Investigation on mechanical properties of surface treated jute-basalt fiber reinforced hybrid epoxy composites: a review

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Globally, accommodating and utilizing electronic plastic waste is one of the major challenges and it is not easy to use due to its non-biodegradability nature. Green polymer composites came to existence to overcome the issue of minimizing plastic waste. So, this study delves into enhancing the mechanical properties of jute-basalt fiber-reinforced hybrid epoxy composites through surface treatment methods, considering the eco-friendly nature of natural fibers. Natural fibers, such as jute, possess inherent sustainability due to their renewable sources, biodegradability, and low environmental impact compared to synthetic alternatives. The investigation arises from the demand for sustainable materials with superior performance in engineering applications. The focus is on optimizing interfacial bonding between fibers and the epoxy matrix to improve overall mechanical performance. Experimental studies assess the impact of different treatments and fiber compositions on mechanical properties such as tensile strength, flexural strength, and impact resistance. Ultimately, this research aims to advance the development of sustainable, high-performance composite materials by clarifying the relationship between surface treatments, fiber composition, and mechanical properties in jute-basalt fiber-reinforced hybrid epoxy composites.

Keywords: Jute fiber, basalt fiber, surface treatment, hybrid epoxy composites, mechanical properties, natural fibers.

INTRODUCTION

Recently, there has been a growing interest in sustainable and biodegradable natural fiber-reinforced composites (FRC) because of their lower environmental impact [1].

Plant-based fibers have several benefits, including favorable thermo-physical properties such as low density, improved thermal conductivity, and effective insulation. Additionally, they possess many benefits like affordability, biodegradability, and minimal energy requirements during material processing.

Natural fiber composites (NFCs) are emerging as promising alternatives to synthetic fiber-reinforced composites in various applications. Technological advancements have enabled the incorporation of jute fiber with synthetic polymers and resins, offering a cost-effective substitute for purposes requiring less load-bearing and expensive synthetic fibers. A few advantages of natural fibers include their reasonable specific strength, affordability, low density, great toughness, and favorable thermal characteristics. Their increased specific strength and stiffness are the results of their low specific weight compared to synthetic fibers like carbon, aramid, and glass. Additionally, they are less abrasive to processing tools and are safe for humans and the environment. However, the mechanical properties of natural fibers are influenced by factors such as moisture content, cultivation area, and processing methods, and they generally exhibit poor thermal stability. Despite these limitations, combining natural fibers with biodegradable matrices creates environmentally friendly 'green' products that fulfill current societal demands. Typically, these composites use biodegradable polymers as the matrix phase and natural fibers for reinforcement. Among lignocellulosic fibers, jute fiber is notable for its high specific strength and modulus, making it particularly effective in enhancing composites. Natural fibers have found applications as strengthening components in the aerospace and automobile sectors, where their high strength-to-weight ratio, renewable nature, and reduced environmental impact make them an attractive alternative to traditional synthetic materials. Furthermore, their use in these industries not only enhances fuel efficiency and reduces emissions but also promotes sustainability and aligns with increasing regulatory and consumer demands for eco-friendly solutions.[2-3].

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Despite several drawbacks such as poor adhesion and leakage, chemical treatments enhanced the mechanical characteristics of polymer composites reinforced with jute fiber (JFRPC). The study highlights the positive effect of chemical treatments on JFRPC, resulting in enhanced mechanical properties in comparison to composites without treatment. These treatments typically involve the use of agents such as alkali, silane, or other coupling agents, which modify the fiber surface and improve the interfacial bonding between the jute fibers and the polymer matrix. Consequently, treated JFRPC exhibits superior tensile strength, flexural strength, and impact resistance, making it a more viable option for high-performance applications in various industries [4].

1. In composite materials, the matrix plays a crucial role as a binding agent, facilitating the transfer of fiber stiffness. However, weak adhesion between the matrix and fibers can lead to undesirable properties, making the composite vulnerable to environmental factors and reducing its lifespan. Therefore, researchers focus on enhancing fiber-matrix adhesion through physical treatments or chemical treatments to improve overall performance. Physical treatments may include methods such as plasma treatment, corona discharge, or ultraviolet irradiation, which modify the fiber surface to increase its roughness and reactivity. Chemical treatments, on the other hand, involve the application of coupling agents, such as silanes, or the use of surface modifiers, such as alkalis or acetylation, to introduce functional groups that enhance bonding at the interface. These enhancements not only improve mechanical properties like tensile and shear strength but also enhance the composite's resistance to moisture, thermal variations, and other environmental stressors. By optimizing the fiber-matrix interface, researchers aim to develop composites with superior durability, reliability, and performance for applications in demanding fields such as aerospace, automotive, and construction [5].

Natural fibers offer numerous advantages, such as low cost and eco-friendliness, which make them a better alternative to synthetic fibers in various applications. These fibers, sourced from plants, animals, or minerals, are renewable and biodegradable, significantly reducing environmental impact compared to their synthetic counterparts. Additionally, natural fibers often exhibit excellent mechanical properties, such as high specific strength and stiffness, which can be advantageous in load-bearing applications. Their inherent biodegradability ensures that they do not contribute to long-term pollution, aligning with the growing global emphasis on sustainability and reducing carbon footprints [6].

Based on where they came from, these fibers might be divided into three categories: plant, animal, and mineral fibers. Natural minerals provide the basis for mineral fibers like asbestos and basalt, which are valued for their exceptional strength and heat resistance in high-temperature and fire-resistant applications [7-8].

Natural fibers excel due to their affordability, lightweight quality, durability in processing, and widespread accessibility. Furthermore, their non-toxic characteristics make them a popular and environmentally friendly choice. The cost-effectiveness of natural fibers stems from their abundance and renewable nature, which ensures a steady supply and lower production costs compared to synthetic fibers. Their lightweight nature contributes to easier handling and transportation, as well as improved energy efficiency in applications where weight reduction is crucial, such as in the automotive and aerospace industries [8].

Figure 1 depicts the categorization of natural fibers.

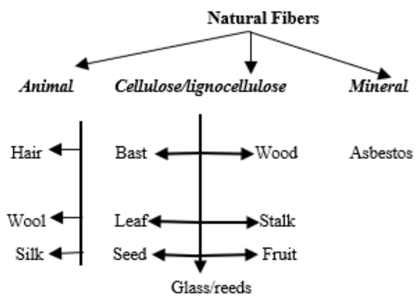

Fig. 1. Classification of natural fibers (Open assess) [9]

Jute fibers are eco-friendly since they are fully recyclable and biodegradable. They have a moderate moisture absorption capacity, provide good thermal and acoustic insulation, and do not irritate the skin. Nowadays, 3.2 million tons of jute fiber are produced annually across the world and are utilized in many different applications [10].

Jute is a bast fiber extracted from the inner part of the plant and holds significant importance as a natural fiber on a global scale. Predominantly produced in countries such as Bangladesh, India, China, Nepal, and Thailand, these nations collectively account for 95% of the world's jute fiber production. Jute fibers exhibit varied chemical properties based on their type, with cellulose, hemicelluloses, lignin, pectin, wax, and moisture being their main constituents. The fiber and the matrix in the composite structure don't stick together well because cellulose, hemicellulose, and lignin lead to poor interfacial adhesion between the fiber and matrix. Therefore, chemical treatments are the most effective method to improve how well dissimilar materials stick together and make them stronger [11]. This makes the material not as strong as it could be due to the presence of chemical constituents in the untreated jute fiber. Kokot [12] found that sodium hydroxide (NaOH) treatment is used to clean and purify cellulose, removing both natural and artificial impurities. This process also enhances the amount of crystalline cellulose and gives the material a textured (rough) surface. The original crystal structure of cellulose I is transformed into cellulose II during this treatment.

