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Effect of Hybridization on Mechanical Characteristics of Hemp, Bamboo, and Jute Reinforced Epoxy Bio Composites

Manjeet Chahar[1,*], Rajneesh Kumar[2]

Abstract

In the present study, hemp, jute and bamboo fibres have been reinforced with epoxy resin to develop several bio-composites (hemp/epoxy, jute/epoxy, bamboo/epoxy, hemp/jute/epoxy, hemp, bamboo, epoxy and hemp/jute/bamboo/epoxy). Their mechanical characteristics (impact strength, flexural strength, and tensile strength) have been evaluated by conducting standardized ASTM tests on the fabricated bio-composite specimens. Among these, the hybrid epoxy composite reinforced with hemp, jute, and bamboo fibers has exhibited superior tensile and impact strengths, reaching 56.37 MPa and 10.91 KJ/m2, respectively. Notably, the hemp/epoxy bio composite demonstrated the greatest flexural strength, achieving 156.78 MPa, followed by the hemp/jute/bamboo/epoxy hybrid composite, which has a flexural strength of 145.56 MPa. The findings of this study reveal that all developed fiber-reinforced composites possess mechanical characteristics that surpass those of pure epoxy resin, indicating their potential for advanced material applications. This research contributes to the growing body of knowledge on sustainable material engineering and highlights the viability of these bio-composites as eco-friendly alternatives in various industries.

Keywords: Natural fibres, Hybridization, Bio-composites, Mechanical characteristics, NFRCs.

INTRODUCTION

Natural fibre-reinforced composite materials are gaining importance due to their superior properties, e.g., lightweight, high specific strength and stiffness, corrosion resistance, wear resistance, carbon neutrality, and cost-effectiveness compared to synthetic fibers. These materials have a wide range of applications, e.g., in automobiles, aerospace, electronics, structural and structural applications [1]. Composite materials are composed of two or more different materials at the macroscopic level. Each material constituent has different physical, chemical, mechanical, thermal, optical, and magnetic properties. Composites have different and superior properties from combining materials acting individually. Material components are divided into two categories, namely reinforcement and matrix. The reinforcement material is generally discontinuous, strong, and stiffer and possesses superior properties to the matrix, which is continuous, weaker, and less stiff. Matrix serves two purposes in composite: first, to bind the reinforcement, and second, to transfer the external load to the reinforcement, which results in enhanced composite properties [2]. The use of composite materials was reported first in around 1500 BC in Egypt and Mesopotamia. They made buildings using a mixture of mud and straw. Later, in 1200 AD, using wood, bone, and animal glue, Mongols invented a new composite and made a bow with that composite. In the 1900s, synthetic resins like

***Author for Correspondence**
Manjeet Chahar
E-mail: manjeetchahar541@gmail.com

[1]Research Scholar, Department of mechanical engineering, DCRUST, Murthal, Sonipat, Haryana, India
[2]Associate Professor, Department of mechanical engineering, DCRUST, Murthal, Sonipat, Haryana, India

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polyester, vinyl, phenolic, and polystyrene were developed. The properties of the composite are further enhanced by the reinforcement of fibres with resins. In 1935, Owens Corning made the first fiber-reinforced composite. The developed composite was solid and lightweight. During the Second World War, there was a significant advance in the field of composites, and laboratory work was introduced into actual practice. In the 1970s, the composite industry was revolutionized due to advancements in resin and reinforcements [3].

