development in this field hold the potential to drive innovation across various industries, providing sustainable and high-performance solutions to complex engineering challenges (Aruchamy *et al*. 2023).

Jute fiber, derived from the stems of the *Corchorus* plant, is known for its strength, durability, and eco-friendly characteristics. Jute has found applications in various industries, including textiles, packaging, construction, and automotive (Shah *et al*. 2021; Malik *et al*. 2024). The cultivation of jute is sustainable and environmentally friendly, as it requires minimal pesticide and fertilizer use and has a relatively low carbon footprint compared to synthetic fibers. Jute fibers have several properties that make them suitable for composite materials (Ramesh and Deepa 2024). They have high tensile strength, making them ideal for reinforcing polymer matrices to enhance mechanical properties such as strength and stiffness. Additionally, jute fibers exhibit good moisture absorption and biodegradability (Karimah *et al*. 2021). Jute fiber composites are composite materials in which jute fibers are used as reinforcement within a polymer matrix. These composites offer a compelling alternative to traditional materials due to their favorable balance of strength, weight, and cost. Common polymer matrices used in jute fiber composites include thermosetting resins like epoxy and polyester, as well as thermoplastic polymers such as polypropylene and polyethylene (Wang *et al*. 2019). Table 1 presents the comprehensive comparison of the properties of jute and banana stem leaf fibers with other natural fibers.

The production process of jute fiber composites usually consists of several steps. First, jute fiber is processed to remove impurities and improve its quality (Chandekar *et al*. 2020). Jute fibers are then combined with the polymer matrix by techniques such as compression molding, injection molding or filament winding, depending on the desired shape and properties of the final composite (Raghavendra *et al*. 2014). The properties of jute fiber composites can be tuned by adjusting parameters such as fiber orientation, fiber fraction, and matrix material. By optimizing these parameters, researchers and engineers can achieve composites with specific mechanical, thermal, and acoustic properties suited to their intended applications. In terms of applications, jute fiber composites have been utilized in a wide range of industries (Rangasamy *et al*. 2021; Manickaraj *et al.* 2024d). In automotive manufacturing, they are used for interior components, door panels, and seat backs to reduce vehicle weight and improve fuel efficiency. In the construction industry, jute fiber composites find applications in roofing materials, wall panels, and reinforcement for concrete structures. Additionally, jute fiber composites are used in consumer goods such as furniture, luggage, and sporting equipment due to their lightweight and durable nature (Devarajan *et al*. 2022). The chemical structure of the Jute and BSL fiber is shown in Fig. 1.

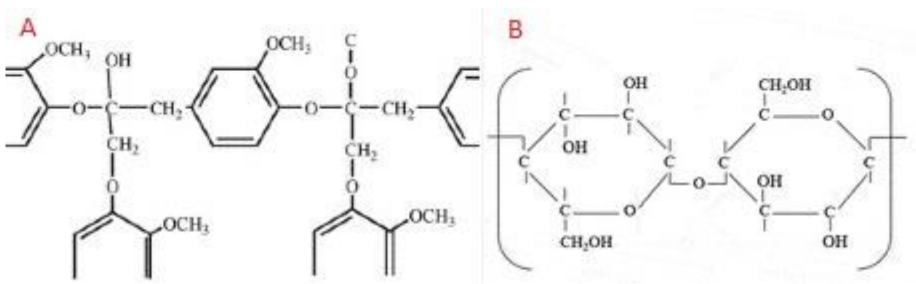

Fig. 1. Chemical structure (A) Jute fiber, (B) BSL

The growing interest in sustainability and eco-friendly materials has led to increased research and development efforts in jute fiber composites. As advancements continue to be made in composite processing techniques, matrix materials, and fiber treatments, jute fiber composites are expected to play an increasingly significant role in addressing the challenges of sustainability and resource conservation in the manufacturing industry (Karunakaran *et al*. 2022; Gokul *et al.* 2024).

Tamarind powder composites are innovative materials that combine tamarind powder, a by-product of the tamarind fruit, with various matrix materials to create a range of functional and sustainable materials. Tamarind powder is derived from the seeds and pulp of the tamarind fruit, which is cultivated in tropical regions for its culinary and medicinal properties (Kumar *et al*. 2018). The incorporation of tamarind powder into composite materials offers several advantages. Tamarind powder is rich in phenolic compounds, antioxidants, and other bioactive substances, which can impart beneficial properties to the composite, such as improved mechanical strength, thermal stability, and resistance to environmental degradation (Goudar *et al*. 2020). Tamarind powder is biodegradable and renewable, making it an environmentally friendly alternative to synthetic fillers and reinforcements. The fabrication of tamarind powder composites involves mixing the tamarind powder with a suitable matrix material, such as a polymer resin or cementitious binder (Srinivasan *et al*. 2020). The mixture is processed by compression molding, extrusion, or casting to form the desired shape and structure of the composite. The properties of the composite can be tailored by adjusting parameters such as the ratio of tamarind powder to matrix material, the particle size and distribution of the tamarind powder, and the processing conditions (Babu *et al*. 2020).

Tamarind powder composites have been applied in various fields, including construction, automotive, packaging, and biomedical engineering. In construction, tamarind powder composites have been used as a sustainable alternative to conventional building materials, such as cement and concrete (Naik *et al*. 2019; Girimurugan *et al*. 2022; Mylsamy *et al*. 2024; Manickaraj *et al.* 2024c). The addition of tamarind powder can improve the mechanical properties and durability of the composite, while also reducing its environmental impact and carbon footprint.

Fibrillation is the process of separating fiber bundles into finer individual fibers, increasing their surface area and bonding capacity. For BSL fibers, this is achieved through mechanical, chemical, or enzymatic treatments that break down the plant material into smaller fibrils. The outer layer of the banana stem leaf is scraped or chemically treated to isolate cellulose fibers. Fibrillation enhances the fiber's ability to bond with the matrix in composites, improving mechanical properties such as tensile strength and flexibility. Here is a comparison of the differences between jute and BSL fibers in Table 1.

This table summarizes the key differences between jute and BSL fibers, highlighting their structural, mechanical, and chemical characteristics, which are essential for understanding their behavior and suitability in composite materials.