Mukherjee [13] delved into an in-depth exploration of jute fiber mechanical properties in their research, revealing significant insights into the effects of alkali treatment on their tensile characteristics. Their investigation focused on a targeted treatment methodology aimed at eliminating hemicelluloses and/or lignin from the fibers, thereby altering their inherent composition and structure. Through meticulous experimentation and analysis, they elucidated the profound influence of this treatment process on the tensile properties of jute fibers, uncovering key correlations between treatment parameters and mechanical performance. This comprehensive understanding of the interplay between chemical treatment and mechanical behavior not only advances fundamental knowledge in the field but also holds immense potential for informing the development of tailored treatment protocols to optimize jute fiber properties for various applications. Mukherjee *et al.*'s research thus represents a pivotal contribution to the broader body of knowledge surrounding natural fiber mechanics, offering valuable insights that can catalyze advancements in material science and engineering.

Gassan [14] recently conducted a study focusing on the fatigue behavior of epoxy composites reinforced with untreated and alkali-treated jute. Through an incremental loading approach, the researchers measured the dynamic modulus, strength, and specific damping capacity of the composites.

The findings from the study unveiled a significant trend: the utilization of treated fibers and a higher fiber content displayed a correlation with reduced fatigue resistance. Specifically, the investigation focused on key mechanical parameters of jute fabrics, including tensile strength, flexural strength, and interlaminar shear strength, to evaluate the effects of oligomeric siloxane treatment. These parameters served as critical indicators in assessing the efficacy of the treatment and its impact on the overall mechanical performance of the jute fabrics [15].

Khondker [16] conducted a study that demonstrated that composites comprising jute and polypropylene (PP), integrating specially treated jute yarns, showcased notable enhancements in tensile and bending properties. The incorporation of these treated jute yarns resulted in substantial improvements, with both strength and modulus experiencing approximate increases of 14% and 10%, respectively. These findings underscore the effectiveness of treating jute yarns in enhancing the mechanical properties of jute-PP composites, thereby suggesting a promising avenue for reinforcing such materials.

Gupta [4] presents a method to enhance mechanical properties by doing chemical treatments of jute fiber as opposed to untreated jute fiber.

With an average annual growth rate of 30%, the basalt fiber composite materials industry in China is growing quickly. China's rapidly developing society needs high-performance, low-cost fiber with independent intellectual property rights. Applications for basalt fiber are numerous and include aircraft, architecture, the chemical industry, medicine, electronics, and agriculture. It is a material that finds usage in both military and civilian contexts [17].

The rapid pace of technological advancement has always pushed the limits of engineering materials. Over the past century, the development of new materials has accelerated to keep up with the changing demands in construction, transportation, and other fields. To achieve superior performance from existing materials, engineers have created combinations of different materials that together exhibit enhanced properties compared to their components. Modern technologies often require materials with unique combinations of properties that traditional metals, ceramics, and polymers cannot provide. This is particularly true for materials needed in construction and transportation. Composites have emerged as viable alternatives to metal alloys in various applications, including construction, automotive, marine, aerospace, and sports equipment. These composites are made by combining different materials to achieve performance levels that no single material could achieve on its own. Today, most materials are not used in their pure form because no single material possesses all the necessary properties. The concept of composite materials is not new, the use of composites dates back to ancient times. Even the human body can be considered a composite, composed of bones and flesh. Basalt fiber, derived from solidified volcanic lava, is renowned for its exceptional strength and high-performance characteristics. Utilizing advanced manufacturing techniques, basalt fibers (BFs) are produced by melting basalt rocks at high temperatures and then extruding the molten material into thin fibers. These fibers exhibit remarkable mechanical properties, including high tensile strength, resistance to corrosion, and thermal stability [18].

Basalt fiber production mirrors the process used for making glass fibers, commencing with the extraction of basalt from quarries, followed by crushing and thorough cleaning. At a scorching temperature of 1500°C, the basalt undergoes melting, transforming into a molten state. This liquefied material is then extruded through minuscule apertures to create continuous strands of basalt fiber. These fibers boast superior mechanical properties, particularly heightened tensile strength, rendering them highly desirable for various applications. Notably, manufacturing basalt fiber proves to be more economically viable compared to producing glass fibers. Moreover, the energy consumption during production is relatively moderate, averaging around 5 kilowatt-hours per kilogram of material. This eco-friendly aspect further contributes to the appeal of basalt fibers as a sustainable alternative in the composite materials industry [19].

Basalt fibers, derived from natural basalt, offer unparalleled strength and reliability, ideal for crafting robust structures. Originating from rocks infused with various minerals such as sodium, potassium, magnesium, calcium, and iron, basalt fibers inherit a diverse array of properties. Within these fibers lie resilient bundles, comprised of sturdy threads and fabrics, enhancing their durability. This strength renders basalt fibers indispensable for creating a diverse array of cost-effective structural components. Whether used in construction, aerospace, automotive, or marine applications, these fibers serve as the backbone of modern engineering, ensuring longevity and performance in a multitude of scenarios [20].

Lee [21] evaluated the weight retention and tensile strength retention of basalt fiber in alkaline solutions as well as its chemical stability. They saw differences in the distribution of weights that were impacted by the different alkaline conditions that were investigated. In the early phases of immersion, there was a noticeable decrease in tensile strength regardless of the alkaline solution utilized. It's interesting to see that basalt fibers retained significantly more weight in a 0.4% NaOH solution than in a 10% NaOH solution. In conditions where cement hydrates, basalt fiber demonstrated superior weight retention compared to glass fiber and exhibited greater stability under alkaline conditions. This suggests that basalt fiber may offer advantages over glass fiber in terms of durability and performance in applications where exposure to alkaline environments is a concern. The findings underscore the potential of basalt fiber as a reinforcement material in construction and other industries where chemical stability and strength retention are paramount. Further research could delve deeper into understanding the mechanisms underlying the observed differences in stability and performance between basalt and glass fibers, informing more efficient and sustainable material choices in various engineering applications.

Qin [22] conducted a comprehensive study investigating the influence of various lengths (6 mm, 9 mm, and 15 mm) and proportions (ranging from 3% to 10%) of basalt fibers on the properties of asphalt mastics. Their research revealed a notable enhancement in the characteristics of asphalt mastics upon the inclusion of basalt fibers, particularly in terms of crack resistance. Remarkably, among the different fiber lengths examined, the 6 mm basalt fibers exhibited superior performance in both asphalt adsorption and strength. This superiority was attributed to their ability to establish a more extensive contact area with the asphalt mastic compared to the longer 9 mm or 15 mm fibers. The study highlighted the significant role played by the number of fibers and their adsorption characteristics in influencing the high-temperature rheological properties and crack resistance of the asphalt mastics. This observation underscores the complex interplay between fiber content and asphalt matrix interaction, which ultimately dictates the performance of the composite material. By elucidating these relationships.

John [23] examined how basalt fiber, including chopped fibers, minibars, rebars, and meshes, can be utilized to reinforce concrete. Concrete typically struggles with transmitting tensile loads due to its low strength and flexibility, leading to the formation of faults and the expansion of cracks under strain. The findings of the review revealed that incorporating basalt fiber into concrete, with specific characteristics such as a length ranging from 6 to 36 mm, diameter between 10 and 25 μm, and a maximum volume percentage of approximately 2%, can significantly enhance the strength performance of the concrete.

The objective of this review is to give insight into the basics of jute and basalt fiber, its structure, its constituents, and its chemical, physical, and mechanical properties. This study also provides information about the various surface treatments used on the fibers and their effects on the mechanical properties. The purpose of the surface treatments is to remove the hemicellulose and lignin for better interfacial bonding between the fiber and the matrix. It also gives an insight into the various methods used to develop the jute/basalt-reinforced hybrid composites.

Chemical properties of jute and basalt fibers

Fibers possess distinct compositions and exhibit varying chemical properties, influencing their utility in different applications. Jute fibers, for instance, are prized for their biodegradability and eco-friendliness, whereas basalt fibers are celebrated for their exceptional resistance to high temperatures and superior mechanical attributes.

Jute fiber consists of various constituents such as cellulose, hemicellulose, lignin, pectin, wax, etc. and Figure 2 illustrates a perspective of jute fabric, showcasing its texture and weave pattern. In jute fiber, the major content is cellulose (45-73%), hemicellulose (12-24%), lignin (5-26%), and others mentioned in Table 1. To improve the adhesion between jute fiber and matrix constituents like hemi-cellulose, lignin, and pectin need to be removed or modified so that hindering can avoid the interaction of jute fiber and matrix. Thus, alkaline treatment is a common method to remove these constituents, and this promotes better interfacial bonding.