Wambua et al., 2003 studied the properties of composites with different natural fibres and found that characteristics of these composites have in good comparison with glass-reinforced polypropylene composite. Results showed that among these (hemp, kenaf, sisal, coir) fibres reinforced composites, hemp fibre provides superior properties. It was also investigated that the specific strength of hemp was greater than glass-reinforced fibre [4]. Bamboo fibre falls in the stalk fibre category of natural fibres. It is obtained from starchy bamboo plants extracted from bamboo culms. Bamboo culm has a cylindrical shell and high strength in the direction parallel to fibres. Bamboo fibres possess excellent properties, e.g., high tensile strength, high specific strength, low cost, readily available, biodegradable, etc. Bamboo fibre is composed of three ingredients mainly, cellulose, hemicellulose and lignin. Bamboo fibre is economical because it is found in abundance in tropical and subtropical regions and also, grows very fast, reaches maximum strength just in 3 to 4 years and obtains maturity in 5 years. The ultimate strength of bamboo is the same as the yield strength of mild steel, and the specific strength of bamboo is many times greater than steel. It can take load both in tensile and compression. The tensile strength of bamboo fibre can reach up to 350 MPa. That's why bamboo fibre is a better option for reinforcement in composites. Surfaces treatments improve strength of bamboo fibres. Moisture intake has an adverse effect on the mechanical and physical characteristics of bamboo fibre [5]. Also, bamboo fibre is very resilient and durable [2]. Hemp fibre falls in bast fibre category of natural fibres. Its scientific name is cannabis sativa. Hemp is composed of mainly cellulose, hemicellulose, lignin, and pectin. The characteristics of hemp fibre depend upon above mentioned constituents, retting process, separating technique, age, rainfall during growth and geographic region. The increase in cellulose content enhanced the stiffness and strength of hemp fibre. In recent years, the use of hemp has exponentially increased in various applications due to its better characteristics like high strength, high stiffness, biodegradability, recyclability, and sustainability. The mechanical properties of hemp fibre can be improved by surface treatments. Hemp is mainly cultivated in the European Union, China, Central Asia, and the Philippines [6]. Flax is native to Europe, while hemp, jute, ramie, kenaf, and sisal have been of greater importance in Asia [7]. Jute fibre falls in bast fibre category of natural fibres. It is cultivated in abundance in India and Bangladesh. Jute is composed of mainly cellulose, hemicellulose, lignin, and pectin. Jute fibre has many advantages over synthetic fibres like lightweight, high specific strength, high flexural strength, low processing cost, easily available, low production energy, biodegradable etc. Moisture absorption has an adverse effect on the characteristics of jute fiber. Its properties can be enhanced by surface treatments [8]. Jute fibre has excellent wear properties [9]. And also, jute fibre has high impact strength [10].

The characteristics of composites are affected by the volume fraction of fibre in the composite. Moisture absorption increases in hemp-reinforced unsaturated polyester composite with an increased volume fraction of hemp fibre. Moisture absorption has an adverse effect on the properties of the composite [11]. Swapan et al., 2011 found that the strength of industrial hemp fiber-reinforced polylactide biocomposites improved with an increase in fiber content and also observed that alkali and saline treatment influence the mechanical properties [12]. Swapan et al., 2012 further investigated the effect of fibre content on the flexural properties of hemp fibre reinforced with polyester and polylactide resins and observed that flexural modulus was enhanced with an increase in fibre content. Still, it was also observed that fibre content has an adverse effect on flexural strength. The study also revealed that alkali and saline treatments have a positive impact on flexural strength and flexural modulus [13]. The characteristics of the composite depend upon fibre orientation. Hemp, jute reinforced hybrid composite has higher tensile, flexural and impact strength at 90 degree orientation as compared to 30 and 45 degree orientations [14]. Padmanabhan et al., 2024 studied the effect of stacking sequence of natural fibers on mechanical characteristics of aluminum-DMEM [15]. The characteristics of the composite are affected by various parameters e.g., selection of fibre and matrix, interface strength, fibre orientation, manufacturing, porosity, etc. mechanical characteristics can be enhanced by optimizing these parameters [16]. Prasanna Venkatesh, 2018 studied the effect of fibre weight percentage on the mechanical properties of hybrid bamboo/sisal-reinforced unsaturated polyester composite. Optimum mechanical properties (tensile, flexural, impact strength) were obtained with 20% fibre weight and 15 cm of fibre length with equal weight fraction of bamboo/sisal fibres [17]. Ramasubbu et al., 2024 and sumesh et al., 2023 also demonstrated the effect of weight percentage of natural fiber on the mechanical behaviour of the composite [18, 19]. Krimah et al., 2021 observed that fibre strength depends upon the microstructure, chemical composition and cross–sectional area of the fibre. Presence of higher cellulose content and lower lignin content in fibre enhanced tensile strength of fibre. Moisture absorption was dependent on hemicelluloses and lignin content in fibre. Other parameters that affect the strength of fiber are fiber extraction method, environmental conditions, method of harvesting, and harvesting time [20].