In the automotive industry, tamarind powder composites have been investigated for use in interior components, body panels, and structural reinforcements. The lightweight and sustainable nature of tamarind powder composites make them attractive for applications where weight reduction and environmental sustainability are priorities (Jeyaprakash *et al*. 2021; Sumesh *et al*. 2023). In packaging applications, tamarind powder composites have been explored as a biodegradable and compostable alternative to conventional plastic packaging materials. The incorporation of tamarind powder can improve the strength, barrier properties, and biodegradability of the composite, making it suitable for a range of packaging applications, including food packaging, agricultural packaging, and disposable containers (Kiruthika *et al*. 2012; Goutham *et al*. 2023). In biomedical engineering, tamarind powder composites have been investigated for use in tissue engineering, drug delivery, and medical device applications. The biocompatibility and bioactivity of tamarind powder make it an attractive candidate for use in composite materials for medical applications (Karthikeyan *et al*. 2022). Overall, tamarind powder composites represent a promising class of materials with diverse applications and potential benefits in terms of sustainability, functionality, and performance. Continued research and development efforts are expected to further expand the range of applications and enhance the properties of tamarind powder composites, making them an increasingly attractive option for a wide range of industries (Kiruthika and Veluraja 2017; Selvi *et al*. 2019).

Table 1. Jute Fiber *vs.* BSL (Pujari *et al*. 2014; Neto *et al*. 2022; Elfaleh *et al*. 2023)

Property	Jute Fibers	BSL (Banana Stem Leaf) Fibers
Source	Derived from the stem of the *Corchorus* plant	Derived from the leaves of the banana plant
Structure	Smooth and relatively uniform surface	Rougher texture due to higher lignin content
Tensile Strength	High tensile strength	Lower tensile strength than jute
Flexibility	Moderate flexibility	Higher flexibility due to finer fibrils
Chemical Composition	High cellulose content, low lignin	Higher lignin and cellulose content
Moisture Absorption	Moderate to low moisture absorption	High moisture absorption (hydrophilic)
Degradation Resistance	Less resistant to microbial degradation	More resistant to microbial degradation due to higher lignin content
Processing	Easier to process due to smooth texture	More complex due to rough texture
Environmental Impact	Biodegradable and eco-friendly	Biodegradable and eco-friendly, often considered more sustainable due to agricultural waste utilization

Banana and jute fibers may have different strengths, stiffness, or elongation properties, and their combination could result in a composite with a balanced set of mechanical properties, potentially improving both tensile strength and impact resistance. The interaction between the fibers could result in synergistic effects that are not achievable by using one fiber alone, such as better stress distribution and enhanced fiber-matrix bonding.

This study fills a research gap by exploring the underutilized combination of jute, banana stem leaves, and tamarind shell powder in epoxy composites, focusing on how varying fiber proportions influence mechanical properties. Unlike prior studies that lack detailed insights into such hybrid configurations, this work identifies the optimal jute-to-banana stem leaf ratio for enhanced performance and employs FTIR and SEM analyses to link mechanical improvements with chemical and morphological characteristics, advancing the development of high-performance natural fiber composites for engineering applications.

EXPERIMENTAL

Materials

The fibers sourced from jute and banana stem leaf plants underwent meticulous treatment processes in the Anamalai area of Coimbatore District, Tamil Nadu, India, utilizing both water retting and mechanical techniques. Water retting, a traditional method, immersed the plant stems to facilitate microbial breakdown of non-fibrous components, ensuring cleaner and more flexible fibers, especially effective for jute fibers. Meanwhile, mechanical techniques, likely including cutting and scraping, were employed to extract resilient fibers from the tougher banana stem leaves, preserving their structural integrity. Figure 2 illustrates the mechanical extraction and subsequent retting process for banana stem leaf fibers, while Fig. 3 showcases the collection of jute fibers from jute plants.

Fig. 2. (A) Banana stem leaf (BSL), (B) BSL extraction, (C) BSL fiber

Fig. 3. (A) Jute fiber plant, (B) Jute fiber

Fiber Preparation and Composite Compatibility

Following extraction, fibers likely underwent cleaning, drying, and sizing to optimize compatibility with the epoxy resin matrix. The epoxy resin and hardener used were sourced from Covai Seenu Company, Coimbatore, with the resin grade specified as [Epoxy Resin LY556 and Hardener HY951]. Tamarind seeds were processed into a fine powder, as depicted in Fig. 4, harnessing their cellulose content and antioxidant properties for composite enhancement. The seeds were first cleaned to remove impurities and then dried thoroughly to reduce moisture content. Subsequently, they were ground using a high-speed mechanical grinder to achieve a fine powder. The resulting powder was screened using a mesh sieve to ensure uniform particle size, making it suitable for consistent integration into the composite matrix. The selection of treatment methods was based on fiber characteristics and composite requirements, ensuring the fibers were uniform, clean, and amenable to composite fabrication. These steps culminated in the production of high-quality composites with tailored mechanical properties (Nguyen and Nguyen 2021; Palanisamy *et al.* 2023).

Fig. 4. (A)Tamarind seed, (B) tamarind powder

Fig. 5. Composite specimens for all tests

Composite Fabrication

To make the composite, jute and BSL fibers were cut into 300 mm lengths. The composite layers were made up of four that alternated between jute and banana stem leaf fibers. The method began with the application of a mixture of TSP and epoxy resin on an aluminium foil cover. The first layer was made of jute fiber, then a mixture of epoxy resin, TSP, and hardener, and finally banana stem leaf fiber imbedded in resin. This layering sequence was repeated, allowing each layer to dry before applying the next. Subsequently, the composites were subjected to conditions of 130 °C and 30 bar pressure for 60 min before being demolded (Kar *et al*. 2023; Manickaraj *et al*. 2024b). The final dimensions of the laminate measured 300 x 300 x 5 mm. Figure 5 shows specimens cut for as per ASTM Standards to various test.

Methodology

Figure 6 shows a general scheme for the experimental work. As shown, the jute and banana materials were placed in the category of fibers, whereas the tamarind seen powder was regarded as a filler. After mixing the ingredients, they were pressed in the molding process, forming the composites, which were subject to testing.