To improve the adhesion between jute fibers and the matrix in composite materials, it is essential to modify or remove certain constituents like hemi-cellulose, lignin, and pectin. These components can interfere with the bonding process, leading to weaker composites. One effective method to enhance fiber-matrix adhesion is alkaline treatment, which involves immersing jute fibers in an alkaline solution. This treatment removes impurities and increases surface roughness, thereby promoting better interfacial bonding and enhancing the overall strength of the composite.

Basalt fibers, in contrast, are composed mainly of silica (SiO_2: 43-60%), alumina (Al_2O_3: 11-20%), calcium oxide (CaO: 5-15%), magnesium oxide (MgO: 1.3-16%), and iron oxide (Fe_2O_3: 4.02-16%), along with other minor constituents (Table 2). The high silica content endows basalt fibers with excellent thermal stability, enabling them to withstand extreme temperatures. Alumina and iron oxide enhance the mechanical strength, while calcium oxide and magnesium oxide contribute to the chemical resistance and overall durability of the fibers. Figure 3 provides a visual representation of basalt fabric, showcasing its dense weave and robust texture, which are critical for applications requiring high mechanical strength and thermal stability.

The combination of jute and basalt fibers into a hybrid composite material leverages the unique advantages of each fiber. Jute contributes to the composite's lightweight and sustainable nature, while basalt offers robustness and thermal resistance. This synergy results in a composite material that is not only strong but also environmentally friendly, suitable for applications across various industries such as automotive, aerospace, construction, and sports equipment.

The integration process involves customizing fiber orientation, volume fraction, and matrix composition to optimize the properties for specific applications. Current fabrication techniques for bio-composites, such as pultrusion, hand lay-up, spray lay-up, resin transfer molding, compression molding, extrusion, injection molding, and filament winding, offer diverse benefits in terms of processing efficiency, material properties, and cost-effectiveness. For example, compression molding, depicted in Figure 4, is highly valued for producing high-strength parts with excellent surface finish, while filament winding is ideal for manufacturing strong, hollow, cylindrical structures.

Fig. 2. Jute Fabric

Fig. 3. Basalt Fabric

Future research may focus on developing more sustainable resins, utilizing recycled fibers, and optimizing fiber-matrix interfaces. Such innovations will promote the broader adoption of these composites, supporting a more sustainable future in material design and engineering.

Table 1. Chemical constituents of jute fiber

Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Wax (%)	Pectin (%)	Moisture (%)	Ref.
45-71.5	13.6-21	12-26	-	-	-	[24]
58-64	18-24	15.75	0.4-0.8	0.2-0.5	-	[25]
61-73	13.6-23	12-16	-	-	-	[26]
61-63	13.0	5-13	-	-	-	[27]
64.4	12	11.8	0.5	0.2	1.1	[4]
60-72	12-24	11-24	0.5	0.2	-	[11]
61-71.5	12-13	13.6-20.4	0.5	0.2	12.6	[1]
71.5	13.4	13.1	0.6	0.2	-	[28]

Table 2. Chemical constituents of basalt fiber

Key constituents	Composition (%)					
	[29]	[30]	[31]	[32]	[33]	[34]
SiO_2	48.8-51	52.8	43-58	45-60	51.56	56.81
Al_2O_3	14-15.6	17.5	11-20	12-19	18.24	16.89
CaO	7-11	8.59	7-13	6-15	5.15	9.68
MgO	6.2-16	4.63	4-12	3-7	1.30	2.40
Na_2O+ K_2O	1.9-2.2	-	-	2.5-6	-	-
Na_2O	-	3.34	-	-	6.36	-
Fe_2O_3+FeO	7.3-13	-	-	7-18	-	-
Fe_2O_3	-	10.3	8-16	-	4.02	10.77
TiO_2	0.9-1.6	1.38	-	0.9-2	1.23	-
P_2O_5	-	0.28	-	-	-	-
Cr_2O_3	-	0.06	-	-	-	-

Table 3. Physical properties of jute fiber

Properties	Values					
	[35]	[36]	[37]	[38]	[39]	[40]
Diameter (µm)	5-25	20-200	25-30	20-200	-	90-115
Density (g/cm^3)	1.23	1.3-1.45	-	1.3-1.49	1.46	1.5
Length (mm)	0.8-6	-	120	1.5-120	1.5-5	-
Moisture content (%)	-	-	-	12.5-13.7	12	-
Areal density (g/m^2)	-	-	-	-	-	-

Table 4. Physical properties of basalt fiber

Properties	Values			
	[41]	[42]	[17]	[33]
Moisture content (%)	0.15	-	-	-
Density (g/cm^3)	2.64	-	2.65-3.05	2.733
Diameter (mm)	0.0166	-	-	0.01025
Areal density (g/m^2)	-	300	-	-

PHYSICAL PROPERTIES OF JUTE AND BASALT FIBER

Jute is a natural plant fiber widely recognized for its environmentally friendly characteristics, making it a viable alternative to synthetic fibers [34]. The diameter of jute fibers generally spans from 5 to 200 micrometers, and its density typically varies between 1.23 and 1.5 grams per cubic centimeter. Additionally, the moisture content of jute fibers usually falls within the range of 12 to 13.7%, as indicated in Table 3.

Jute, often hailed for its sustainability, serves as an eco-friendly substitute for man-made fibers due to its biodegradability and renewable nature. This plant-based fiber generally features diameters ranging from 5 micrometers at the finer end to as much as 200 micrometers at the coarser end. The density of jute fibers, which influences their weight and strength, is typically observed to be between 1.23 and 1.5 grams per cubic centimeter. Moreover, these fibers possess a moisture content that usually lies between 12 and 13.7%, providing a balance between flexibility and durability, as detailed in Table 3.

Basalt, derived from volcanic rock, is highly esteemed for its remarkable heat resistance. This natural material forms the basis for basalt fibers, which are noted for their exceptional tensile strength, surpassing that of E-glass fibers. Furthermore, basalt fibers exhibit a robust resistance to chemical degradation, outperforming carbon fibers in this regard. Table 4 provides an in-depth look at the physical properties of basalt fibers, including their moisture content, density, and diameter. Basalt, a product of volcanic activity, is celebrated for its outstanding thermal resistance, making it an ideal candidate for high-temperature applications. The fibers produced from basalt rock are particularly notable for their impressive tensile strength, which is significantly higher than that of traditional E-glass fibers. In addition to their mechanical strength, basalt fibers also offer superior resistance to chemical corrosion when compared to carbon fibers, making them highly durable in harsh chemical environments. The detailed physical properties of these fibers, such as moisture content, density, and diameter, are comprehensively outlined in Table 4.

DEVELOPMENT OF JUTE/BASALT EPOXY COMPOSITES

Jute and basalt epoxy-reinforced composites represent a frontier in material science, combining high performance with distinctive properties. Researchers have developed these composites by integrating natural jute fibers and basalt fibers with epoxy resin, achieving a balance between mechanical strength and sustainability. Jute fibers, known for their biodegradability and low cost, pair excellently with basalt fibers, which are prized for their superior mechanical properties and thermal stability. The result is a composite with an impressive strength-to-weight ratio, enhancing material performance while reducing the environmental footprint. The development of these reinforced composites signifies a crucial advancement towards creating environmentally friendly materials suitable for diverse industrial applications. These composites are particularly valuable in sectors such as automotive, aerospace, construction, and sports equipment, where there is a growing demand for materials that are lightweight, durable, and sustainable. The adaptability of these composites allows for customization in fiber orientation, volume fraction, and matrix composition, enabling precise optimization for specific use cases [43].

Currently, bio-composites are manufactured using a variety of techniques traditionally used for synthetic composites. These techniques include the pultrusion method, hand lay-up, spray lay-up, resin transfer molding, compression molding, extrusion, injection molding, and filament winding. There are distinct advantages to each of these methods in terms of processing effectiveness, material properties, and cost-effectiveness. For example, compression molding is renowned for producing high-strength components with excellent surface finishes, while filament winding is ideal for creating robust, hollow, cylindrical structures.