Among the thermoset resins, epoxy, polyester, and vinyl ester are the most widely used resins due to their superior properties. Thermoset resins have superior properties, e.g., low resin viscosity, high chemical resistance, good adhesion, good thermal stability, and superior mechanical properties compared to thermoplastic resins. These resins also have some disadvantages, like brittleness and non-recyclability [21]. Epoxy resin possesses outstanding mechanical and electrical properties, high adhesion strength, and good heat resistance and can be used in most applications as an additive and as a laminating resin, e.g., coating, automobile, aerospace, biomedical, electronic materials, etc. Epoxy resins show superior mechanical properties than polyester. The tensile, flexural and impact strength of epoxy resin is superior to polyester resin. Jeyapragash et al., 2020 research aims to explore the mechanical behavior of epoxy composites reinforced with natural fibers [22, 23].

In this work, hemp, bamboo, and jute in long fibrous form are utilized as reinforcements in epoxy matrices. Based on the literature review, the effect of the hybridization of these fibres with epoxy on mechanical characteristics has not been analyzed. The primary objective of this investigation is to assess how the reinforcement of these natural fibers influences the mechanical characteristics of the developed composites. Specifically, this study evaluates these bio composites' tensile strength, flexural strength, and impact strength.

METHODOLOGY

Fibres and Matrix

Hemp (in fibrous form) was purchased from Hemp Organisation Pvt. Ltd., Delhi (India). Jute in fibrous form was purchased from Himanshu Jute Fab, Ashok Vihar, Delhi, and Bamboo in fibrous form was purchased from Vruksha Composites, Guntur, Andhra Pradesh (India). Hemp, Jute, and Bamboo in the fibrous form are shown in Figure 1. In this study, Epoxy resin LY556 and hardener HY 951 were used as matrix material and mixed in a ratio of 10:1. Epoxy resin and hardener were purchased from Herenba Instruments & Engineers, Chennai (India). A hardener was used to cure epoxy resin. Wax was used as a releasing agent and purchased from Paramount Polish Processors Pvt. Ltd., New Delhi.

Surface Treatment

Surface treatments like alkali and saline improve the mechanical characteristics of the composites (Kushwaha & Kumar, 2011; Shalwan & Yousif, 2013; Sood & Dwivedi, 2018) [24,25,26]. Neves et al., 2020 comparatively analyzed the mechanical properties of hemp-reinforced epoxy and polyester composite and found that hemp-reinforced composite has superior tensile and flexural strength at 30% fiber volume. The maximum tensile and impact strength of the hemp-reinforced epoxy composite was 50.5 MPa and 76.7 MPa, respectively, and for the hemp-reinforced polyester composite, these were 49.1 MPa and 25.4 MPa, respectively. In this work Hemp, Jute and Bamboo fibres are dipped for 76 hours in 5% NAOH solution and then dried in oven [27]. Chaudhary et al., 2018 investigated the effect of hybridization on the properties of jute, hemp, and flax fibres reinforced epoxy composite. Composites were prepared using the hand lay-up method. Fibres were reinforced with Epoxy resin in 1:3 by weight. Mechanical characteristics enhanced due to hybridization. This work concluded that (jute, hemp, flax) fibres reinforced hybrid composite has the best mechanical characteristics compared with other hybrid composites [28].