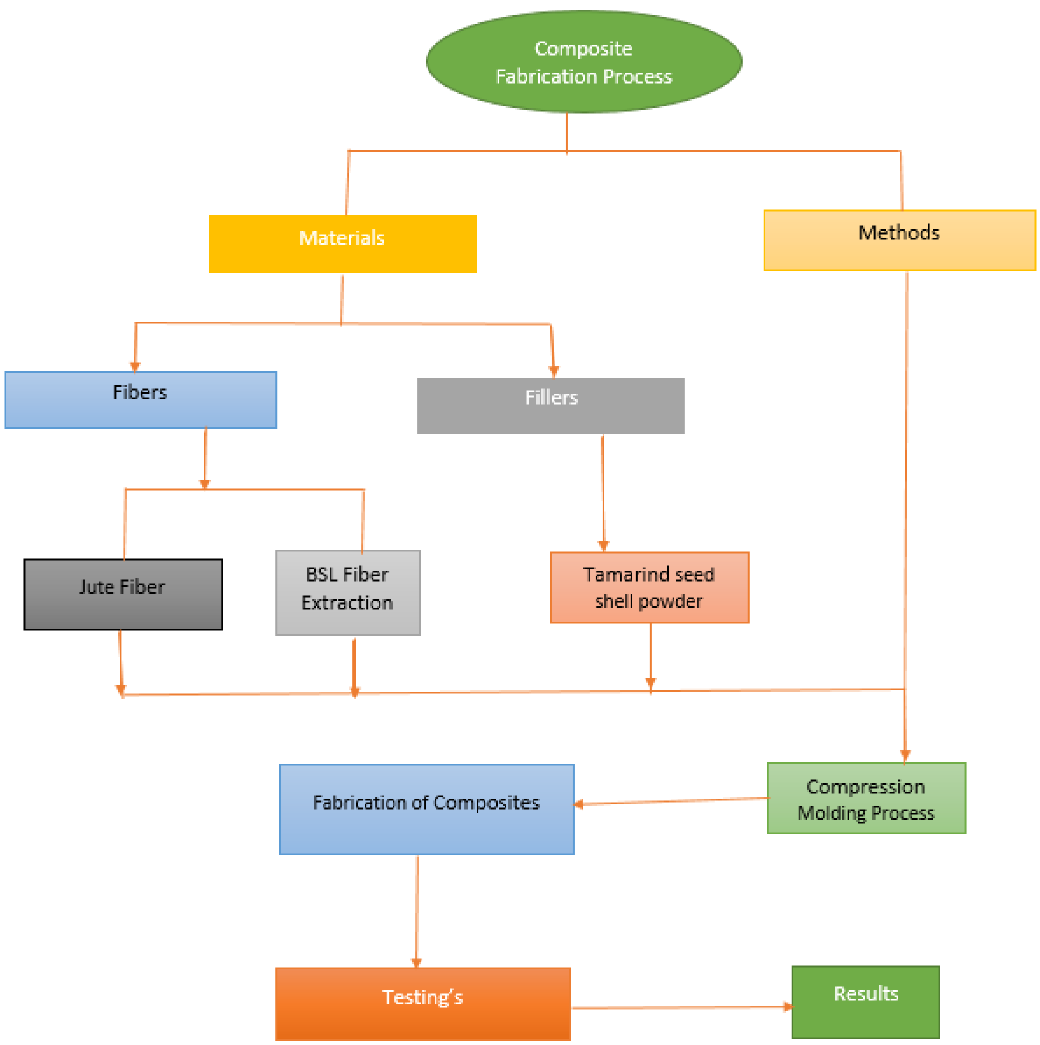

Fig. 6. Simple diagram of methodology process

Composite Designation

Table 2 outlines the composition of composite samples, detailing the fiber content (Jute and BSL), filler content (TSP), and epoxy resin content for each sample. Additionally, it includes a designation for each composite based on its composition. The final column presents the blend designations.

Table 2. Mix Compositions and Designations

Sl No	Fiber Content (%)		Filler Content (%)	Epoxy Resin (%)	Composite Designation
	JUTE	BSL	TSP		
1	5	25	10	60	5J25BSL
2	10	20	10	60	10J20BSL
3	15	15	10	60	15J15BSL
4	20	10	10	60	20J10BSL
5	25	5	10	60	25J5BSL

Mechanical Testing

A test bench machine (Model: MTS 810, Zwick/Roell Z100) was used to conduct mechanical tests. Tensile performance was evaluated in accordance with ASTM D3039 (2014) (Pinnell *et al.* 2005) standards using samples measuring 250 mm x 25 mm x 5mm at a speed of 2 mm/min. Flexural tests were also performed on the same machine following ASTM D7264 (2015) (Kumar *et al.* 2019) requirements. The size of the specimen was 125 mm x 13 mm x 5 mm. Impact energy values were determined using the test bench machine (Model: Instron CEAST 9050) in accordance with ASTM D256 (2023) (Adhikari and Gowda 2017) standards, with samples sized 60 x 12 x 5 mm. Five samples were used for each test, and the outcomes were recorded (Balaji *et al.* 2020). Hardness, an important mechanical attribute that indicates a material's resistance to scratching or indentation, was measured using a Shore D durometer (Model: Mitutoyo HH-338). The mean hardness values of the composites were determined by making two indentations in each sample. Specimens were prepared in compliance with ASTM D2240 (2021) (Bahtiyar *et al.* 2023).

Interlaminar Shear Strength

Fiber-reinforced polymer composites are prone to a key type of failure known as shear failure. The Interlaminar Shear Strength (ILSS) method assesses a sample’s resistance to shear loading by measuring layer strength and providing an in-plane shear modulus. ILSS samples are heated for five h, from 80 to 120 °C, and then cooled gradually before being tested and uses an ASTM D2344 2022 (Kotik and Ipina 2021). An equation was utilised to calculate the ILSS, and testing was performed at a cross-head velocity of 5 mm/min (Manickaraj *et al*. 2023). Standard specimen size for this test was 25 mm x 25 mm with a thickness of 5 mm. ILSS was determined through the application of Eq. 1,

$$ILSS = F/\pi dl \tag{1}$$

where d is the sample diameter, F is a ratio of the observed force to the force needed for debonding, and l represents the length of the fiber implanted in the matrix.

Water Absorption Test

To find the water absorption percentage of the hybrid composites containing jute/banana stem leaf (BSL) fibers, the samples were left at room temperature for 5 days while submerged in water. The ASTM D570 (2022) criteria () were followed in the preparation of the test specimens (Hassan *et al*. 2019; Manickaraj *et al*. 2022; Ramasubbu *et al*. 2024). The standard size for the water absorption test is typically 50 mm x 50 mm (2 in x 2 in) with a thickness of 5 mm. Once the specified soaking time had passed, the samples were removed from the water and gently cleaned with a soft cloth before being allowed to dry. After that, the samples were weighed to see how well the composites absorbed moisture. The equation (2) used to calculate water absorption in composite materials according to ASTM D570 is,

$$W = (W_2 - W_1) / W_1 \times 100 \quad (2)$$

where W is the water absorption percentage (%), W_1 is the initial weight of the specimen before immersion (g), and W_2 is the weight of the specimen after immersion for a specified period (grams).