Table 5 outlines the fabrication methods used for hybrid composites, demonstrating the flexibility and adaptability of these processes to handle different material combinations and design requirements. Figure 4 depicts compression molding machines, which are frequently used in the production of reinforced composites. These machines apply heat and pressure to mold and cure the composite material, ensuring uniformity and high structural integrity.

Fig. 4. Compression molding machine

Table 5. Fabrication methods to develop jute/basalt composites.

Matrix	Reinforcement	Process	Outcomes	Ref.
Epoxy	Jute epoxy (treated with 20% NaOH)	Compression molding technique	Reports indicate that jute treated with sodium hydroxide exhibited enhanced mechanical properties compared to untreated jute, with a tensile strength of 97 MPa and flexural strength of 80 MPa.	[44]
Epoxy	Jute/basalt reinforced hybrid epoxy composites	Hybrid composite laminates are prepared using the hand lay-up process	The results indicate that the composite's tensile strength, bending resistance, in-plane shear strength, and bearing capacity were all improved by hybridizing jute and basalt fibers.	[45]
Epoxy	Jute/basalt hybrid epoxy composites	Vacuum-assisted resin infusion	The study findings indicate that jute/basalt hybrid laminates exhibited superior impact energy absorption and flexural properties compared to laminates made solely of jute fibers. These hybrid laminates also showed greater resistance to aging over time. Moreover, the results suggest that jute/basalt hybrid laminates, Particularly, hybrid laminates having a sandwich-like structure showed better aging endurance than hybrid laminates with an intercalated configuration.	[42]
Polyester	Jute/glass fiber reinforced polyester	Pultrusion	The research examined how a hybrid composite made of polyester, jute, and glass fibers interacts with water. It was discovered that integrating glass fibers into the composite increased its ability to resist water absorption and exposure to moisture led to a significant decline in the flexural and tensile properties of the hybrid composites due to water absorption.	[46]
PLA (Polylactic acid)	Green composites reinforced with jute fiber and polylactide	Injection molding	The results indicate that using well-combined pellets in the injection molding process can improve the produced composites' tensile strength and Young's modulus.	[47-49]
PBS (Polybutylene Succinate)	Basalt fiber reinforced with PBS	Injection molding method	Since more basalt fibers work synergistically to improve the tensile and flexural characteristics of the PBS matrix, the tensile strength of the matrix increases from 31 to 46 MPa, while the flexural strength increases from 18 to 71 MPa.	[50]
Epoxy	Basalt epoxy contains tourmaline micro/nano particles (0.5-2 wt%)	Resin transfer molding with vacuum technique	While the tensile and flexural modulus exhibited increases of 27% and 153%, respectively, the tensile and flexural strength rose by 16%.	[51]

PLA (Polylactic acid)	Basalt fiber/polylactic acid composite	Plasma polymerization is used in hot press compression molding and air pressure glow discharge (APGD) to modify the surface of basalt fiber.	The study revealed that the composite showed a 45% increase in strength and an 18% increase in modulus compared to the untreated composite. The most effective plasma polymerization treatment for basalt fibers was found to be at a plasma exposure time of 4.5 min.	[52-53]

SURFACE TREATMENT OF FIBER

a) *Alkaline treatment.* This treatment alters the surface chemistry of the fibers by eliminating impurities, waxes, and hemicelluloses, resulting in increased surface roughness and enhanced fiber-matrix adhesion. The primary objective of the alkaline treatment was to mitigate the hydrophilicity of the jute fibers. Prior research indicated that alkaline treatment not only decreases hydrophilicity but also enhances the wettability of epoxy with jute fibers. In this study, the jute fibers underwent immersion in a 5% NaOH solution for 2 hours at a temperature of 25°C. This treatment process is a well-established method for modifying the surface characteristics of natural fibers, promoting better adhesion and compatibility with polymer matrices such as epoxy. By reducing the hydrophilicity and enhancing wettability, the alkaline treatment lays the groundwork for improving the overall performance and mechanical properties of jute-based composite materials [54].

The most used chemical modification process for jute fibers is alkaline treatment. Sodium hydroxide, or NaOH, is a popular alkaline treatment for jute fiber. Alkali is used to treat jute fiber to eliminate non-cellulosic materials including hemicellulose, lignin, wax, and oils from its exterior. Jute fibers treated with alkali lose their moisture-associated hydroxyl groups, which reduces their hydrophilicity. Water molecules are created when NaOH interacts with jute fiber, and Na-O joins forces with the fiber's cell wall to produce fiber-cell-O-Na groups. Fiber-cell-OH + NaOH = Fiber-cell-O-Na + H2O + pollutants.

Alkalization is a basic surface treatment for natural fibers, involving sodium hydroxide. This process alters cellulose's structure, producing short crystallites. When cellulose is placed in a solution containing alkali metal hydroxide, it transforms from cellulose I to cellulose II. Water is created when the OH- of NaOH and the H+ of cellulose mix, forming Cell-O-Na+. Alkalization removes impurities from jute fibers' surfaces. It has been used aqueous NaOH for different periods, followed by washing and neutralizing with dilute acetic acid. Used an ultrasonication bath, oven-drying for 24 hours, and ultrasonicated with aqueous NaOH for 1 hour. Alkalization improves the mechanical properties of fiber-reinforced composites, including impact strength, fatigue, compressive strength, flexural strength, and dynamic behaviors [55]. Jute fiber is used to chemically treat to enhance the interfacial bonding between fiber and hydrophobic matrices. The common method used is alkali to do surface modification of natural fibers and jute fiber is treated with 0.5, 4, and 25 wt.% of NaOH solution at ambient temperature for 24 hours, 30 min, and 20 min respectively, and it been found that jute fiber treated with 0.5 wt.% NaOH is an efficient way to optimize the mechanical properties of natural fiber-reinforced composites [56].

b) *Alkali-bleaching.* The effects of hydrogen peroxide bleaching and alkali treatment on the tensile properties of short jute fiber composites have been investigated. For the composites, different weights of treated and untreated jute fiber were mixed with the PLA matrix. The tensile strength and modulus of the composites treated with 10% NaOH and bleached with H_2O_2 were found to be 7.5% and 40% higher, respectively, than those of the untreated composites. Climate, age, and digestion all influence the structure and chemical composition of jute fibers. They are made up of 60% cellulose, 12% lignin, pectin, moisture, and ash content. They also withstand air temperatures of up to 100°C without degrading [55]. Alkali bleaching plays a crucial role in enhancing the quality and performance of jute fibers for various applications, including composite materials, by refining the fiber surface and removing undesirable components.

c) *Silane and alkali-silane treatment.* Silane treatment, utilizing reactive silane molecules, plays a crucial role in enhancing the bonding between fibers and polymers in composite materials. Specifically, alkali-silane treatment intensifies the reactivity with the fiber surface, resulting in superior bonding. Both silane treatments contribute to improving interfacial adhesion, consequently strengthening the composite's overall performance, durability, and strength. This heightened bonding between fibers and the polymer matrix not only enhances mechanical properties but also reinforces the material's ability to withstand environmental stresses, making it an indispensable technique in composite material fabrication.

Silane molecules have special parts on both ends that work together to build a bridge: one end connects with the water-loving parts of the jute fiber, and the other end connects with the water-repelling parts of the polymer matrix [56]. When natural fibers are treated with silane, it reacts with the fibers' surface to create stronger bonds. This happens when silane molecules hydrolyze and form silanol groups, which then bond with the hydroxyl groups on the fiber surface. These bonds can be either covalent or hydrogen. Common types of silanes used include alkyl, amino, meth acryl, and glycidoxy. Silane treatment enhances the strength of fibers and increases their resistance to water, especially when there is a strong bond between the silane and the matrix [57].