Figure 1. Depicts Hemp, Jute, and Bamboo in fibrous form.

Fabrication of Specimen

Hemp, jute, and bamboo reinforced hybrid epoxy composite was fabricated by hand lay-up method. The mold used for the fabrication of the hybrid composite was made of mild steel. The mold cavity has dimensions 200*180 mm, and the upper part of the mold has dimensions 199.5*179.5 mm. Seven composite specimens were fabricated by taking different fibres at a time, i.e., hemp/epoxy, jute/epoxy, bamboo/epoxy, hemp/jute/epoxy, hemp/bamboo/epoxy, and hemp/jute/bamboo/epoxy composite. In all composites, the weight fraction of fibers was kept constant at 20%, and the remaining 80% was epoxy. In hybrid composite hemp/jute/bamboo/epoxy, the weight contribution of each fibre was equal. Firstly, a PVC polythene was coated on upper and lower mold surfaces. Then, wax was applied to the mold surface to avoid sticking the resin with the mold surface. Fibres were hammered and combed to make them straight, then placed in the mold cavity. After that, epoxy resin was poured on the fibres. Before pouring, epoxy resin and hardener were mixed in 10:1 and stirred for proper mixing. After that, a metallic roller was gently rolled over to remove bubbles and gasses. In the end, a dead weight of 20 kg was put on the mold, and the composite was allowed to cure at room temperature for 24 hours. After that, the composite was removed from the mold, and the specimen was cut for mechanical testing according to ASTM standards. The complete fabrication process is shown in Figure 2.

Mechanical Characterization

Tensile Testing

A universal testing machine has been used to tensile test composite specimens. Specimens were cut into a rectangular shape of 115 mm*19 mm*4 mm. Tensile tests were performed according to ASTM D638 type IV standards involving a cross-head speed of 5 mm/min with a gauge length of 25 mm. Data on the load vs displacement curve was obtained. A typical load-displacement curve obtained for tensile testing of hemp/jute/bamboo/epoxy composite is shown in Figure 3.

Flexural Testing

A universal testing machine has been used for flexural testing of composite specimens. Specimens were prepared according to ASTM D790 for flexural tests, and dimensions were 127 mm*12.7 mm*4 mm. Data on the load vs displacement curve was obtained for flexural tests. The typical load vs. Extension curve obtained for flexural testing of hemp/jute/bamboo/epoxy composite is shown in Figure 4.

Impact Testing

Izod impact testing machine has been used for impact testing of composite specimens. The specimens were prepared according to ASTM D256 for impact testing. A notched izod impact test was performed

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to measure impact energy for the composite specimens, as shown in Figure 5. Specimens were cut in rectangular shapes of dimensions 64 mm*12.7 mm*4 mm.

