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Article

Comparative analysis on mechanical and physical properties of jute-banana fiber reinforced epoxy-based hybrid composites: impact of fiber orientation

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ABSTRACT

Natural fibers are eco-friendly and an alternative to synthetic fibers. In this study, a hybrid epoxy-based composite reinforced with jute and banana fibers with their different orientation [J(Uni)-B(Uni), J(Uni)- B(Bi), J(Bi)-B(Uni), J(Bi)-B(Bi)] matrix was evaluated. This research experimentally investigated the physical and mechanical properties, such as theoretical and experimental density, void content, water absorption, tensile strength, impact resistance, and hardness, by varying fiber orientation in the matrix. Key findings demonstrate that fiber orientation significantly influences the mechanical properties and microstructure of the composite. Specifically, orientation has a notably enhanced effect on tensile strength, hardness, and impact resistance, while conversely exhibiting a reduced influence on void formation within the matrix. Among the tested configurations, sample S4, featuring unidirectionally oriented Jute and Banana fibers, delivered the highest tensile strength (53.72 MPa) and hardness (58 HRM), coupled with the lowest observed void content (2.44%). Furthermore, sample S3, combining unidirectional Jute with bidirectional Banana fibers, achieved superior impact resistance (30.86 KJ/m^2) compared to other orientations, while also maintaining the lowest level of hydrophilicity (0.79%). These composites have the potential to be an option for material choice that can be used in a high-strength and impact scenario.

1. Introduction

Research and engineering have shifted their attention in recent decades from conventional materials to composite materials. Although glass and carbon fiber reinforcement are the most popular, natural fiber has been the subject of study by various academics due to its numerous advantages, including its acceptable specific strength, low density, affordable price, CO_2 neutrality, and biodegradability, among others. Thus, the scientific community and numerous industries highly regard natural fiber composites due to their exceptional strength, high durability, and environmental sustainability. Sustainability is one of the primary motivating forces for all of the studies. In several non-load-bearing applications, non-sustainable materials must be replaced with sustainable ones. The concern for the environment is growing daily. The demand for a developed and sophisticated future is constant. The field of materials will undergo a significant transformation as a result of this goal, and new materials with improved properties should be introduced. The powerful ability of composite materials to provide the desired physical, chemical, or mechanical qualities has already been demonstrated. Natural fiber is a fantastic innovation in this field for meeting global demand, and it would be a new level if it could successfully be hybridized with natural fiber to obtain the desired properties [1]. A mixture of natural fibers enclosed in a polymer matrix is referred to as a natural fiber composite. Two components make up a composite. The matrix is one, while the reinforcement is another. Fibers are applied in composites as potential reinforcement in the matrix material. In the past, only synthetic fibers, including glass fiber and carbon fiber-reinforced composites, were used due to their low cost and superior mechanical properties. Although the scientific community is continually working to enhance the mechanical properties of natural fiber composites, they are now being used more frequently. A composite fiber system is introduced into the matrix, which is a homogeneous, monolithic material. The composite component's net form, the distribution of loads among the fibers, the binding of the fiber reinforcement, and the surface quality are all controlled by the matrix. Ceramic matrix, metal matrix, and polymer matrix are the three primary categories of matrix materials. The three primary categories of polymers are thermosets, thermoplastics, and elastomers. In thermoplastics, there are secondary linkages between the molecular chains. Thermoplastic materials include polystyrene, Teflon, Acrylic, Nylon, and others. In thermosetting polymers, primary bonds hold molecular chains together, which are then held together by robust cross-links. Thermosetting polymers have a high melting point and tensile strength. Thermoplastic plastic has a lower molecular weight than thermosetting plastic. Vinyl ester resin, epoxy resin, and polyurethane are a few examples of thermosetting polymers. Epoxy resin is a pre-polymer that is frequently applied in a variety of industries, as coating, high-performance composites, and adhesives [2]. There has been a remarkable rise in research into bio-based polymers in recent years as a result of expanding environmental and economic worries, as well as the unpredictability that comes with limited petrochemical assets. Epoxy is a biodegradable and environmentally friendly, bio-based resin. Both terms allude to non-toxic, renewable plant-based resins.

The main purpose of reinforcement in composite materials is to boost the mechanical properties of the plain resin system. Every other fiber used in composites has unique features that affect the composite properties in various ways. Different kinds of fibers are used as reinforcement in the natural fiber reinforced composite. Natural fibers are fibers that are good for the environment because they come from plants and forests. They are renewable, biodegradable, and can be used without harming the environment. The origin of natural fibers, whether they come from plants, animals, or minerals, is used to categorize them. There are six different kinds of natural fibers. They include bast (jute), leaf (banana), grass, and reed (rice, wheat), seed (cotton), core (hemp), and all other sorts of fibers (wood and roots) [3]. Due to their lightweight qualities, high strength, and high rigidity, composite materials are used. The lightweight quality is crucial for lower fuel use and lowers fuel costs. In certain circumstances, the raw materials are readily available, which will lower the cost of raw resources. The mechanical qualities are excellent. Composite materials allow for design freedom throughout the production process, enabling the creation of numerous intricate and sophisticated products. The primary benefit of natural fiber composites is their accessibility to natural fiber. Natural fiber composites are fire-resistant and do not release any hazardous fumes. Natural fibers are recyclable and biodegradable. We can alter the characteristics of natural fiber chemically. Natural fiber clothing is especially pleasant in the summer since it absorbs moisture and perspiration. It is being utilized in the papermaking sector. Products made from synthetic natural fibers also have the benefit of withstanding large weights without breaking. Two types of plants produce natural fiber. Primary plants like jute, sisal, and hemp are grown only for their fiber content. Secondary plants like pineapple and coir are grown for their fiber content as a byproduct. Natural fibers frequently have a distinctive set of qualities, such as mechanical and thermal characteristics. The primary chemical components of plant fibers include wax, cellulose, lignin, hemicellulose, and pectin. The geographical area where the plants are grown affects the fiber content. The amount of cellulose and lignin a fiber contains determines its physical properties. Fibers with a high cellulose content and a low lignin content will have the right mechanical characteristics. Properties of different fibers are listed in Table 1 and Table 2.