In this study, a silane solution was mixed with methanol and stirred for 5 minutes. The fibers were then soaked in this solution for 60 minutes to ensure thorough infiltration and surface treatment. After soaking, the fibers were meticulously rinsed with distilled water to remove any residual chemicals and impurities, ensuring that the silane coating adhered uniformly to the fiber surface. The treated fibers were then left to dry for 12 hours in a controlled environment to allow complete evaporation of any remaining solvent and to enable the formation of a strong chemical bond between the silane and the fiber surface [58].

In another experiment, fibers were submerged in a 0.5 wt% silane solution for 1 min and then kept at 50°C for 4 h. A solvent was prepared by dissolving a liquid siloxane solution, and the jute fabrics were treated with an alkaline solution and sonicated to enhance surface reactivity. The fabrics were then immersed in the siloxane solution for 1 h to ensure thorough treatment. Following this, the treated fabrics were dried at 60°C for 24 h to ensure complete curing and stabilization of the chemical treatment, enhancing their mechanical properties and adhesion characteristics [59].

The study concludes that silane treatment of alkalized jute fiber can increase specific tensile strength due to the effective interaction between silane and hydroxyl groups on the fiber surface.

d) *Hydroxybenzene diazonium salt treatment.* Typically, treatments of jute fiber are conducted to modify the surface properties, with one such treatment involving the use of benzene diazonium salts. Jute fibers were immersed in a 5% NaOH solution for 10 minutes in an ice bath. Then, a cooled solution of o-hydroxy benzene diazonium chloride was added and stirred for 10 minutes. The fibers are then washed with soap solution and water, followed by drying. Similar treatments were done using m-hydroxy benzene diazonium chloride and p-hydroxy benzene diazonium chloride in both alkaline and acidic conditions. It has been found that treated jute fibers showed decreased tensile strength, tenacity, and moisture absorption compared to untreated fibers. Among treatments using ortho, meta, and para hydroxy benzene diazonium salts, the highest tensile strength and tenacity were observed with o-hydroxy benzene diazonium salts, followed by m-hydroxy benzene diazonium salts, and then p-hydroxy benzene diazonium salts [60].

e) *Plasma and alkali-plasma treatment.* Plasma treatment and alkali-plasma treatment are advance. ed techniques used to modify the surface of natural fibers like jute, enhancing adhesion with the matrix. Sever [61] conducted a study on jute fiber/high-density polyethylene (HDPE) composites, focusing on enhancing the properties of jute fabrics through surface treatment with oxygen plasma. Both low-frequency (LF) and radiofrequency (RF) plasma systems were utilized, with plasma power adjusted to 30, 60, and 90 W for 15 min. X-ray photoelectron spectroscopy (XPS) analysis was employed to assess the impact of oxygen plasma treatment on the functional groups of jute fibers. Another study investigated the improvement of jute fiber quality through treatment with plasma generated from helium and acrylic acid. Treatment duration varied from 30 s to 120 s at a plasma power of 3 kV and 20 kHz. Additionally, alkali treatment using different NaOH concentrations (3%, 5%, and 7% w/w%) was applied to the jute fibers. Composite materials were created by combining 20% jute with 80% polylactic acid (PLA) in the injection molding process. Comparative analysis revealed that plasma-treated jute/PLA composites exhibited superior mechanical properties compared to untreated or alkali-treated counterparts. Specifically, the plasma-treated jute/PLA composite demonstrated significant enhancements, including a 28% increase in tensile strength, a 17% increase in Young's modulus, and a 20% increase in flexural strength, highlighting the beneficial effects of plasma treatment on the mechanical performance of jute/PLA composites [62].

f) *Permanganate treatment.* Permanganate is a chemical compound that contains the permanganate group, represented by the formula MnO_4.In this treatment, alkaline-treated jute fibers are immersed in a 50% permanganate acetone solution for a specified duration, followed by drying at 40°C for 5 hours to eliminate excess solvent and moisture. This permanganate treatment reduced the hydrophilic nature of the jute fibers, resulting in decreased water content in the JFRP (jute fiber reinforced polymer composite [63]. Thus, moisture content was eliminated from the fiber, resulting in increased strength.

g) *Glycine treatment.* Treatment aims to modify the surface properties of the yarns, potentially enhancing their performance in diverse applications. Cotton yarn samples were treated with a 20% w/v glycine solution at a 1:100 yarn-to-liquor ratio and reflux at 100°C for 24 hours with constant stirring. Treatments were conducted at pH 3, 4, 7, and 11, adjusted using sodium hydroxide or hydrochloric acid. Control treatments without glycine were also performed. After treatment, the yarns were washed with deionized water and dried at 50°C overnight. Remadevi [64] Alkali-treated and untreated jute yarns were subjected to treatment with aqueous glycine solutions at various concentrations (5, 10, 15, and 20 g/l) at 100°C and pH 7 for 1.5 h using an infrared lab dyeing machine. Additionally, four pH levels (3, 5, 7, and 11) were tested using 10 g/l aqueous glycine solutions to evaluate their impact on alkali-treated jute yarns. Afterward, all samples were rinsed with distilled water and then dried in an oven at 50°C for a minimum of 5 h. Glycine treatment can affect the characteristics of jute yarns, such as their strength, flexibility, and compatibility with other materials. It was observed that glycine treatment applied to alkali-treated jute yarn resulted in a notable improvement in the packing of fibers within the yarn structure as well as tensile strength and strain properties showing an impressive increase of approximately 105% and 50%, respectively, compared to untreated jute yarns [65].

MECHANICAL PROPERTIES OF JUTE/BASALT COMPOSITES

Natural fibers offer a host of advantages, including impressive mechanical properties, significant specific strength, cost-effectiveness, lightweight composition, biodegradability, and non-abrasiveness. To enhance the mechanical properties of composite materials reinforced with basalt fibers, hybridization with other natural fibers such as jute, kenaf, hemp, and sisal can be employed. Basalt fiber is often preferred for its cost-effectiveness and widespread availability, making it a popular choice in this regard.

Mishra [18] examined a combination of jute and epoxy to create a hybrid composite and discovered that it resulted in stronger flexural, tensile, and impact properties. It was noticed that the composite displayed improved mechanical bonding between the jute fibers and the epoxy matrix, attributed to the effective stress transfer at the fiber-matrix interface. This enhancement in bonding likely resulted from the inherent compatibility between the jute fibers and the epoxy resin, as well as potential surface treatments applied to the fibers to increase adhesion. The study's findings underscore the potential of jute-epoxy hybrid composites in applications requiring high mechanical performance, where the synergy between natural fibers and polymer matrices can be leveraged to produce durable, lightweight, and environmentally friendly materials.

Zamri [67] examined the effects of water absorption on a glass-fiber and jute composite. It was discovered that once the composite absorbed water, its mechanical attributes—such as its flexural and compression strengths—significantly dropped. Therefore, surface treatments of the fiber are necessary to improve the mechanical characteristics of reinforced composites. Researchers combined a substance known as polylactide with 50% jute fiber to create a composite. They applied a 5% solution of a substance known as aqueous NaOH (Sodium hydroxide) to cure it. Because of this treatment, the fiber's surface became rougher, improving the jute fibers' ability to adhere to the polylactide substance. Tensile strength and flexural modulus were enhanced as a result of the rougher surface's higher interfacial adhesion between the jute fibers and the polylactide matrix. Additionally, the hydrophilic nature of the jute fibers was reduced, resulting in decreased water absorption and enhanced dimensional stability of the composite [68].

The jute/epoxy composite was crafted using a hand lay-up technique, followed by treatment with a 20% NaOH solution to enhance the adhesion between the jute fibers and the epoxy matrix. Similarly, a jute/polypropylene composite was formed using the same technique, with the jute fibers treated using a 7% NaOH solution. Investigations revealed that alkaline treatment increased tensile strength and flexural strength, indicating improved interfacial bonding and compatibility between the treated jute fibers and the polymer matrices [44].

Jute fiber is renowned for its lightweight nature and relatively high specific modulus, making it particularly suitable for applications that require both stiffness and strength in composite materials. This natural fiber, derived from the jute plant, is also prized for its biodegradability, renewability, and cost-effectiveness, which contribute significantly to the sustainability of composite materials. Its high specific modulus means that jute fiber provides considerable stiffness per unit weight, an advantage that is crucial in industries like automotive and aerospace where weight reduction is essential for improving fuel efficiency and performance.