FTIR Characterization

In this experiment, FTIR analysis was used to analyse the chemical makeup and components of both jute and banana stem leaf (BSL) fiber (Almeshaal *et al*. 2022; Johny *et al*. 2023). To create an infrared spectrum, the disc sample preparation method was employed. The FTIR analysis was performed using a Fourier Transform Infrared Spectrometer (Model: Thermo Scientific Nicolet]. The spectra were recorded in the range of 4000 cm^{-1} to 400 cm^{-1} with a resolution of 4 cm^{-1}. The samples were analyzed using the standard transmission mode.

SEM

SEM was used to evaluate the morphological representations of the generated composites (Manickaraj *et al*. 2023). The Zeiss EVO 18 scanning electron microscope was used to examine the fracture surfaces of the composites. The specimens were examined under an acceleration voltage of 20 kV and at a working distance of 10 mm. High-resolution images were captured to observe the surface features and fiber-matrix interactions of the samples

RESULTS AND DISCUSSION

Tensile Test

The tensile strength results for composite designations (5J25BSL, 10J20BSL, 15J15BSL, 20J10BSL, 25J5BSL) demonstrated a clear and consistent increase with higher composite designation, indicating more content of particles. Beginning with a base value of 17.5 MPa for neat epoxy, the tensile strengths progress systematically from 32.4 MPa for 5J25BSL to 40.4 MPa for 20J10BSL. This progression indicates a positive correlation between composite designation and tensile strength, suggesting that as the designation advances, the material's ability to withstand tensile forces improves significantly (Salman 2020; Nurazzi *et al*. 2021). The observed trend reflects enhanced structural integrity and resistance to deformation, which are critical in applications requiring robust mechanical performance. Composites corresponding to 20J10BSL often involve tailored material compositions or refined manufacturing processes aimed at reinforcing mechanical properties. Notably, designations 20J10BSL and 25J5BSL exhibited superior tensile strength compared to lower designations, highlighting their potential for high-performance applications (Ban *et al.* 2021). The systematic increase in tensile strength with 20J10BSL can be attributed to optimized material compositions, refined manufacturing processes, improved interfacial bonding, and reduced structural weaknesses. These factors collectively contributed to the enhanced mechanical performance of the composites, making them suitable for demanding applications.

Figure 7 illustrates the variation in tensile strength across different composite designations, reinforcing the significance of these results in the field of materials science and engineering.

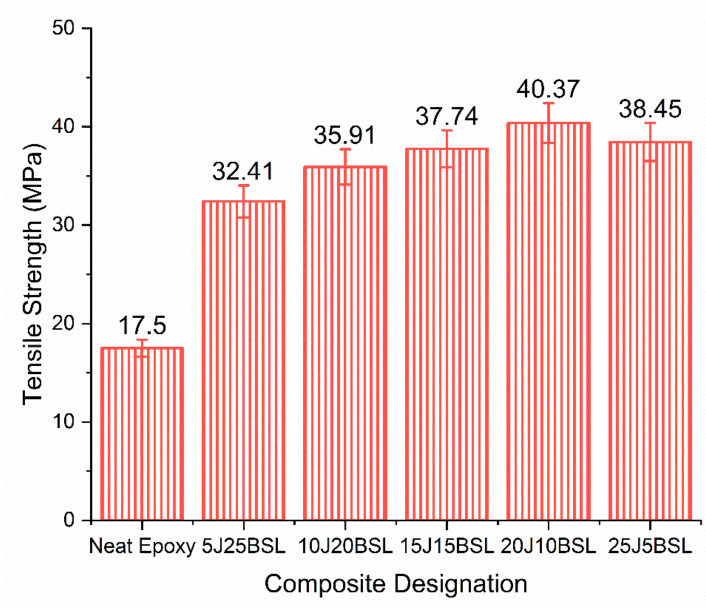

Fig. 7. Tensile strength

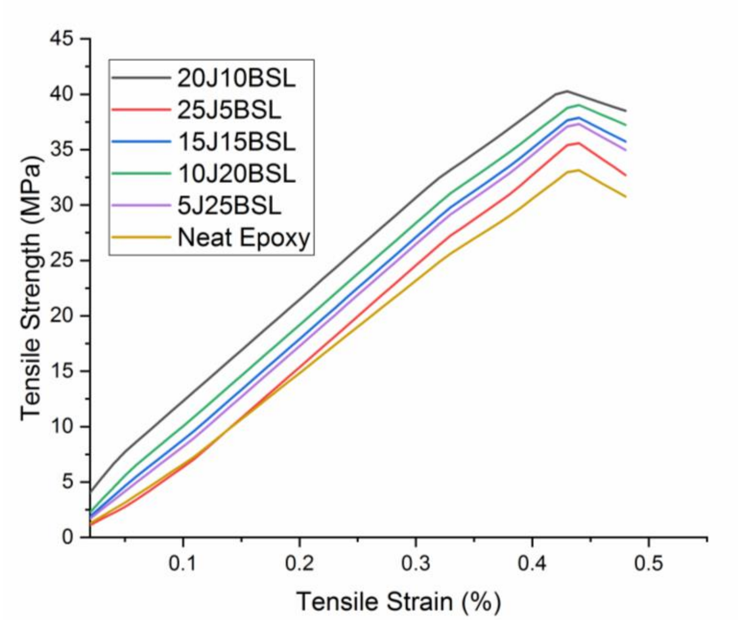

Fig. 8. Tensile strain plot

Strain in the data range from 0.01% to 0.48% indicated the response of the materials respond to increasing forces of deformation. As strain increases, tensile stress generally rises, reaching a peak for each specimen before potentially declining. This pattern indicates how the materials handle increasing deformation, with variations in peak strength and behavior under higher strain levels (Suwas *et al*. 2020; Zhang *et al*. 2021; Chithra *et al.* 2024). Figure 8 shows the various in the tensile strength and strain curve of the various composite specimens.

Flexural Strength

The flexural strength results for composite designations (5J25BSL, 10J20BSL, 15J15BSL, 20J10BSL, 25J5BSL) demonstrated a consistent increase with higher composite designation, starting from a baseline value of 34.0 MPa for neat epoxy. The data showed a progressive increase from 67.2 MPa for 5J25BSL to 86.0 MPa for 20J10BSL, highlighting a positive correlation between designation and flexural strength. This trend underscores the material's enhanced ability to withstand bending forces, indicating superior structural robustness and resistance to deformation (Anike *et al*. 2022; De Souza *et al*. 2020). Specifically, the results highlight that 20J10BSL exhibited the highest flexural strength among the tested designations, positioning it favorably for applications demanding exceptional resistance to bending stresses. These findings provide valuable insights into how composite designation influences flexural strength, empowering material engineers and designers with critical information for selecting materials tailored to specific application requirements. Figure 9 illustrates the variation in flexural strength across different composite designations, reinforcing the significance of these results in advancing materials science and engineering.