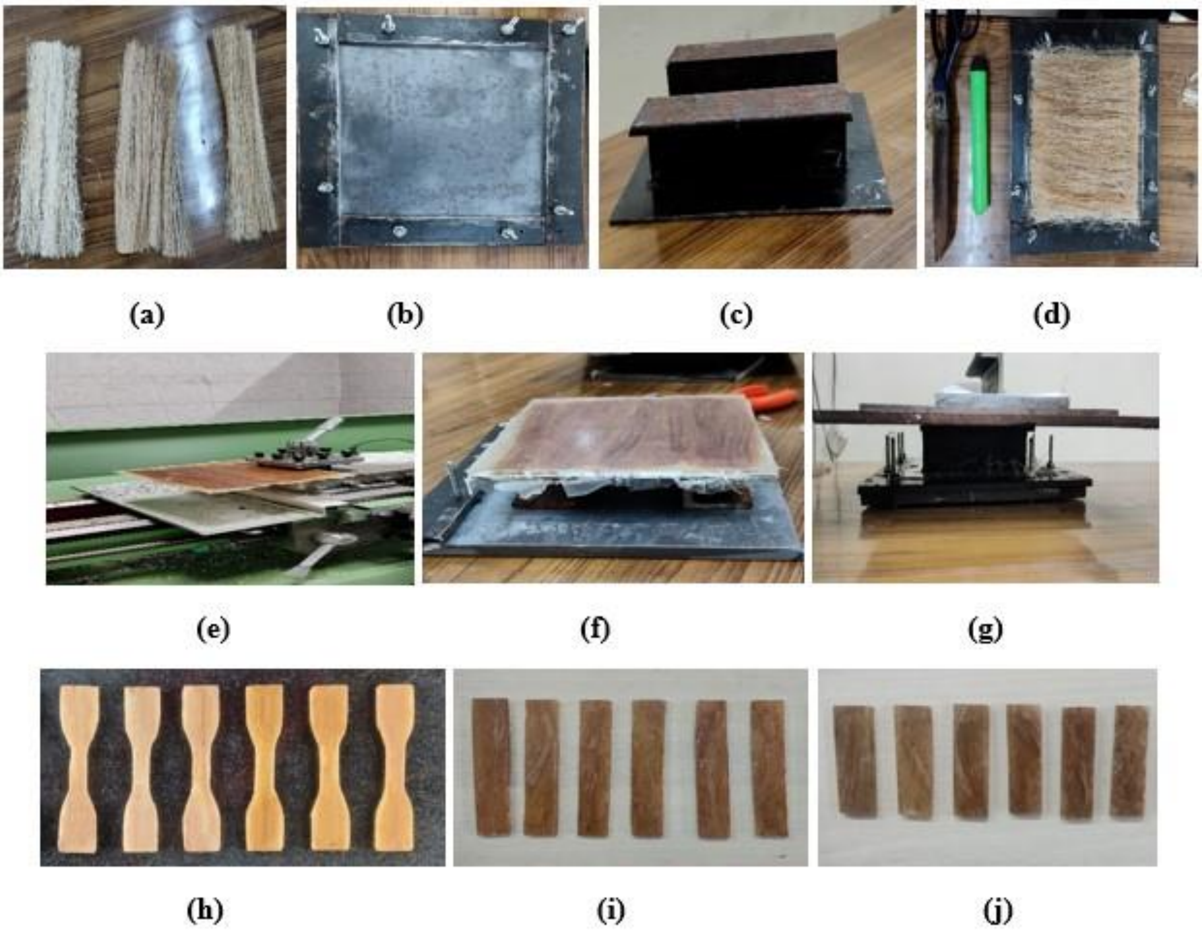

Figure 2. (a) Hemp, Jute, and Bamboo in long fibre form, (b) lower part of mild steel mold, (c) Upper part of mold, (d) Mixture of reinforcement and fibres, (e) Application of load, (f) Composite removed from mold, (g) Cutting of specimen, (h) Tensile specimen according to ASTM D638, (i) Flexural specimens according to ASTM D790, (j) Impact specimen according to ASTM D256.

Figure 3. Tensile specimen before failure and after failure.

Figure 4. Flexural specimen before failure and after failure.

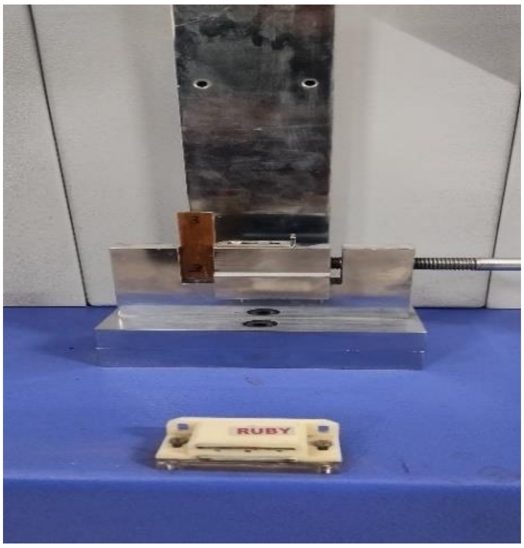

Figure 5. Izod impact testing machine setup.