In contrast, basalt fibers are celebrated for their exceptional ability to withstand high temperatures and their outstanding mechanical properties. These fibers are produced by melting and extruding basalt rock, resulting in a material that can endure extreme thermal environments, such as those encountered in airplane or car engines.

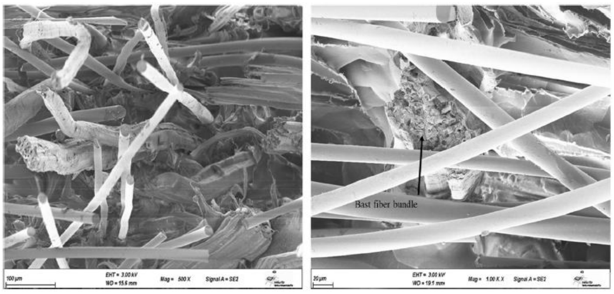

Figure 5. SEM images of PP – hybrid basalt/kenaf composite shows homogeneous distribution of fibers in thermoplastic matrix (Open source) [75]

Basalt fibers exhibit high tensile strength, excellent chemical resistance, and superior thermal stability, making them an ideal choice for reinforcing composites used in demanding conditions. Figure 5 shows the SEM image of PP-hybrid basalt/kenaf composites.

The innovative hybridization of jute and basalt fibers in an epoxy matrix results in a composite material that leverages the unique properties of both fibers. The resulting reinforced epoxy composite benefits from the high-temperature resistance of basalt and the flexibility and lightweight nature of jute fiber. This hybrid composite exhibits a balanced combination of properties that neither fiber could achieve alone. This synergy makes jute-basalt epoxy composites particularly attractive for applications in transportation, construction, and energy sectors, where materials must perform under diverse and challenging conditions.

The mechanical characteristics of jute and basalt fibers, such as tensile strength, Young's modulus, and elongation at the break, are covered in detail in this paper. Various tables offer a thorough summary, showing how the combination of various fibers improves the composite material's performance. A significant factor in the composite's flexibility and capacity for energy absorption is the modest tensile strength and elongation at break that jute fibers generally exhibit. Conversely, basalt fibers have a high Young's modulus and tensile strength, which improve the stiffness and load-bearing capability of the composite.

The fusion of jute and basalt fibers in epoxy composites not only improves mechanical performance but also contributes to sustainability. Jute fibers, being a natural and renewable resource, reduce the overall environmental impact of the composite material. When combined with basalt fibers, which are also derived from natural rock, the composite material supports sustainable development goals by minimizing reliance on synthetic, non-renewable fibers.

Advanced fabrication techniques such as resin transfer molding, compression molding, and filament winding are employed to produce these hybrid composites. Each method offers distinct advantages in processing efficiency and material properties. For instance, resin transfer molding allows for precise control over fiber alignment and resin distribution, resulting in high-quality composites with uniform properties. Compression molding, depicted in Figure 4, is favored for its ability to produce high-strength parts with excellent surface finishes, crucial for structural applications.

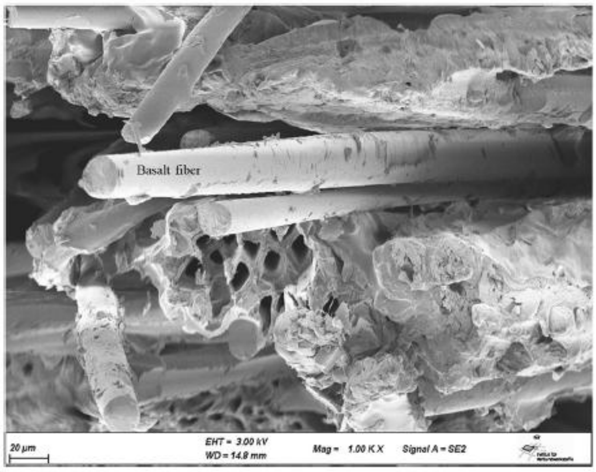

Figure 6. SEM Image of thermoset composite with bast and basalt fibers showing matrix remains on pull out fibers indicating an effective wetting of fibers by matrix (Open source) [75]

The hybrid composite's mechanical properties can be further optimized by fine-tuning the fiber-matrix interface, adjusting fiber volume fractions, and employing novel processing techniques. This level of customization enables the development of composites tailored to specific application requirements, enhancing their performance in real-world conditions. Figure 6 shows the SEM image of bast-basalt/Kenaf Composites. Figure 7 shows the SEM image of basalt composite at 50ºC curing temperature.

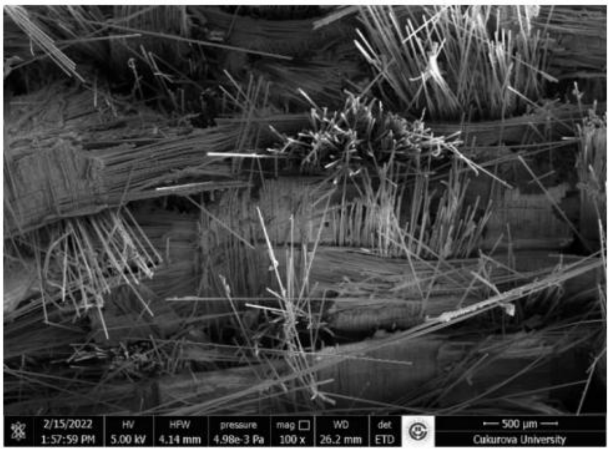

Figure 7. BE composites at 50°C post cure temperature SEM micrograph (Open source) [76].

CONCLUSION

In conclusion, the study underscores the significant potential of natural fibers, particularly jute, in enhancing the mechanical properties of hybrid composites while concurrently promoting environmental sustainability. This investigation has demonstrated that through effective surface treatment techniques, the optimization of the bonding between jute fibers and epoxy matrices can be achieved, which in turn leads to markedly improved mechanical performance of the composites.

The inherent characteristics of jute fibers, such as their high specific strength, low density, and biodegradability, make them an excellent candidate for use in composite materials. These attributes not only contribute to the mechanical enhancement of the composites but also align with the growing demand for sustainable and environmentally friendly materials in various engineering applications. As industries increasingly pivot towards sustainability, the integration of natural fibers like jute into composite manufacturing processes becomes ever more pertinent.

Table 6. Mechanical properties of jute fiber

Properties	Jute fiber							
	[4]	[69]	[41]	[54]	[70]	[39]	[40]	[71]
Tensile strength (MPa)	393-773	450-550	-	290	393-773	400-800	393-773	393-773
Young's modulus (GPa)	13-26.5	10-32	-	28	26.5	10-30	19.0-26.5	13-26.5
Elongation at break (%)	1.16-1.5	1.1-1.5	1.56	-	1.5-1.8	1.5-1.8	1.16-1.80	1.16-1.5
Compressive strength (MPa)	30	35	40	42	36	39	48	50
Flexural strength (MPa)	110	130	100	140	180	185	190	200
Hardness (Shore D)	30	25	20	27	26	28	30	20
Shear strength (MPa)	20	22	27	29	30	21	22	26
Thermal stability (Decomposes at ºC)	210	200	230	220	210	205	230	230
Poisson's ratio	0.2	0.3	0.4	0.3	0.2	0.3	0.3	0.4

Table 7. Mechanical properties of basalt fiber

Properties	Basalt fiber		
	[72]	[73]	[74-76]
Tensile strength (MPa)	2900-3100	2800-4800	2200-2500
Young's modulus (GPa)	85-87	86-90	85-100
Ultimate elongation (%)	3.15	-	-
Compressive strength (MPa)	400	500	800
Flexural strength (MPa)	500	800	900
Hardness (Mohs scale)	6-7	-	6-7
Shear strength (MPa)	60	50	100
Thermal stability up to (ºC)	700	800	900
Poisson's ratio	0.2	0.2	0.3

Surface treatment techniques play a crucial role in enhancing the compatibility between jute fibers and epoxy matrices. The research has explored various methods such as chemical treatments, physical treatments, and hybrid treatments. Chemical treatments often involve the use of substances like silane, alkali, or benzoyl peroxide, which modify the fiber surface, thereby improving adhesion to the matrix. These treatments can effectively remove impurities and increase the surface roughness of the fibers, leading to better mechanical interlocking and stress transfer between the fiber and matrix.