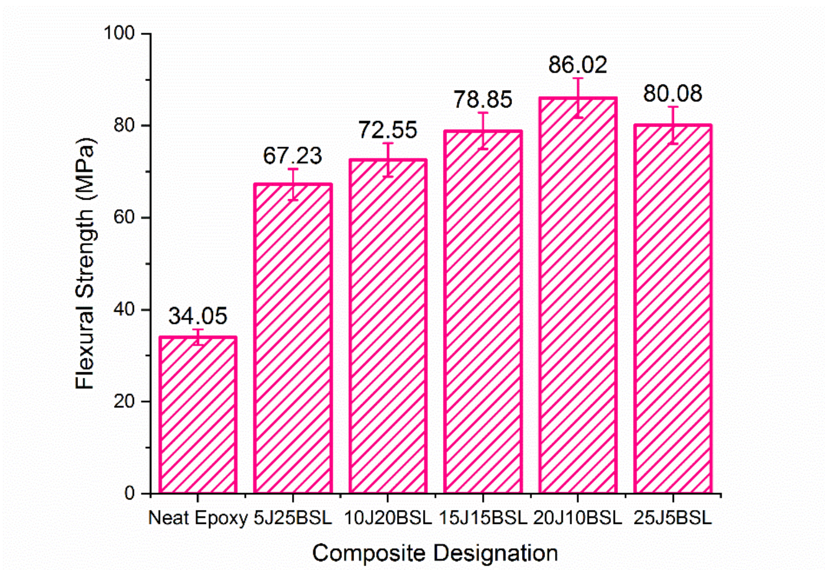

Fig. 9. Flexural strength

The data reveals how flexural strength (in MPa) of five specimens changed with increasing strain (0.01% to 0.45%). As strain rose, flexural stress generally increased for all specimens, reflecting better resistance to bending stress. Each specimen showed a unique pattern, with some reaching higher peak values of flexural strength before eventually declining, while others exhibiting more gradual increases (Zidan *et al*. 2020). This variation highlights differences in material properties and their ability to withstand bending under increasing deformation. Figure 10 shows the flexural strain plot with respect to flexural strength.

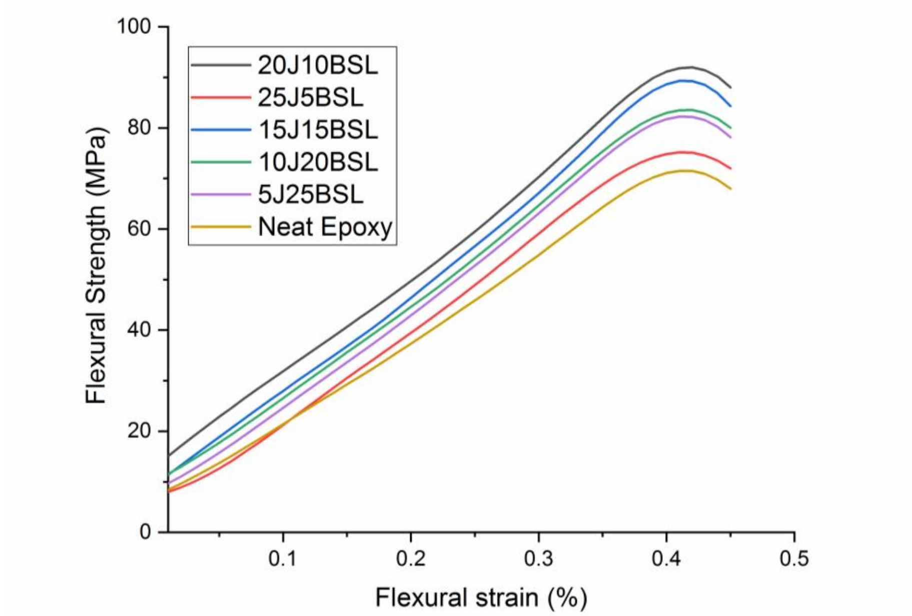

Fig. 10. Flexural strain variations plot

Interlaminar Shear Strength (ILSS)

The interlaminar shear strength (ILSS) results for composite designations (5J25BSL, 10J20BSL, 15J15BSL, 20J10BSL, 25J5BSL) demonstrated a consistent increase in ILSS with higher designation. Starting at 3.52 MPa for 5J25BSL and reaching 4.52 MPa for 20J10BSL, the data suggests a positive correlation between composite designation and interlaminar shear strength (Ashok and Kani 2022). In comparison, the hybrid composites studied here demonstrated ILSS values ranging from 3.52 to 4.52 MPa, with the highest ILSS observed for the 20J10BSL designation. These results indicate competitive interlaminar shear strength compared to previous studies, showcasing the effectiveness of the fabrication techniques and material compositions employed in this research (Zhang *et al*. 2002; Graupner and Müssig 2022). This upward trend indicates an improvement in the material's ability to resist internal shear forces between its layers, reflecting enhanced interlaminar bonding and structural integrity. The observed progression is in line with expectations, implying that 20J10BSL may involve modifications in resin matrix properties or fabrication techniques aimed at strengthening the interlaminar regions (Kim *et al*. 1992; Malik *et al*. 2024). The superior ILSS of the 20J10BSL composite suggests promising potential for applications requiring robust resistance to shear forces. Overall, this comparison underscores the significance of the ILSS results obtained in this study, validating the effectiveness of the hybrid composite formulations in enhancing interlaminar bonding and structural integrity. The results highlight 20J10BSL as having the highest ILSS, making it a promising candidate for applications where resistance to shear forces is crucial (Rao *et al*. 2021; Kumar *et al*. 2023). These findings provide valuable insights for material engineers and manufacturers, aiding in the selection of composite materials based on interlaminar shear strength requirements. The results of interlaminar shear strength (ILSS) are displayed in Fig. 11.