Table 1. Physical properties of natural fibers [4]

Fiber	Density (g/cc)	Elongation (%)	Tensile Strength (MPa)	Young's Modulus (GPa)
Jute	1.3-1.5	1.5-1.8	393-773	26.5
Banana	1.3-1.35	6.54	529-914	27-32
Hemp	-	1.6	690	-
Sisal	1.5	2-2.5	611-635	9.4-22
Coir	1.2	30	175	4-6
Flax	-	2.7-3.2	345-1035	27.6
PPLSF	1-1.2	2-4.5	97-196	2.5-5.4
Cotton	1.5-1.6	7-8	287-597	5.5-12.6

Table 2. Chemical components of natural fibers [5]

Fiber	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Wax (%)
Jute	61-71.5	17.9-22.4	18.8-13	0.5
Banana	83	6-19	5	0.58-1.41
Hemp	70.2-74.4	17.9-22.4	3.7-5.7	0.8
Sisal	78	10	8	2
Coir	37	-	42	-
Flax	64.1-71.9	18.6-20.6	2.2	1.5
PPLSF	58.58	22.8	13.48	0.35

B. Shivamurthy et al. [5] found the physical characteristics of epoxy composites reinforced with jute fibers. Using alkali-treated fibers and cashew nut shell liquid blended epoxy resins, including feasibility testing utilizing tensile and flexural strength. The results show that by utilizing the alkaline-treated jute fibers and a redesigned matrix, it is feasible to create superior composites with mechanical characteristics that exceed jute fiber-strengthened epoxy composition manufactured using unprocessed jute fibers and ordinary epoxy resin. The greatest feature, which turned out to be the best jute fiber composite, had alkali-treated fiber with an estimated tensile strength of 679 MPa and flexural strength of 88.83 MPa. D. Shanmugam et al. [6] investigated the mechanical characteristics, both static and dynamic, of alkaline-treated uninterrupted Palmyra Leaf Stalk Fiber (PPLSF) and jute fibers in an unfilled polyester matrix. Compared to P100 composites, tensile strength and tensile modulus improved by 46% and 65%, respectively, while flexural strength and flexural modulus improved by 56% and 19%, respectively. N. Venkateshwaran et al. [7] studied the composite architectures, mechanics, and physical characteristics. The research demonstrates that composites reinforced with banana fibers have low density, high tensile strength, high tensile modulus, and low elongation at break. The construction, automotive, and industrial industries will find the features indicated to be quite suited. Research conducted by V.S. Srinivasan et al. [8] on the thermal characteristics of natural fiber composites based on banana and flax demonstrated that hybrid composites are superior to mono-fiber-reinforced composites in terms of characteristics. Comparing hybrid composites to single fiber composites, the former can support higher impact and flexural loads. The research for this publication also demonstrates that hybrid composites are stronger than single-fiber composites.

Research by M. Jannah et al. [9] showed that chemically treated banana fiber composites exhibited lower water absorption compared to untreated banana fiber composites. Compared to untreated banana fiber, treated banana fiber has greater flexural and impact strength. To improve physical properties, M. Boopalan et al. [10] evaluated the physical and thermal properties of epoxy hybrid compounds enhanced with jute fiber and banana fiber. The weight-proportioned 50/50 jute and banana fiber reinforced epoxy hybrid composites exhibited improved thermal properties and a lower propensity to absorb water. The tensile strength, flexural strength, and impact strength of composites that contain banana fiber are all increased by 17%, 4%, and 35.5%, respectively. S. Parbin et al. [11] examined the physical features of composites made using natural reinforcing fibers as well as the numerous variables affecting these attributes. The use of natural fibers as a viable alternative to synthetic fibers in a wide range of applications was also emphasized. They claimed that the mechanical properties of these composites make them suitable for low-load implementations such as window panels, decorative items, shock-absorbing pads, fishing equipment, internal airplane sections, lampshades, food trays, as well as internal paneling, among others. According to X. Chen et al. [12], benzylation is a productive way to turn plant fibers into thermal elastic polymers that may be treated according to accepted plastics industry practices. Plant fibers may become more evenly processable by altering the modification, mechanical properties, and biodegradability circumstances. A.K. Bledzki et al. [13] studied the characteristics of fiber-reinforced bio-epoxy composites with different bio-contents from 0% to 100%. Thermal and physical testing findings on organic epoxies and hybrids using jute fiber demonstrate the effect of scale of bio-contents on their specified qualities, as well as the potential for replacing standard epoxy technologies with materials generated from renewable resources. In 2014, jute fiber treated with 5% NaOH solution showed improved mechanical properties compared to treatment with 10% NaOH solution, as studied by Gopinath et al. They conducted a comparative analysis between jute-epoxy and jute-polyester and found that jute-epoxy had a tensile strength of 12.46MPa, exceeding that of jute-polyester (9.24MPa). However, jute-polyester showed better impact strength and hardness than jute-epoxy composite [14]. Rahman et al. [15] discovered that oxidizing jute fiber with sodium periodate and following with urotropine would increase its mechanical qualities, but that doing so would reduce its tensile strength (20, 25, 30, and 35 percent of jute). The poor interfacial area between the fiber matrices increased as the load increased. Due to the use of a new compatibilizer, the final result is a drop in tensile strength with a range of 23.56 to 29.49 MPa, less than the prior research (23 to 55 MPa). With rising loadings up to 30%, impact strength first increased and then declined. With increasing loading, both hardness and water absorption percentage rose, although post-treated composites had lower absorption percentages than raw and oxidized ones, which was preferable. Idicula et al. [16] conducted a thermo-physical investigation of composite materials reinforced with natural fiber (in this case, pineapple leaf fiber), and they conducted experiments showing that the ability of natural fiber to transmit heat was improved as a result of hybridization with glass fiber. The use of sodium hydroxide as a treatment resulted in a 43% increase in thermal conductivity (NaOH). For the treatment with polyester resin, the characteristics of composite materials were improved.