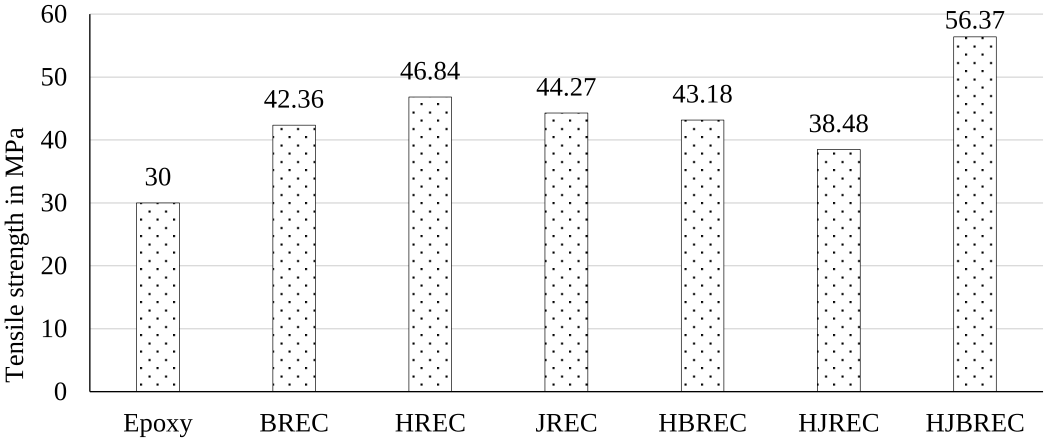

Figure 6. Tensile strength of different fibre-reinforced composites

RESULT AND DISCUSSION

Tensile Test Results

Tensile tests were performed on all the specimens of composites and hybrid composites of hemp/jute/bamboo/epoxy according to ASTM D638 IV type on the universal testing machine. Pure epoxy resin has a tensile strength of 30 MPa. The tensile strength of all composites and hybrid composites was higher than pure epoxy. This is due to that the tensile strength of all fibres i.e., hemp, jute and bamboo was higher than epoxy resin. Maximum tensile strength 56.37 MPa is obtained for hemp/jute/bamboo reinforced hybrid epoxy composite. All fibers show good compatibility with epoxy resin. Jute/epoxy composite has a minimum tensile strength of 42.36 MPa among all composites. Hemp/epoxy has the highest tensile strength of 46.84 MPa in all single-fibre reinforced composites, followed by bamboo/epoxy at 43.18 MPa. Hemp/bamboo/epoxy and hemp/jute/epoxy have tensile strengths of 44.27 MPa and 42.36 MPa, respectively. The tensile test results of all composites and hybrid composites are shown below in Figure 6.

Flexural test results

The flexural strength of the composite was measured according to ASTM D790 by a three-point flexural test. Flexural test results indicate that both flexural strength and flexural modulus enhanced due to incorporation of fibres in epoxy resin. The flexural strength and flexural modulus of pure epoxy are 34.69 MPa and 0.6 GPa, respectively. Hemp/epoxy has the highest flexural strength of 156.78 MPa composites and hybrid composites, followed by hybrid epoxy composite reinforced with hemp/jute/bamboo fibres and these values are 145 MPa and _ GPa respectively. High flexural strength and modulus of hemp/epoxy composite was due to high flexural strength of Hemp fibre and good bonding with epoxy. Bamboo/epoxy composite has a minimum flexural strength of 62.75 MPa among all composites. Hemp/jute/epoxy and hemp/bamboo/epoxy have flexural strengths of 128 MPa and 90.36 MPa, respectively. Bamboo/epoxy and jute/epoxy have flexural strength of 62.75 MPa and 80.38 MPa, respectively. The flexural test results of all composites and hybrid composites are shown below in Figure 7.