On the other hand, physical treatments which are less harmful to the environment, include procedures like plasma treatment, which change the fiber surface without the use of chemicals. Physical treatments increase the wetting qualities of jute fibers by altering their topography and surface energy. This allows the epoxy resin to penetrate the fibers more easily, improving the mechanical properties of the composites.

The study's conclusions demonstrate how significantly the treated jute-epoxy composites' mechanical qualities such as their tensile strength, flexural strength, and impact resistance improved over those of the untreated equivalents. This improvement is directly related to the enhanced stress transfer efficiency at the fiber-matrix interface, which is made possible by the surface treatments' better bonding. These gains are not just slight but significant, suggesting that in some composite applications, surface-treated jute fibers can be a competitive substitute for synthetic fibers.

.Moreover, the environmental benefits of using jute fibers in composite manufacturing cannot be overstated. Jute is a renewable resource that grows abundantly in regions with suitable climatic conditions. Its cultivation requires relatively low inputs of water, fertilizers, and pesticides compared to other fiber crops. Furthermore, jute fibers are biodegradable and pose minimal environmental hazards at the end of their life cycle. By replacing or supplementing synthetic fibers with jute, the overall environmental footprint of composite materials can be significantly reduced.

The integration of jute fibers into composite materials aligns with broader sustainability goals, such as reducing dependence on non-renewable resources and minimizing waste generation. This is particularly relevant in the context of the increasing regulatory and societal pressures to adopt greener manufacturing practices. As industries seek to comply with stricter environmental regulations and meet the sustainability expectations of consumers and stakeholders, the use of natural fibers like jute presents a compelling solution.

Additionally, the adoption of jute fibers in composite manufacturing can have positive socio-economic impacts. Jute cultivation and processing provide livelihoods for millions of farmers and workers, particularly in developing countries. By creating a stable demand for jute fibers, the composite industry can contribute to rural development and poverty alleviation in these regions.

This research underscores the critical importance of integrating sustainable materials into composite manufacturing processes, thereby mitigating environmental impact, and fostering a greener future for engineering applications. By advancing the understanding and application of jute fibers in composites, this study contributes to the broader effort of developing sustainable materials and technologies that can meet the demands of modern engineering while preserving environmental integrity.

REFERENCES

1. M. H. Islam, M. R. Islam, M. Dulal, S. Afroj & N. Karim. *iScience*, 25,103597. (2021) doi: 10.1016/j.isci.2021.103597
2. L. Prasad, A. Saini, V. Kumar., *J. Nat. Fibers,* 18, (2021) doi: 10.1080/15440478.2019.1645789.
3. J. I. P. Singh,, *LNME*, (2021) doi: 10.1007/978-981-16-1079-0_10.
4. M. K. Gupta, R. K. Srivastava, H. Bisaria. *IJFTR*, 5. (2015)
5. Célino, S. Fréour, F. Jacquemin & P. Casari. *Front. Chem.*, 1, 71637. (2014) doi: 0.3389/FCHEM.2013.00043.
6. R. M. Hossain, A. Islam, A. W. Van Vuure, V. Ignaas., *J. Sci. Res.*, 5. (2012) doi: 10.3329/jsr.v5i1.10519.
7. L. Naidu, P. Suman, P. S. V. R. Rao., *IJMPERD* (2016)
8. H. K. Mishra, B. N. Dash, S. S. Tripathy, B. N. Padhi., *Polym Plast Technol Eng.*, 39. (2000) doi: 10.1081/PPT-100100023.
9. E. Taban, F. Valipour, D. D. Abdi & S. Amininasab., *Int. J. Environ. Sci. Technol.*, 18. (2021) doi: 10.1007/S13762-020-03024-0.
10. C. Alves, P.M.C. Ferrão, A.J. Silva, L.G. Reis, M. Freitas, L.B. Rodrigues & D.E. Alves., *J Clean Prod.* 18. *(2010)* doi: 10.1016/j.jclepro.2009.10.022.
11. B.Pradeepa, M.Malathi, K. A.V., *EJEST*, 6. *(2010)* doi: 10.33422/ejest.v6i1.1052.
12. Rust JP, Gutierrez HM.., *Text. Res. J*, 64. (1991) doi:10.1177/004051759406401004.
13. Mukherjee, P. K. Ganguly, D. Surf., *J. Text. Inst*, 84. (1993) doi: 10.1080/00405009308658967.
14. J. Gassan, A. K. Bledzki., *Compos Sci Technol, 59.*. (1999) DOI:10.1016/S0266-3538(98)00169-9.
15. Y. Seki., *MSE*, 508. (2009) doi: 10.1016/j.msea.2009.01.043.
16. O. A. Khondker, U. S. Ishiaku, A. Nakai, H. Hamada. *J. Polym. Environ.* 13. (2005.) doi: 10.1007/s10924-005-2943.
17. Z. Li, J. Ma, H. Ma, X. Xu.. *IOP Conf. Ser.: Earth Environ. Sci.,* 186. (2018) doi: 10.1088/1755-1315/186/2/012052.
18. H. Jamshaid, R. Mishra., *J. Text. Inst,* 107. (2016) doi: 10.1080/00405000.2015.1071940.
19. Ashok kumar R. Tavadi, Y. Naik, K. Kumaresan, N.I. Jamadar, C. Rajaravi., *Int. J. Eng. Sci. Tech.*, 13. (2021) http://dx.doi.org/10.4314/ijest.v13i4.6
20. M. P. Lebedev, O. V. Startsev, A. K. Kychkin., *Heliyon*, 6. (2020) doi: 10.1016/j.heliyon.2020.e03481.
21. J. J. Lee, J. Song, H. Kim.,. *FIBER POLYM*, 15. (2014) doi: 10.1007/s12221-014-2329-7.
22. X. Qin, A. Shen, Y. Guo, Z. Li, Z. Lv., *Constr Build Mater*, 159. (2018) doi: 10.1016/j.conbuildmat.2017.11.012.
23. V. J. John, B. Dharmar., *Struct. Concr*, 22. (2021) doi: 10.1002/suco.201900086.
24. S. Khandaker, D. Akter, Hasan, M. Saifullah, A. Marwani, H.M. Islam, A. Asiri, A.M. Rahman, M.M. Hasan, M.M. Kuba, T. Awual, M.R. Sarker,, *Mater. Chem. Phys.*, 313. (2023) doi: 10.1016/J.MATCHEMPHYS.2023.128586.
25. Md. Zobaidul Hossen, S. Akhter, T. Sharmin Akter, Md. A. R. Dayan., *AJPAB*, 2. (2020) doi: 10.34104/ajpab.020.01770182.
26. S. Shahinur, M. M. Alamgir Sayeed, M. Hasan, A. S. M. Sayem, J. Haider, S. Ura, *Polymers*. 14. (2022) doi: 10.3390/polym14071445.
27. M. Thiruchitrambalam, A. Athijayamani, S. Sathiyamurthy, A. Syed Abu Thaheer., *J. Nat. Fibers.*, 7. (2010) doi: 10.1080/15440478.2010.529299.
28. T. M. Gowda, A. C. B. Naidu & R. Chhaya. 1999. *Compos. - A: Appl. Sci. Manuf.,* 30. (1999) doi.org/10.1016/S1359-835X(98)00157-2.
29. Lapena, M. H., Marinucci, G., Carvalho, O. de.. *Eccm15 (*2014).
30. Pareek, Saha., *(CoAST-2019).* (2019).
31. J. Liu, J. Yang, M. Chen, L. Lei, Z. Wu. *thermochimica Acta*, 660. (2018) doi: 10.1016/J.TCA.2017.12.023.
32. Y. Meng, J. Liu, Y. Xia, W. Liang, Q. Ran, Z. Xie., *Ceram. Int.*, 47. (2021) doi: 10.1016/J.CERAMINT.2021.01.097.
33. J. Militky, V. Kovacic., *Text. Res. J.* 66. (1996) doi:10.1177/004051759606600407
34. M S Rabbi, Tansirul Islam, M M K Bhuiya.. *IJMPERD, 10. (*2020)
35. Rathore, M. K. Pradhan., *Mater. Today: Proc.*, (2017) doi: 10.1016/j.matpr.2017.02.294.
36. M. A. Ashraf, M. Zwawi, M. T. Mehran, R. Kanthasamy, A. Bahadar. *Fibers*, 7. (2019) doi: 10.3390/fib7090077.
37. K. G. Satyanarayana, G. G. C. Arizaga & F. Wypych., *Prog. Polym. Sci.*, (2009) doi: 10.1016/j.progpolymsci.2008.12.002.
38. D. B. Dittenber & H. V. S. Gangarao., *Compos. - A: Appl. Sci. Manuf.* 43. (2012) doi: 10.1016/j.compositesa.2011.11.019.
39. D. Saravana Bavan & G. C. Mohan Kumar., *J. Reinf. Plast. Compos.*, 29. (2010) doi: 10.1177/0731684410381151.
40. K. Ganesan, C. Kailasanathan, N. Rajini, Sikiru O., *Constr. Build. Mater*, 301. (2021) doi: 10.1016/j.conbuildmat.2021.124117.
41. P. Amuthakkannan, V. Manikandan, J. T. WinowlinJappes, M. Uthayakumar., *SECM*, 20. (2013), doi: 10.1515/secm-2012-0144.