The research of Harak et al. revealed that the mechanical properties of hybrid composites, particularly flexural, tensile, and impact characteristics, were considerably enhanced with a composition of 76% Abaca fiber, 20% Areca fiber, and 4% nano-SiO_2, suggesting that the hybridization of these fibers improves performance and mitigates environmental impacts [17]. Sekhar et al. [18] conducted research with the banana fiber and roselle fiber composite, which had 68% higher tensile strength than pure epoxy resin. The mechanical characteristics of composites were improved by adding these natural fibers. In water absorption tests, the composites showed outstanding resistance and a far lower weight gain than pure epoxy resin. Higher weight percentages of roselle fiber in the composite increased water absorption, showing hydrophilic characteristics. According to the findings from the investigation of Venkatesh et al. [19], the mechanical properties of the intralaminar Jute/Sisal/E-Glass fiber-bonded epoxy hybrid Composite were significantly improved. The study found that the hybrid composite had an enhancement of 28.65% in tensile strength, 47% in flexural strength, and 37.41% in impact strength when compared with the composite with zero orientation. These findings indicate that the intralaminar configuration is effective in improving the overall performance of the material. Bio-filler was incorporated by Ganasan et al. [20], particularly NaOH-treated banana fiber and calcined eggshell particulate (CEP), substantially enhanced the thermal insulation properties of the epoxy composites. This investigation also revealed that the addition of CEP significantly improved mechanical properties, with 20 wt% of CEP providing a flexural strength of 36.57 MPa and a modulus of 300.12 MPa at 12 wt% of CEP. Additionally, water absorption decreased to 5.31% at 4 wt% of CEP, indicating enhanced structural characteristics of the bio-composites. This article also includes a comparison of the physical and mechanical properties of jute and banana hybrid fiber composites. The development of banana and jute fiber-reinforced composite material is increasing day by day. Jute and banana are two common types of natural fiber, and are also abundant in Bangladesh. Much work has been done on jute and banana fiber because of their attractive mechanical properties. Epoxy is a biodegradable matrix. So, the researcher is very much interested in replacing fossil fuel-based thermosetting resins with biodegradable epoxy. In the domain of natural fiber composites, numerous researchers have investigated methods to enhance mechanical properties and performance. That's why we selected banana and jute fiber as reinforcement material and epoxy as matrix in this study. The previously mentioned literature review confirms that substantial research has been conducted on the physical and mechanical properties of jute banana hybrid fiber reinforced polymer composites. However, the assessment of the physical and mechanical properties of bidirectional and unidirectional jute banana hybrid fiber reinforced epoxy composites has been inadequately reported. This study implemented both unidirectional and bidirectional banana and jute fibers to create a hybrid composite material, facilitating the clear demonstration of the different orientations of hybrid fiber effects. The physical and mechanical parameters, including theoretical and experimental density, void content, water absorption, tensile strength, impact resistance, and hardness of different orientation hybrid fiber composite materials, were examined.

2. Materials and methods

2.1 Materials

In Bangladesh, jute is known as the "golden fiber," and the Indian subcontinent is where it is most well-known. Jute fiber is a type of natural fiber that is abundantly produced on the Indian subcontinent. In addition to producing the delectable fruit, the banana or plantain plant also yields textile fabric known as banana fiber. Natural fiber is found in bananas. It is made of plants. The banana plant is a large perennial herb with pseudo-stem-like leaf sheaths. In this investigation, banana and jute fibers as reinforcement materials for the composite were procured from the local supplier of Chattogram, Bangladesh (Figure 1). The epoxy resin, the corresponding hardener HY951, and NaOH were supplied by Taj Scientific Limited, Chattogram, Bangladesh.

a) Jute Fiber a) Banana Fiber

Figure 1. Natural fibers for reinforcement

2.2 Fabrication of composite

Fiber extraction, fiber chemical treatment, fiber orientation into the matrix, and composite fabrication method all have an impact on a composite's mechanical and thermal properties (Figure 2). In this experiment, hybrid banana fiber reinforcement composite (BFRC) and jute fiber reinforcement composite (JFRC) were created using the hand layup process.

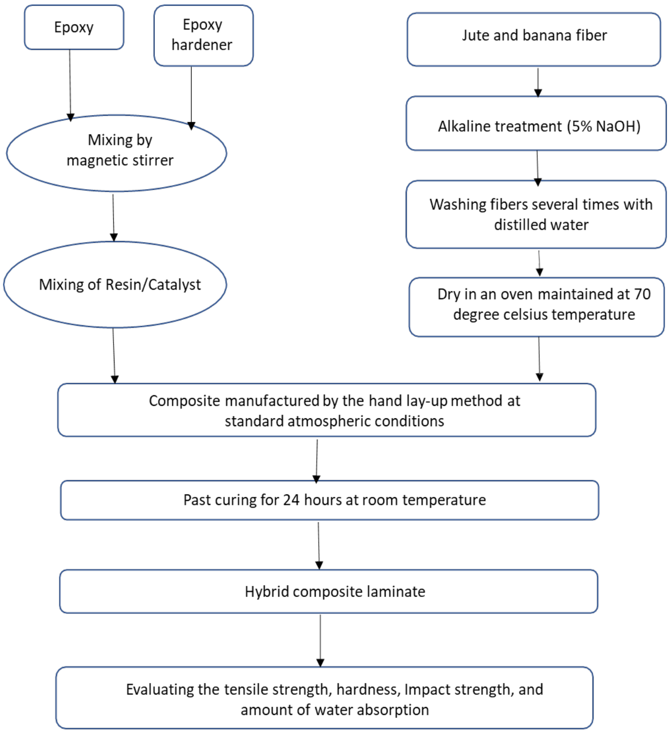


Figure 2. Composite fabrication flowchart

The hydrophilic characteristics of natural fibers and the hydrophobic properties of the polymer matrix are the main fundamental problems with using natural materials as a reinforcing agent for polymer composites. These problems affect the mechanical properties of natural fiber composites. Natural fibers can have their hydrophilic tendencies diminished by applying a chemical treatment (Figure 3). Sodium hydroxide (NaOH), potassium permanganate ($KMnO_4$), silane (SiH_4), and acetic acid (CH_3COOH) are the most commonly used chemical treatments to reduce the hydrophilic properties of natural materials [21]. The surface of the material can be altered while enhancing its strength by chemically treating the fiber to promote bonding between the fiber's surface and the matrix material. The mechanical characteristics of composites are improved while their water absorption is minimized. In this investigation, fiber was chemically treated using NaOH. The fibers were kept submerged for 30 minutes in 5% NaOH at room temperature. Before being immersed in extremely mild HCl to remove the NaOH adhering to the surface of the fibers, the fibers had been washed and rinsed numerous times with deionized water. The fibers underwent several rinses in deionized water and were dried at 80°C for 3 hours.