Impact Test Results

Izod impact test results showed that the impact strength of epoxy resin was enhanced due to the incorporation of fibres (Table 1). Hemp/jute/bamboo fibres reinforced hybrid epoxy composite has the highest impact strength of 10.91 KJ/m^2. Pure epoxy has an impact strength of 3.92 KJ/m^2. Bamboo/epoxy composite has a minimum impact strength of 4.18 KJ/m^2 among all composites. Jute/epoxy composite has the highest impact strength of 7.96 KJ/m^2 among all single-fibre composites due to the high impact strength of jute fiber. Jute/hemp/epoxy and bamboo/hemp/epoxy have impact strengths of 6.89 KJ/m^2 And 4.65 KJ/m^2, respectively. Hemp/epoxy and jute/epoxy have impact strength of 5.21 KJ/m^2 and 4.18 KJ/m^2, respectively. Impact test results of all composites and hybrid composites are shown below in Figure 8.

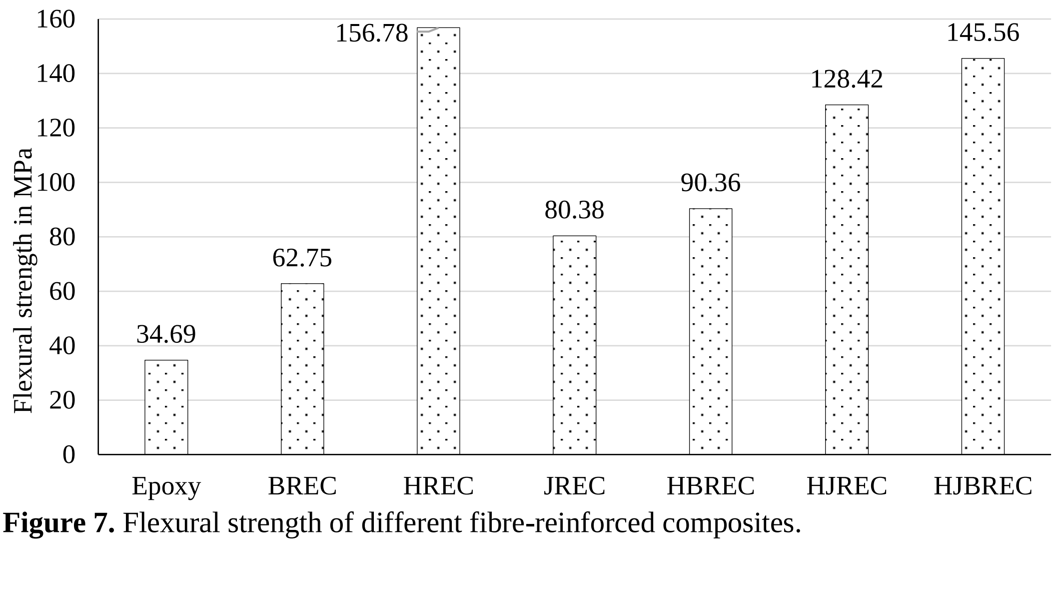

Figure 7. Flexural strength of different fibre-reinforced composites.