42. V. Fiore, T. Scalici, D. Badagliacco, D. Enea, G. Alaimo, A. Valenza., *Compos. Struct.*, 160. (2017) doi: 10.1016/j.compstruct.2016.11.025.
43. P. K. Bajpai, F. Ahmad, V. Chaudhary, *Handb. Ecomat*, 1. (2019) doi: 10.1007/978-3-319-68255-6_98.
44. M. Boopalan, M. J. Umapathy, P. Jenyfer., *Silicon*, 4. (2012) doi: 10.1007/s12633-012-9110-6.
45. H. Alshahrani, T. A. Sebaey, M. M. Awd Allah & M. A. Abd El-baky *J. Compos. Mater.*, 57. (2023) doi: 10.1177/00219983231155013.
46. H. M. Akil, C. Santulli, F. Sarasini, J. Tirillò, T. Valente. *Compos Sci Technol.*, 94. (2014) doi: 10.1016/j.compscitech.2014.01.017.
47. Y. Arao, T. Fujiura, S. Itani, T. Tanaka. *Compos B Eng.*, 68. (2015) doi: 10.1016/J.COMPOSITESB.2014.08.032.
48. J.I.P. Singh, *LNME*, (2020) doi: 10.1007/978-981-15-4059-2_12.
49. J. I. P. Singh, S. Singh., *AJEAT*, 7. (2021) doi: 10.51983/AJEAT-2018.7.2.997.
50. Grzesiak S, Pahn M, Klingler A, Akpan EI, Schultz-Cornelius M, Wetzel B. *Polymers*,14, 790. (2022) doi.org/10.3390/polym14040790.
51. D. G. ArySubagia, L. D. Tijing, Y. Kim, C. S. Kim, F. P. Vista Iv, H. K. Shon. *Compos B Eng.*, 58. (2014) doi: 10.1016/j.compositesb.2013.10.034.
52. D. Kurniawan, B. S. Kim, H. Y. Lee, and J. Y. Lim. *Compos B Eng.*, 43. (2011) doi: 10.1016/j.compositesb.2011.11.007.
53. S. Mohanty, J. Inder Preet Singh, V. Dhawan, S. Singh, A. Belaadi. *AIP Conf. Proc.*, 2962. (2024) doi: 10.1063/5.0192257.
54. Haq E, Saifullah A, Habib A, Azim AYMA, Alimuzzaman S, Dhakal HN, Sarker F., *Heliyon*, 10. (2024) doi: 10.1016/j.heliyon.2024.e24345.
55. N. Chand & M. Fahim., *NFRPC Tribology*, (2021) doi: 10.1016/B978-0-12-818983-2.00004-9.
56. M. M. A. Sayeed & A. Paharia., *J. Text. Inst.*, 110. (2019) doi: 10.1080/00405000.2019.1610998.
57. L. Pickering, M. G. A. Efendy, T. M. Le, *Compos. - A: Appl. Sci. Manuf.*, 83. (2016) doi: 10.1016/J.COMPOSITESA.2015.08.038.
58. M. Ramesh & C. Deepa., *J. Mater. Chem., (2024)* doi: 10.1039/D3TA05481K.
59. Sever., *J. Reinf. Plast. Compos.*, 29. (2010) doi: 10.1177/0731684409339078.
60. A. Kabir, M. R. Islam & M. M. Huque., *POLYM-PLAST TECH ENG*, 45. (2006) doi: 10.1080/03602550600553796.
61. K. Sever, S. Erden, H. A. Gülec, Y. Seki & M. Sarikanat, *Mater. Chem. Phys.*, 129. (2011) doi: 10.1016/J.MATCHEMPHYS.2011.04.001.
62. Gibeop, D. W. Lee, C. V. Prasad, F. Toru, B. S. Kim, J. Il Song., *Adv. Compos. Mater.*, 22. (2013) doi: 10.1080/09243046.2013.843814.
63. Engr. O. M. chubuike, C. C. Ebele, Engr. I. F. Ifeanyi, E. S. Okwuchukwu, O. E. Festus. *IJAERS.*, 4. (2017) doi: 10.22161/IJAERS.4.2.4.
64. R. Remadevi, S. Gordon, X. Wang, R. Rajkhowa., *J. Text. Inst.*, (2023) doi: 10.1080/00405000.2023.2240639.
65. Md. Ashadujjaman, Abu Saifullah, Darshill U Shah, Minglonghai Zhang, Mahmudul Akonda, Nazmul Karim, Forkan Sarker., *Mater. Res. Express*, 8. (2021) doi: 10.1088/2053-1591/ABFD5E.
66. R. Ganesh, P. Anand., *Mater. Today: Proc.*, 59. (2022) doi: 10.1016/J.MATPR.2022.03.327.
67. H. Zamri, H. M. Akil, A. A. Bakar, Z. A. M. Ishak, L. W. Cheng., *J. Compos. Mater.*, 46. (2012) doi: 10.1177/0021998311410488.
68. B. K. Goriparthi, K. N. S. Suman, N. Mohan Rao. *Compos. - A: Appl. Sci. Manuf.*, (2012) doi: 10.1016/j.compositesa.2012.05.007.
69. Alves, C., Ferrão, P., Silva, A., Reis, L., Freitas, M., Rodrigues, L.B., Alves, *D. J. Clean. Prod., 18.* (2010) doi: 10.1016/j.jclepro.2009.10.022.
70. Faruk, A. K. Bledzki, H. P. Fink, M. Sain., *Prog. Polym. Sci.,* 37. (2012) doi: 10.1016/j.progpolymsci.2012.04.003.
71. M. Chandrasekar, M. R. Ishak, S. M. Sapuan, Z. Leman, M. Jawaid., *PLAST RUBBER COMPOS.*, 46. (2017) doi: 10.1080/14658011.2017.1298550.
72. V. Ramesh, P. Anand. *Mater. Today: Proc...*, (2020) doi: 10.1016/j.matpr.2020.05.406.
73. P. Jagdeesh, Sanjay, Suchart,, *Constr. Build. Mater.,* 436. (2024) doi: https://doi.org/10.1016/j.conbuildmat.2024.136834
74. V. P. Sergeev, Y. N. Chuvashov, O. V Galushchak, I. G. Pervak, N. S. Fatikova. (1994) doi.org/10.1007/BF00559548 1994.
75. Saleem, A., Medina, L., Skrifvars., *J Polym Res 27*, 61. (2020) doi.org/10.1007/s10965-020-2028-6.
76. Karacor, B., & Özcanlı, M., *IAREJ*. 6. (2020) https://doi.org/10.35860/iarej.1089568