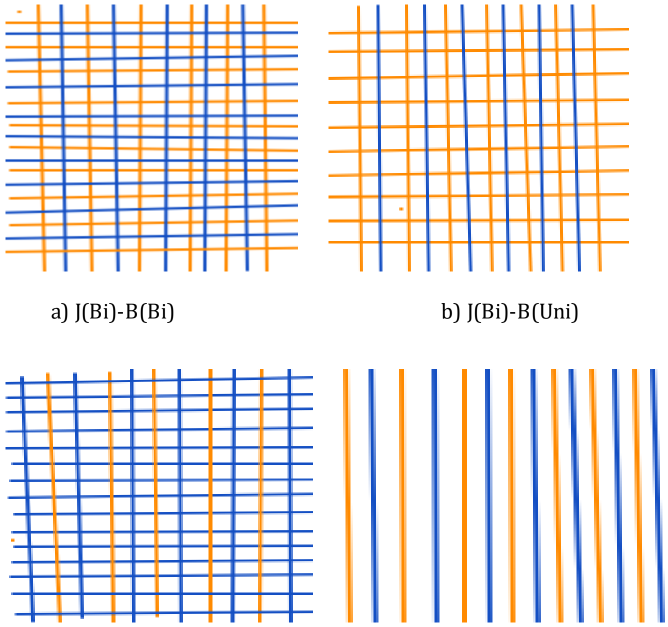
(a) (b)

Figure 3. Chemical treatment of jute and banana fiber: (a) Jute Fiber in NaOH solution, (b) Banana Fiber in NaOH solution

Fiber alignment affects the geometry of the mold cavity as the injected material flows through the mold, which directly affects mechanical properties. Fiber orientation in a composite refers to how individual fibers are placed in a fiber-reinforced polymer composite to allow for the best structural arrangement [22]. In composite materials, a part's strength is significantly impacted by fiber orientation. Four common fiber-reinforced composite orientations are unidirectional, random, bidirectional, and multidirectional (Figure 4). The mechanical and chemical properties of an injection-molded object may be considerably enhanced by fiber orientation, regardless of the direction of the fibers within the material. For each fiber orientation, composite materials exhibit diverse physical properties. Bidirectional and unidirectional fiber orientations were used in this project to create composites. Reviewing the literature, we selected 30 wt% total fiber content for every sample to get optimal results in properties [23]. Table 3 illustrates the orientation and loading of the fiber in every sample.

Table 3. Orientation and percentage of fiber in composites

Sample ID	Orientation	Jute Fiber Content (wt%)	Banana Fiber Content (wt%)	Epoxy resin Content (wt%)
S1	Jute (Bidirectional) and Banana (Bidirectional) - (J(Bi)-B(Bi))	15	15	70
S2	Jute (Bidirectional) and Banana (Unidirectional) - (J(Bi)-B(Uni))	15	15	70
S3	Jute (Unidirectional) and Banana (Bidirectional) - (J(Uni)-B(Bi))	15	15	70
S4	Jute (Unidirectional) and Banana (Unidirectional) - (J(Uni)-B(Uni))	15	15	70



a) J(Bi)-B(Bi) b) J(Bi)-B(Uni)

c) J(Uni)-B(Bi) d) J(Uni)-B(Uni)

Figure 4. Schematic drawing of different fiber orientations (Orange color line – Jute fiber, Blue color line – Banana fiber)

By traditional hand lay-up light compression molding technique, different orientations of epoxy-based hybrid fiber composites with 30 wt% of banana and jute fiber, maintaining a 1:1 ratio of jute and banana fibers, were produced. Two different types of fiber orientation, such as unidirectional and bidirectional, were implemented for this study. The composition and designation of various composites fabricated using epoxy are shown in Table 3. At first, the epoxy was mixed with hardener HY951 in a ratio of 10:1 using a magnetic stirrer. Then, the fiber was placed in a mold, and the epoxy resin with hardener was continually poured until all of the filaments were thoroughly saturated. After allowing the mold to be applied at a pressure of 0.1MPa from the top to perfectly harden at room temperature for 24 hours, the specimens were gently removed from the mold. After taking the samples S1, S2, S3, and S4 from the mold, all samples were cut precisely using a cutting disk to make the specimen as per ASTM standards for physical and mechanical tests (Figures 5-7).

2.3 Tensile test

Using an Instron tensile tester, the tensile characteristics of bidirectional and unidirectional hybrid composites were determined. The test was carried out by ASTM D638. Four specimens were tested, and the results were reported. A Universal Testing Machine (UTM) is displayed in Figure 8. Specimens before and after a tensile test are shown in Figure 9 and Figure 10, respectively.