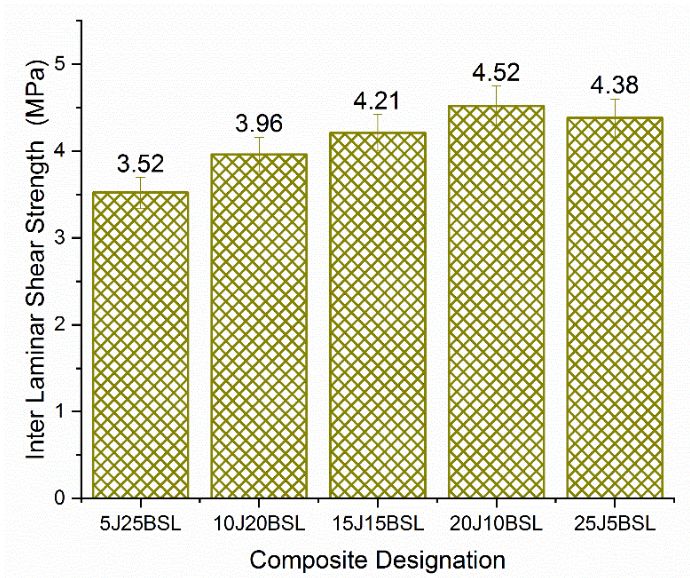

Fig. 11. Interlaminar shear strength (ILSS)

Impact Strength

The impact strength results demonstrated a consistent enhancement with increasing composite designation, starting from a baseline value of 1.05 J for neat epoxy. There was a clear progression from 2.56 J for 5J25BSL to 3.56 J for 20J10BSL, indicating improved toughness and resistance to fracture (Ahmed *et al*. 2021; Sharma *et al*. 2021). This trend suggests that 20J10BSL led to better absorption and endurance of impact forces, which is crucial in applications where impact resistance is a critical requirement. These improvements are expected with 20J10BSL due to adjustments in material composition or processing methods aimed at strengthening impact properties. For example, the 20J10BSL composite, exhibiting the highest impact strength, likely benefited from enhanced fiber-matrix interactions and optimized fiber distribution within the matrix. A comprehensive discussion on impact strength should delve into the mechanisms of energy absorption. This involves explaining how factors such as fiber orientation, distribution, and interfacial bonding influence the dissipation of impact energy (El-Abbasy 2023; Taghizadeh *et al*. 2024; Vescovini *et al*. 2024). Well-aligned fibers and uniform distribution effectively distribute stress, thereby hindering crack propagation and enhancing overall toughness. Moreover, strong bonding between fibers and the matrix facilitates efficient stress transfer, enabling the composite to withstand impact forces effectively. Additionally, factors such as fiber length and aspect ratio contribute, with longer fibers bridging cracks and reinforcing the matrix structure. By elucidating these mechanisms, the discussion provides insights into the factors driving the observed increase in impact strength with higher composite designation. This information can guide engineers in optimizing composite formulations for applications requiring superior resistance to impact loading. Figure 12 illustrates the impact energy results across different composite designations, reinforcing the significance of these findings in materials science and engineering.

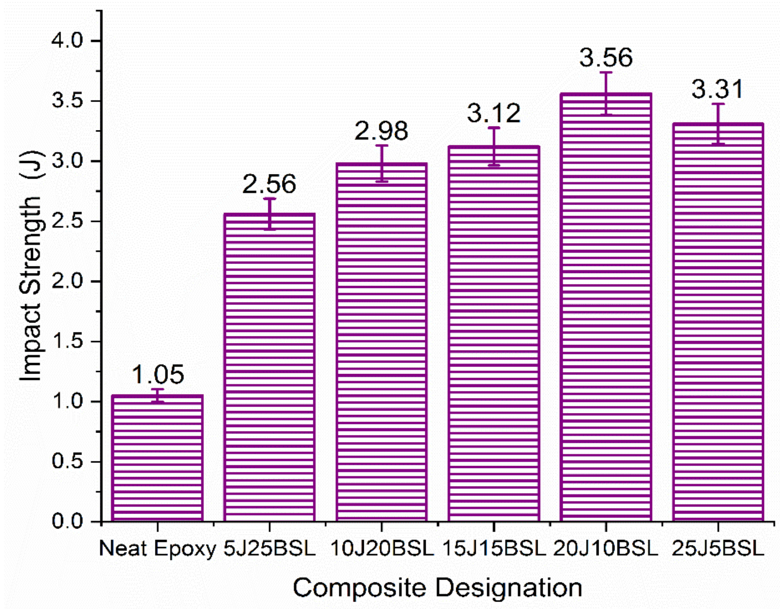

Fig. 12. Impact strength

Hardness

The hardness results for composite designations (5J25BSL, 10J20BSL, 15J15BSL, 20J10BSL, 25J5BSL) revealed a consistent increase in hardness with higher designation, with a baseline value of 6.93 SD for neat epoxy. Starting at 73.2 for 5J25BSL and reaching 83.75 for 20J10BSL, the data showed a clear positive correlation between composite designation and hardness. This progression signifies that as the designation advances, the materials become progressively harder, indicating improved resistance to indentation and wear (Domagała *et al*. 2021; Rajak *et al*. 2021; Mohd Bakhori *et al*. 2022). The observed increase in hardness suggests enhanced durability, making these composites well-suited for applications requiring robust performance over extended periods. This enhancement aligns with expectations, as higher composite designations typically involve adjustments in filler content or reinforcement strategies aimed at bolstering material hardness. Notably, the results underscore 20J10BSL as having the highest hardness among the tested composites, highlighting its potential for applications demanding superior resistance to abrasion and wear. For example, in automotive manufacturing, such composites could be utilized for components such as gears, bearings, and brake parts that endure substantial frictional rubbing. Similarly, in construction, they could be applied to flooring, decking, and structural elements to withstand heavy foot traffic and environmental conditions. In aerospace contexts, where materials face extreme operational demands, the enhanced hardness can ensure prolonged reliability and performance of critical components. Figure 13 illustrates the variation in hardness across different composite designations, emphasizing the significance of these findings in optimizing material selection for various industrial applications.