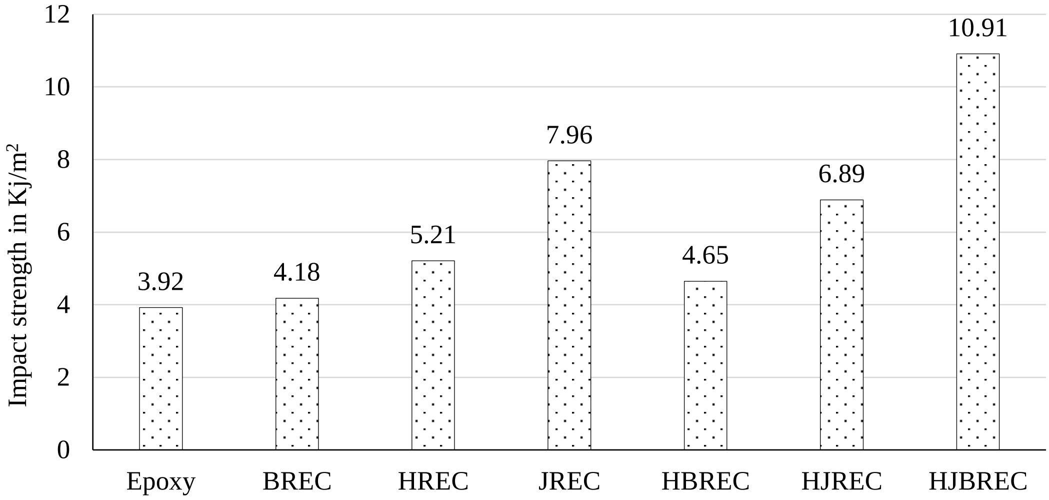

Figure 8. Impact strength of different fibre-reinforced composites.

Table 1. Comparison of tensile strength, flexural strength and impact strength of present work with some bio-composites and hybrid composites discussed in literature [28-35].

Fibre/Matrix	Composite fabrication method	Fiber orientation	Chemical treatment	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (KJ/m^2)
H/J/B/Epoxy	Hand lay up	Unidirectional/ 15 wt%	Alkali	56.37	145	10.91
J/H/Epoxy	Hand lay up	Bi-directional fiber sheet/25 wt%	-	42.19	86.6	6.93
H/J/B/Polyester	Compression molding	Bi-directional/ 20 wt%	Alkali	47.84	239.36	18.33
J/Epoxy	Compression molding	Short fibre	Alkali	92.74	185	-
Snake grass/Polyester	Hand lay up	Unidirectional	-	35.89	75.29	-
Abutilon/Epoxy	Hand lay up	Unidirectional	Alkali	67	206.4	11.0
CGFs/PFs/ Epoxy	Hand lay up	3-6 mm/randomly oriented	Deionized water	44.82	56	1.3
Sisal/Epoxy	Compression molding	-	Alkali	53	86.40	6.07
G/J/B/Epoxy	Hand lay up	-	Alkali	103.46	56.65	6.8

CONCLUSION

In this article, a number of composites and hybrid composites were fabricated using hemp/jute/bamboo as reinforcement in fibrous form and epoxy resin as matrix. Various tests have been performed to evaluate the mechanical characteristics of these bio-composites.

Following are the conclusions based on those tests:

- Mechanical characteristics (i.e., tensile strength, Young's modulus, flexural strength, flexural modulus, and impact strength) enhanced due to the reinforcement of natural fibres in the epoxy resin. This shows that these fibres have good compatibility with the epoxy matrix.
- The Highest tensile strength of 56.37 MPa has been obtained for hemp/jute/bamboo fibre-reinforced hybrid epoxy composite among all composites and hybrid composites, which is 87.90% higher than that of pure epoxy material.
- Jute-reinforced epoxy composite has a minimum tensile strength of 44.27 MPa, which is due to the poor bonding of jute fiber with epoxy resin.
- The highest flexural strength of 156.78 MPa has been obtained for hemp/epoxy composite among all composites and hybrid composites, followed by hemp/jute/bamboo/epoxy hybrid composite, which has a flexural strength of 145.56 MPa. The flexural strength of hemp/epoxy composite and

hemp/jute/bamboo/epoxy hybrid composite has 352% and 319% higher values, respectively, than pure epoxy material.

- Bamboo-reinforced epoxy composite shows a minimum flexural strength of 62.75 MPa.
- Highest impact strength of 10.91 KJ/m^2 has been obtained for hemp/jute/bamboo fibre-reinforced hybrid epoxy composite among all composites and hybrid composites, which is 178.30% higher than that of pure epoxy material.
- Bamboo-reinforced epoxy composite has a minimum impact strength of 4.18 KJ/m^2 among all single-fibre composites.

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Declaration of Interests

The author(s) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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