2.4 Hardness test

Rockwell is a scale for determining the hardness of a material based on the indentation hardness. A penetration of an indenter under a major load is compared to the penetration under a minor load to measure this test. Different scales are used for different materials to measure this test. ASTM E18 was the standard that was used for the test.

a) J(Bi)-B(Bi) b) J(Bi)-B(Uni) c) J(Uni)-B(Bi) d) J(Bi)-B(Bi)

Figure 5. Hybrid composite laminate

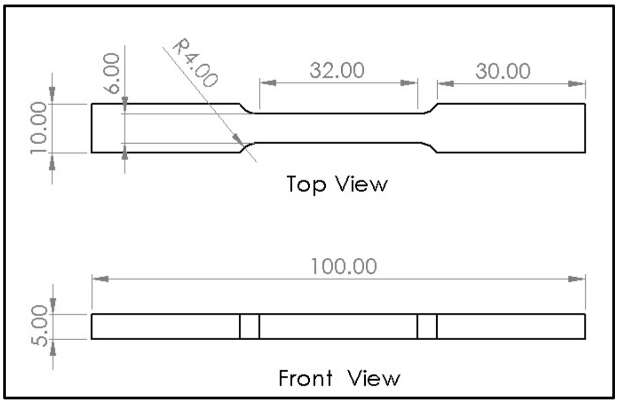


Figure 6. 2D drawing of tensile test specimen

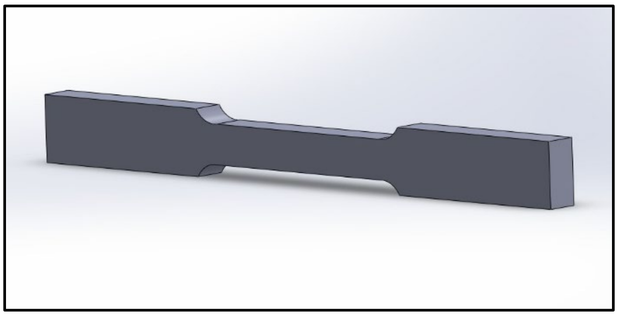


Figure 7. 3D design of tensile test specimen

Figure 8. Universal testing machine

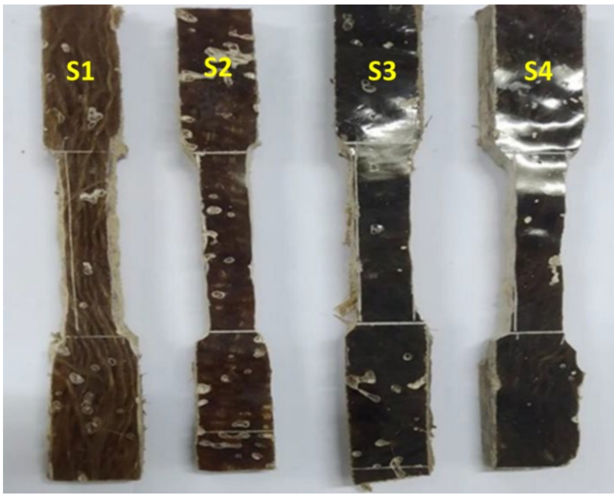


Figure 9. Specimens before the tensile test

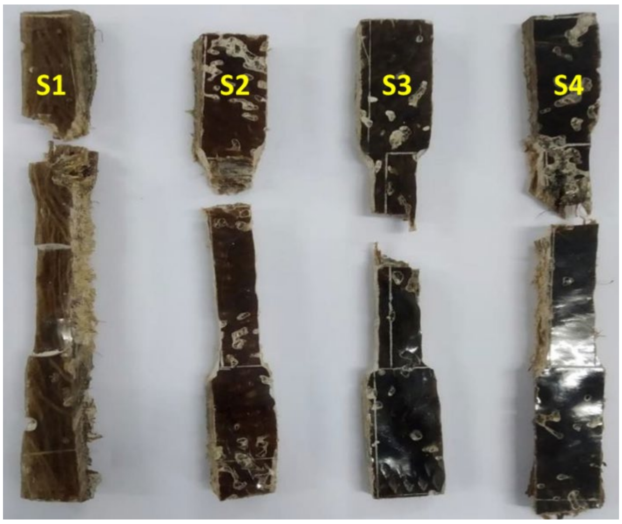


Figure 10. Specimens after the tensile test

The Rockwell hardness can be calculated using the following formula:

$$Hardness = (N-hd) \quad (1)$$

Where, d = depth in mm, h and N are the scale factors which depend on the scale on which the test is carried out.

In this study, scale M was used, with an indenter diameter of 6.35mm, and the major load was 100kg (Figure 11).

Figure 11. Hardness testing machine

2.5 Impact test

The impact test is a technique used to evaluate material toughness, impact strength, and notch sensitivity. The impact test determines the amount of impact a material can withstand. Impact testing often falls into one of two categories. The Charpy impact test and the Izod test are two types of impact tests. In this study, we used the Charpy impact test method to measure the impact strength. The distinction between the Charpy test and the Izod test is that the sample is kept horizontally in the Charpy test, but in the Izod test, the sample is kept vertically. The test was carried out in accordance with ASTM E23. The impact strength test can be calculated from the following formula:

$$Impact\ strength = \left(\frac{mgR(\cos\beta - \cos\alpha)}{A}\right) \quad (2)$$

Where

m = Mass of the pendulum (kg)

R= Radius of pendulum

g = Gravitational acceleration (ms-2)

α= Rise angle (degree)

β= Fall angle(degree)

A = cross-sectional area of the specimen (m^2)

Figure 12 and Figure 13 illustrate the 2D and 3D drawings of the impact test specimen, respectively. Additionally, the Charpy impact testing machine and the specimens before and after the impact tests are shown in Figures 14-16.