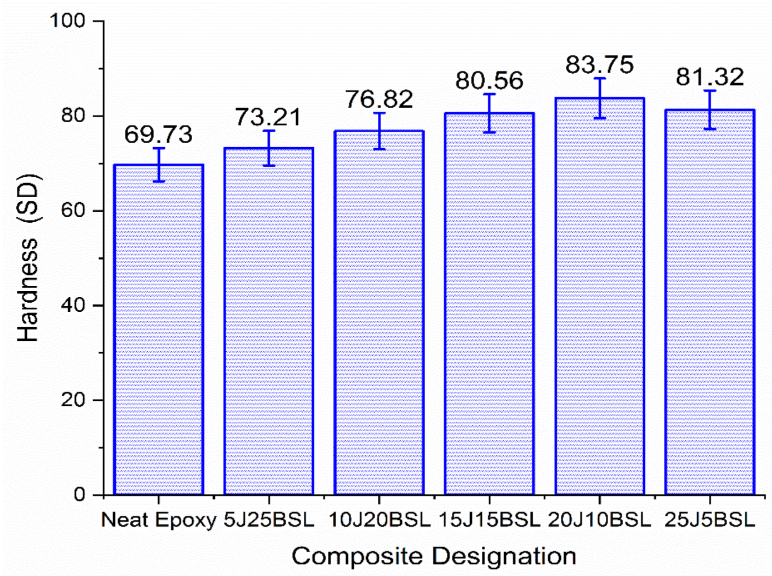

Fig. 13. Hardness

Water Absorption

The water absorption outcomes across composite designations (5J25BSL, 10J20BSL, 15J15BSL, 20J10BSL, 25J5BSL) demonstrate discrepancies in the absorbed water percentage. By analyzing the initial and final weights and calculating the absorbed water percentage, valuable insights into the materials' moisture vulnerability are obtained (Al-Hajaj *et al*. 2018). The data reveals a consistent rise in water absorption with increasing composite designation, from 48.0% for 5J25BSL to 58.9% for 25J5BSL. This suggests varying porosity and hydrophilic characteristics influenced by composition or fabrication methods. The higher water absorption in 20J10BSL indicates a higher proportion of hydrophilic components; this is in accord with jute fibers' known tendency of moisture absorption due to their cellulose structure's hydroxyl groups (Sathiyamoorthy and Senthilkumar 2020). Conversely, lower designations may feature a higher polymer matrix ratio, with typically lower water absorption. Factors affecting absorption include fiber-matrix interface quality and treatment methods, where better bonding reduces moisture ingress pathways. Fiber treatments, such as surface modifications, can alter hydrophilicity, impacting overall absorption. Long-term durability may be compromised by water absorption, leading to dimensional instability, mechanical property reduction, and interface degradation. Understanding these influences is vital for designing moisture-resistant composites for sustained performance in practical applications. (Abd El-baky and Attia 2019; Xu *et al*. 2024). The findings of water absorption are displayed in Fig. 14.

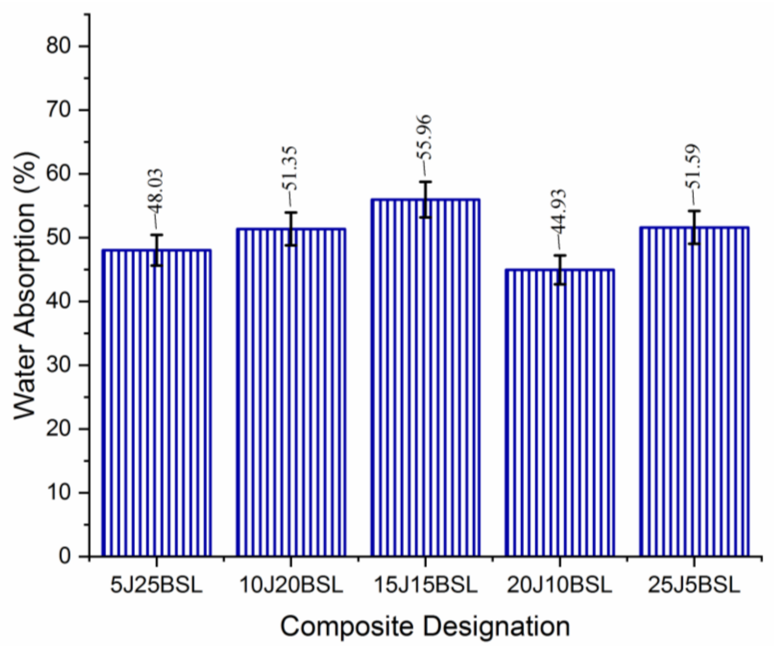

Fig. 14. Water absorption

Fourier Transform Infrared Spectroscopy

The results of Fourier transform infrared spectroscopy are shown in Fig. 15. The prominent peak residing at 1650 cm^{-1} represents the amide-I band—a resonance stemming from the stretching vibration of the C=O bond within the amide group (Schweitzer-Stenner 2021). In the context of composite materials, such as bio-natural fiber-reinforced epoxy hybrids, this peak often arises from the presence of proteins or nitrogen-containing compounds inherent in the natural fibers. Between 1600 and 1000 cm^{-1}, multiple peaks correspond to specific functional groups and molecular vibrations intrinsic to the analyzed materials (Radha and Wang 2023). The signal at 2794 cm^{-1} signifies C-H asymmetric bending vibrations, while the discernible peak at 832 cm^{-1} (Indran *et al*. 2018) is attributed to out-of-plane stretching motions. The peak at 2251 cm^{-1} represents wax or oil constituents (Manimaran *et al*. 2021). The stacked FTIR spectra allow for a clear comparison of peak shifts, which indicate the interactions between the epoxy matrix and the reinforcing fibers such as jute fibers and BSL. Notable changes in the peaks may suggest the formation of hydrogen bonds, ester linkages, or other chemical interactions that contribute to the strengthening of the composite. By analyzing these spectral changes, the chemical bonding mechanisms between the fibers and the matrix can be better understood, providing insight into the structural integrity and performance of the hybrid composites.