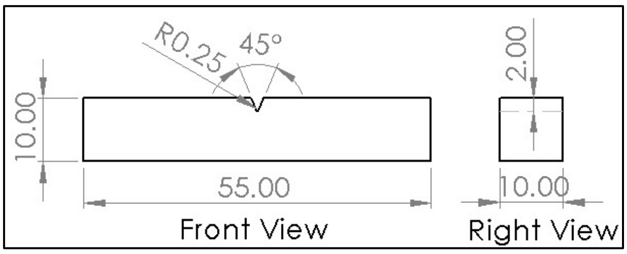


Figure 12. 2D drawing of impact test specimen

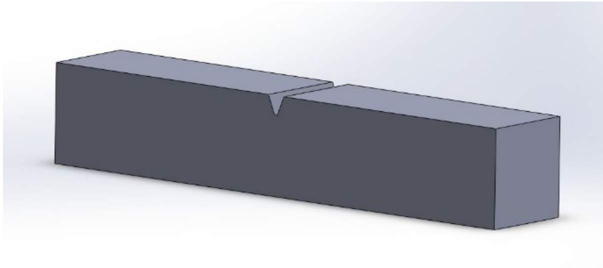


Figure 13. 3D design of impact test specimen

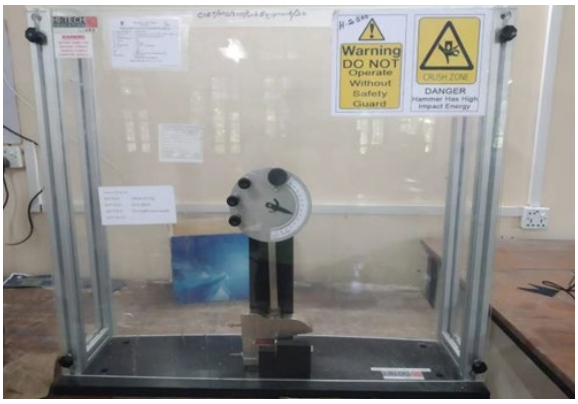


Figure 14. Charpy impact testing machine

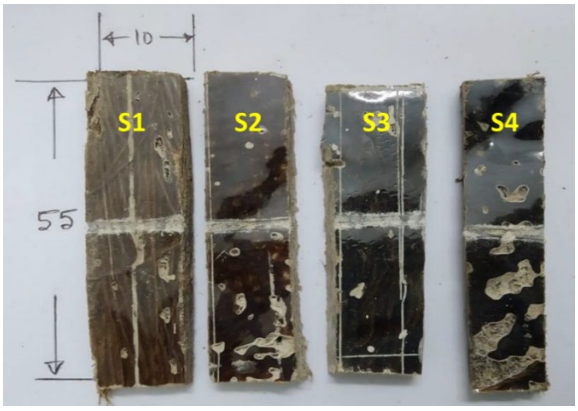


Figure 15. Specimens before the impact test

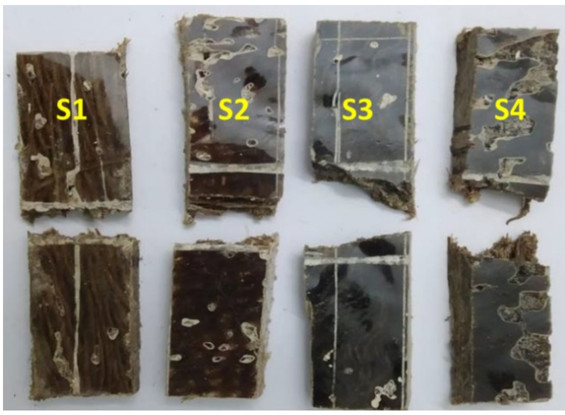


Figure 16. Specimens after the impact test

A water retention test was carried out following ASTM D570 by placing samples in a beaker of water at ambient temperature for a predetermined amount of time. Each specimen's moisture content is computed as follows:

$$\text{Water absorption } \% = \left(\frac{W_w - W_d}{W_d}\right) x\ 100\% \qquad (2)$$

where, W_d = *dry weight of the specimen in grams*, W_w = *wet weight of the specimen in grams.*
Figure 17 demonstrates immersed specimens in distilled water.

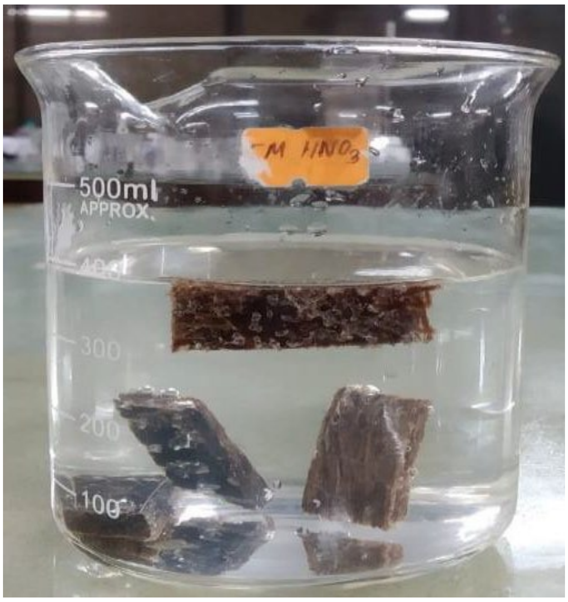


Figure 17. Immersed specimens in distilled water

2.6 Density

The water immersion method was used to calculate the experimental density (ρ_{ex}) of every composite sample. The following equation was used to measure the theoretical density (ρ_{th}) [24].

$$\rho_{th} = \frac{1}{\frac{W_{f1}}{\rho_{f1}} + \frac{W_{f2}}{\rho_{f2}} + \frac{W_e}{\rho_e}} \qquad (3)$$

where,
W_{f1} = mass of jute fiber
W_{f2} = mass of banana fiber
W_e = mass of epoxy resin
ρ_{f1} = density of jute fiber
ρ_{f2} = density of banana fiber

The percentage of void content (V_c) was calculated from theoretical density and experimental density using the following formula [24].

$$V_c = \frac{\rho_{th} - \rho_{ex}}{\rho_{th}} \qquad (4)$$

3. Result and discussion

3.1 Tensile test

The influence of fiber orientation on the tensile strength of the fiber composites is shown in Figure 18. The maximum tensile strength, 53.7211 MPa, was found in sample 4, which is the combination of jute and banana fiber with both unidirectional orientation and 30% fiber loading. This is due to the parallel direction between the fiber and the tensile force loading. The unidirectional orientation of both jute and banana fiber in the composite allows the fibers to effectively carry the tensile load along their length. This combination of alignment provides efficient load transfer from the matrix to fibers, which reduces stress concentration points compared to bidirectional arrangements. Prashanth B H et al. also reported a finding that was identical to this one [24]. Table 4 indicates the tensile strength of the fiber composites used in this experiment.

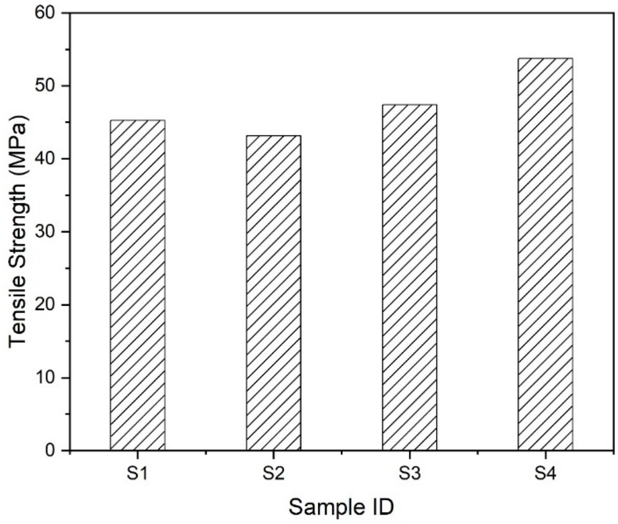


Figure 18. Effect of fiber orientation on tensile strength and modulus of elasticity of fiber composites

Table 4. Tensile strength of fabricated fiber composites

Sample	Fiber Orientation	Tensile Strength (MPa)
S1	J(Bi)-B(Bi)	45.2488
S2	J(Bi)-B(Uni)	43.1278
S3	J(Uni)-B(Bi)	47.3699
S4	J(Uni)-B(Uni)	53.7211

3.2 Impact Test

Figure 19 demonstrates the effect of fiber orientation on the impact strength of fiber composites. The maximal impact strength of 30.86 kJ/m^2 was observed in sample 3, which comprises unidirectional jute fiber and bidirectional banana fiber. This results from the sample 3 hybrid configuration (unidirectional jute combined with bidirectional banana), which offers an optimal equilibrium between stiffness and ductility. The unidirectional jute layer provided significant stiffness and directional strength, enabling the composite to withstand initial deformation. The bidirectional banana layer, exhibiting enhanced flexibility and ductility, absorbed and diffused impact energy from various directions, therefore mitigating fracture development. This combination mitigated premature brittle failure and facilitated increased overall energy absorption. Similar trends have been documented by Bhati et al. [25]. Table 5 demonstrates the impact strength of the fiber composites utilized in this experiment.

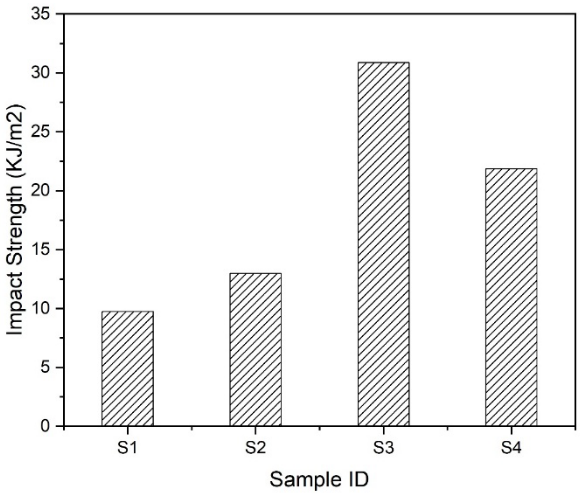


Figure 19. Effect on the impact strength of fabricated fiber composites

Table 5. Impact strength of fabricated fiber composites

Sample ID	Fiber Orientation	Impact Strength (KJ/m²)
S1	J(Bi)-B(Bi)	9.74
S2	J(Bi)-B(Uni)	12.97
S3	J(Uni)-B(Bi)	30.86
S4	J(Uni)-B(Uni)	21.87

3.3 Hardness test

Figure 20 reveals how fiber orientation affects the hardness of hybrid jute banana fiber composites. The highest hardness recorded was 58 in sample 4, which consists of a mixture of jute and banana fiber, featuring both unidirectional orientations. Hardness quantifies the ability to withstand surface deformation. The unidirectional configuration of fibers in sample 4 presumably produces a more homogeneous and dense fiber distribution. This architecture also facilitates an increased fiber volume fraction, which contributes to decreased void volume and porosity, restricting the surface's capacity to flex under stress. A parallel pattern of increasing hardness values with 40 wt%, both unidirectional fiber orientations, has also been observed by Devireddy et al. [23]. Table 6 demonstrates the hardness of the fiber composites tested in this experiment.

Table 6. Hardness of fabricated fiber composites

Sample ID	Fiber Orientation	Rockwell Hardness Number (HRM)
S1	J(Bi)-B(Bi)	55
S2	J(Bi)-B(Uni)	49
S3	J(Uni)-B(Bi)	53
S4	J(Uni)-B(Uni)	58

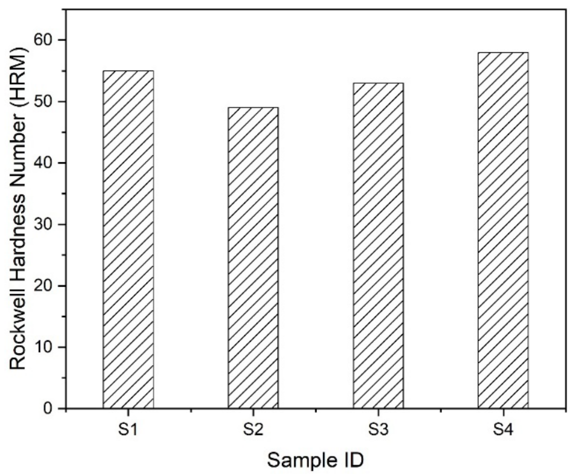


Figure 20. Effect on hardness of fabricated fiber composites

3.4 Water absorption

Figure 21 depicts the impact of fiber orientation on the water absorption of fiber composites. The optimum combination of jute and banana fiber, with jute oriented unidirectionally and banana oriented bidirectionally, resulted in the lowest water absorption of 0.79% in sample 3. As the jute fibers exhibit a unidirectional orientation, resulting in a reduced number of fiber ends being exposed on both the surface and the cut edges. The fibers are aligned in a single direction, resulting in only their ends being directly exposed to water. The resin coating on the sides of the fibers impedes the absorption of water. On the opposite side, the bidirectional banana fibers may have functioned as a woven shield, exhibiting slightly lower hydrophilicity than jute due to an increased lignin and wax content, thereby diminishing direct moisture penetration through the surface. Previous studies have also seen a tendency that is almost identical to this one [26]. Table 7 presents the water absorption of the fiber composites tested in this experiment.