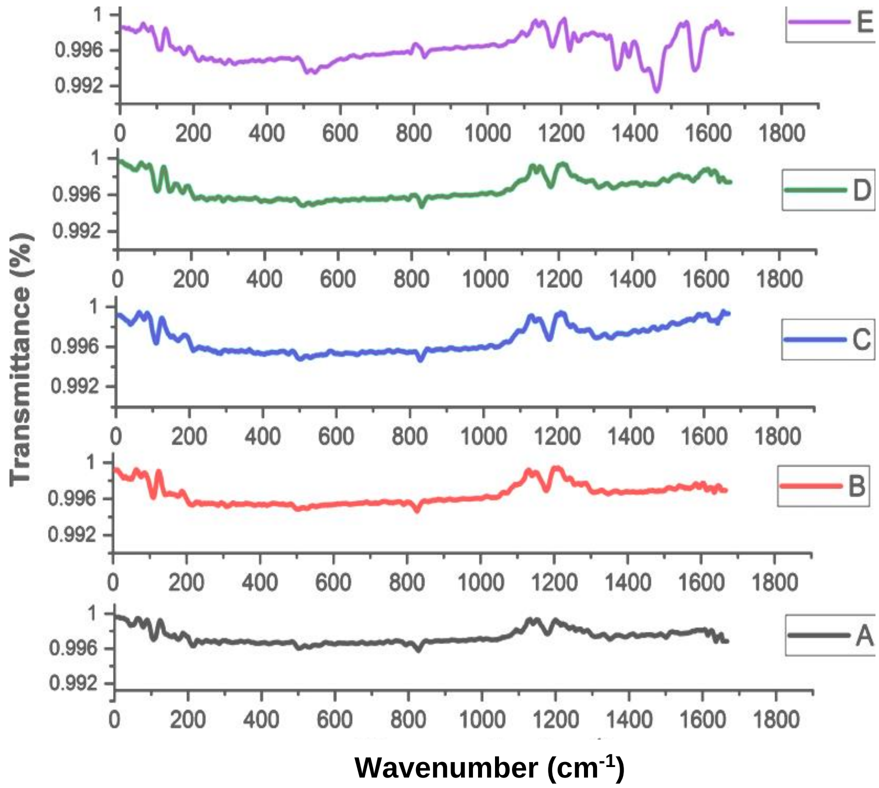

Fig. 15. FTIR analysis. (A) 5J25BSL, (B) 10J20BSL, (C) 15J15BSL, (D) 20J10BSL, (E) 25J5BSL

Scanning Electron Microscopy

Figure 16 shows the SEM image of 20J10BSL. Figure 16A shows the presence of numerous fiber pullout and voids**,** indicating poor bonding between the fibers and the epoxy matrix. This weak interfacial adhesion likely leads to reduced load transfer between the fibers and the matrix, resulting in lower tensile strength and an increased potential for mechanical failure (Palanisamy *et al.* 2022; Kurien *et al.* 2023). The fiber pullout observed suggests that the fibers had not been effectively anchored within the matrix, weakening the composite's overall integrity. In contrast**,** Fig. 16B illustrates fiber dispersion and the presence of microcracks**.** The good adhesion between the fibers and the matrix is evident in the reduced occurrence of fiber pullout and the resistance to crack propagation. This strong interfacial bonding enhances the composite's tensile strength by facilitating efficient load transfer between the fibers and the epoxy matrix (Amir *et al.* 2017; Ashraf *et al.* 2023). However, the microcracks and agglomerations observed in the image suggest potential issues with the matrix curing process, which could affect the composite's mechanical performance. Despite these signs, the adhesion in these composites appeared better than in unfilled sisal epoxy composites. The observed agglomerations suggest potential issues with matrix curing, which could impact mechanical performance.

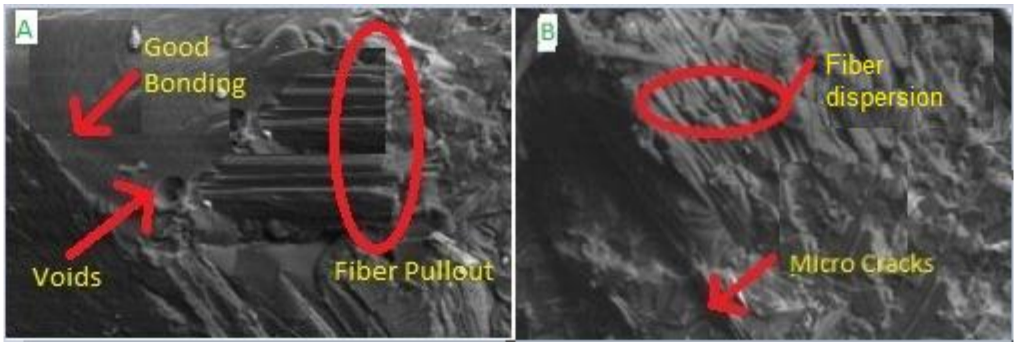

Fig. 16. (A) Fiber pullout, voids, good bonding; (B) Fiber dispersion

Overall, SEM analysis aids in correlating micro structural features, such as fiber-matrix bonding and crack propagation, with the mechanical properties observed in tensile testing, providing valuable insights into fracture mechanisms and overall composite performance.

CONCLUSIONS

1. Tensile strength represents the maximum amount of stress that a material can withstand before breaking under tension. In this dataset, the composite designation with 20% jute and 10% banana stalk leaf (BSL) fibers offered the highest tensile strength (40.4 MPa). This implies that the composition containing 20% BSL fibers and 10% jute fibers had the best resilience to stretching pressures of the combinations tested. As the percentage of BSL fibers declined or jute fibers increases, the tensile strength decreases slightly, as demonstrated by the lower values in the other categories.
2. Flexural strength assesses a material’s capacity to withstand distortion during bending. Similar to tensile strength, the 20% jute and 10% BSL composite showed the highest flexural strength at 86.0 MPa, demonstrating more resilience to bending forces than other compositions. Again, the trend indicates that a mix of 20% BSL fibers and 10% jute fibers improved flexural characteristics.
3. Impact strength refers to a material’s ability to absorb energy during fracture under abrupt loading. Once again, the 20% jute and 10% BSL composite had the maximum impact strength at 3.56 J, indicating that it was better able to sustain rapid loads or impacts than the other classifications.
4. Interlamellar shear strength (ILSS) assesses the strength of the bond between layers of a composite material. Consistently, the 20% jute and 10% BSL composite showed the highest ILSS value at 4.52 MPa, indicating stronger interlaminar bonding than the other compositions.
5. Hardness measures a material's resistance to indentation and scratching. The 20% jute and 10% BSL composite once again had the highest hardness value (83.8 SD), suggesting higher resilience to surface deformation when compared to other designations.

6. Water absorption results varied across composites and showed no correlation with fiber %. However, the 20% jute and 10% BSL composite had a moderate water absorption of 52.4%, indicating adequate moisture resistance.
7. The present study used Fourier transform infrared (FTIR) and scanning electron microscopy (SEM) investigations to explore chemical bonding and morphological properties, respectively, offering further information about the composites' composition and structure.
8. Overall, the 20% jute and 10% BSL composite surpassed other compositions in terms of tensile strength, flexural strength, impact strength, ILSS, and hardness. In addition, owing to dispersion, fiber content, homogeneity, interfacial bonding, and synergistic effects, 25% jute and 5% BSL performed worse than 20% jute and 10% BSL. This implies that the combination of 20% jute and 10% BSL fibers gave the most favorable mechanical qualities among the examined compositions, making it a suitable contender for applications that require high-performance materials.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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