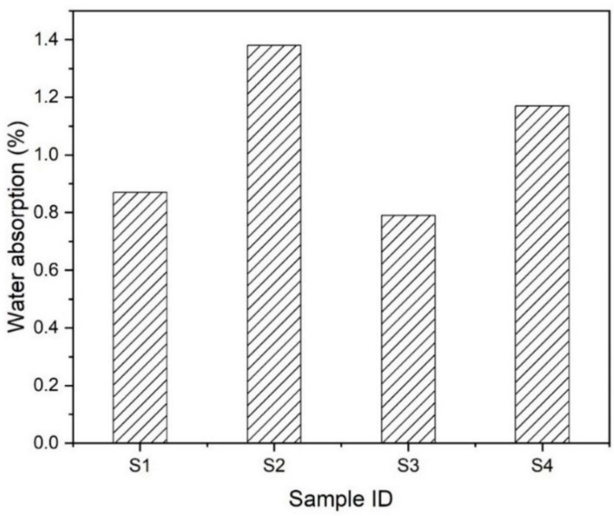


Figure 21. Effect of fiber orientation water on absorption of fabricated fiber composites

Table 7. Water absorption of fabricated fiber composites

Sample ID	Fiber Orientation	Water Absorption (%)
S1	J(Bi)-B(Bi)	0.87
S2	J(Bi)-B(Uni)	1.38
S3	J(Uni)-B(Bi)	0.79
S4	J(Uni)-B(Uni)	1.17

3.5 Density

Figure 22 presents the impact of fiber orientation on the water absorption of fiber composites. The maximum experimental density and minimum void content were found in sample 4, which are 1.232 g/cm^3 and 2.438% respectively. The increased density and reduced void content in Sample 4 can be attributed to the structural configuration of the fibers and the consequent resin infiltration properties. In sample 4, jute and banana fibers are oriented unidirectionally, facilitating a more homogeneous and compact configuration devoid of interlacing points. This configuration creates linear, uninterrupted fiber pathways that may be more efficiently saturated by the resin during hand lay-up, hence diminishing air entrapment and minimizing void occurrence. Voids are air-filled cavities that reduce composite density and degrade mechanical characteristics. The minimum void fraction in the sample indicates a more compact composite structure. The integration of optimal fiber packing and minimum air infiltration elucidates why sample 4 attains both the greatest density and the least void content. Table 8 represents the density and void content of fiber composites.

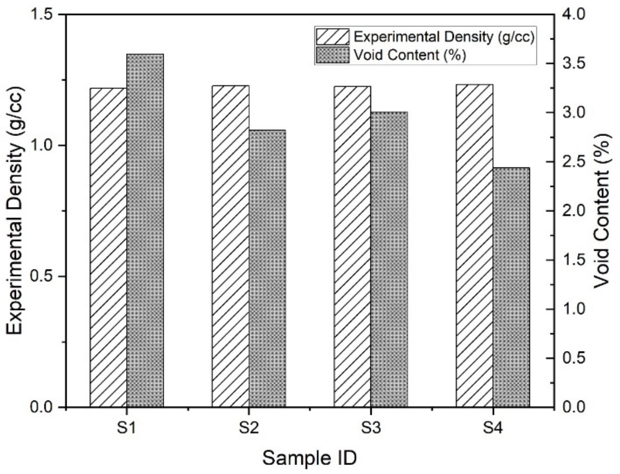


Figure 22. Effect of fiber orientation on experimental density and void content of fabricated fiber composites

Table 8. Hardness of fabricated fiber composites

Sample ID	Fiber Orientation	Theoretical Density (g/cc)	Experimental Density (g/cc)	Void Content (%)
S1	J(Bi)-B(Bi)	1.263	1.218	3.595
S2	J(Bi)-B(Uni)		1.227	2.819
S3	J(Uni)-B(Bi)		1.225	3.006
S4	J(Uni)-B(Uni)		1.232	2.438

4. Conclusion

This study evaluated the effects of fiber orientation, including unidirectional and bidirectional, on the physical and mechanical properties of jute/banana fiber reinforced epoxy composites. It addresses theoretical and experimental density, void content, water absorption, tensile strength, impact resistance, and hardness as the physical and mechanical properties by varying fiber orientation in the matrix. Key findings indicated that fiber orientation has increased effects on tensile strength, hardness, and impact resistance; however, it has a decreased effect on void formation in the composite matrix. Among all the tested samples, having both Jute and Banana fiber in unidirectional orientation (S4) exhibits higher tensile strength (53.72 MPa), and hardness (58 HRM) while having lower void contents (2.44%) in the composite matrix. Additionally, the sample having Jute fiber in unidirectional and Banana fiber in Bidirectional orientation (S3) shows higher impact resistance (30.86 KJ/m2) than other orientations while maintaining minimum hydrophilicity (0.79%). Applying these composites, sample 4 (S4) composites can be used in a scenario where the strength and hardness of materials are desired, such as a motorcycle helmet, a car, and an airplane body. Similarly, sample 3 (S3) can be used in high-impact applications, such as helmet production. Sample 3 exhibits minimal water absorption; therefore, it can be used as a skimmer surface material for oil/water separation. This research acknowledges limitations, including the formation of defects on the composite-matrix surface due to the unequal pressure distribution during fabrication by the hand layup method. Future research should focus on using a nanofiller that can reduce the void in the composite matrix. Additionally, the chemical treatment of fibers and the orientation of fibers should not be limited to horizontal and vertical directions.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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