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Characterizing the mechanical behavior of eco-friendly hybrid polymer composites with jute and Sida cordifolia fibers

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ABSTRACT

Introduction. Recognition of the medicinal properties of plants is an integral part of traditional Indian health systems such as Unani, Siddha, Naturopathy and Ayurveda. Among others, *Sida cordifolia*, a member of the Malvaceae family, is especially celebrated in Ayurvedic medicine for its outstanding chemical properties. This plant grows in the subtropical and tropical climate of India and symbolizes the global shift towards more environmentally friendly materials. Given the rising environmental concerns, there is an increased demand for biodegradable and renewable resources for industrial applications, especially for reinforcing polymer matrices with natural fibers. **The purpose of this study** is to investigate the effectiveness of *Sida cordifolia* fibers combined with jute for reinforcing polylactic acid (*PLA*) composites. This highlights its potential to improve both environmental quality and mechanical properties of materials. **Materials and method.** The study involved the fabrication of four different composite specimens: : a solely 4-layered jute fiber mat, untreated Sida cordifolia fibers combined with a 4-layered jute mat, and Sida cordifolia fibers treated with benzoylation combined with a 4-layered jute mat. These composites were subjected to mechanical testing focusing on tensile strength and flexural strength. Its microstructural analysis was also carried out. **Results and discussion.** The results show that benzoylation-treated *Sida cordifolia* fibers exhibit significantly higher strength compared to its untreated counterparts. At the same time, an increase in the proportion of *Sida cordifolia* fibers in composites while maintaining a constant total mass correlates with an increase in the strength of the materials. These results indicate that *Sida cordifolia* and jute fiber-reinforced *PLA* composites can provide a competitive, environmentally friendly alternative to synthetic fiber-reinforced composites in a variety of industrial applications. In conclusion, treated natural fibers like *Sida cordifolia* can significantly improve the mechanical properties of polymer composites, supporting its use as environmentally friendly, high-performance materials in a variety of industries. This research not only promotes the use of natural fibers for commercial applications, but also contributes to the larger goal of sustainable materials science.

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Introduction

Natural composites are intrinsic to nature itself, the most obvious example of which is wood, a composite of long cellulose fibers held together by lignin. Composite materials are a combination of two or more different components that retain its individual properties without merging or dissolving. This unique combination gives the composite special characteristics, enhancing its functionality. Composite materials have played an important role in various fields throughout history. As early as 1500 BC, ancient civilizations such as the Egyptians and Mesopotamians used a mixture of mud and straw to construct durable structures,

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demonstrating the long-standing usefulness of composite materials. This ancient method, still used in brick blocks today, provides structures with impressive resistance to compression, tearing, and bending [1].

The demand for composite materials increased significantly, propelling the fiber-reinforced polymers (*FRP*) industry forward. By 1945, the industry was using more than 7 million pounds of glass fibers to produce a wide range of products, primarily for military purposes. After the war, the use of composites expanded rapidly, especially in the 1950s, when innovators began to introduce it into areas such as aerospace, construction, and transportation. The remarkable corrosion resistance of *FRP* composites quickly gained recognition, especially in the public sector [2].

The composite materials industry is currently evolving, especially in the renewable energy sector. Innovations in composite materials are critical to the development of larger wind turbine blades. Engineers can design composites to meet specific performance requirements. This involves reinforcing the composite in one direction by aligning the fibers to increase strength, while intentionally leaving weaker areas in less critical directions. Furthermore, choosing the suitable matrix materials allows engineers to tailor properties such as resistance to heat, chemicals, and weathering [3].

In recent years, there has been a growing interest in the use of natural fibers as an alternative to synthetic fibers, driven by environmental awareness and the imperative of sustainable development. The aim of this paper is to provide a detailed overview of the scientific and technological advances underlying composite materials, as well as its manufacturing technologies and various applications [1].

Green Composites

Growing awareness of environmental issues worldwide has led to the development of recyclable, biodegradable, cost-effective green materials based on environmentally friendly components. This trend has fostered the growth of a community of researchers and designers seeking to reduce the environmental impact of polymer composite production. Green composites are a special type of composite materials in which either the matrix, the reinforcing phase, or both are produced from natural components. These materials are made by combining plant fibers with natural resins, which represents a significant step forward in creating more environmentally friendly and biodegradable materials. This development not only offers solution to the escalating environmental crisis, but also addresses the problems associated with waste management and the depletion of fossil resources [4].

The basic components of green composites are the matrix and the reinforcing component. The matrix can be either a non-biodegradable petroleum-based material, such as epoxy resins, or a biodegradable polymer, such as polylactic acid (*PLA*). The load-bearing reinforcement is the second important component. The matrix and the reinforcement together determine the overall characteristics of the composite. These composites can be tailored to specific purposes or requirements, allowing for the creation of both partially and fully biodegradable composites. Fully biodegradable composites are often referred to as biopolymers or green polymers; however, composite materials that are only partially biodegradable can also significantly reduce its environmental impact compared to traditional materials [2].

Researchers are actively studying the physical and mechanical properties of such composites, making certain assumptions within defined limits, to assess its applicability. The key advantages of green composites are its cost-effectiveness, light weight, and environmental friendliness, making it an attractive alternative in a variety of applications.

Reinforcement Components in Green Composites

Reinforcement components play a key role in the production of sustainable composites by acting as load-bearing elements that improve the mechanical properties of the polymer system. These materials are critical to improving the robustness as well as the overall strength and stiffness of composite materials. In green composites, natural fibers such as jute, flax, ramie, and sisal can be used as a reinforcement component. These biofibers are embedded in the polymer matrix, forming a dispersed phase that absorbs stress and improves the mechanical integrity of the composite [5]. The characteristics and structure of the fibers depend on several factors, including its volume ratio, orientation, shape, and bonding to the matrix. The fibers in the matrix can be either woven or non-woven, with woven patterns typically consisting of continuous perpendicular yarns. Depending on its arrangement in the matrix, the fibers are classified as unidirectional or bidirectional. Depending on the type of fibrous reinforcing component used, green composites can also be divided into materials with continuous reinforcing fibers in unidirectional and bidirectional forms and materials with dispersed reinforcing fibers [6].

Natural fibers come in various types, including bast fibers, leaf fibers, seed fibers, fruit fibers, and stem fibers. Understanding the chemical composition and interfacial adhesive bonding of these fibers is important for optimizing the performance of natural fiber-reinforced composites. The key components of these fibers include cellulose, hemicellulose, lignin, pectin, waxes, and water-soluble substances. Despite its advantages, natural plant fibers have several disadvantages, such as high moisture absorption, which can lead to fiber swelling and dimensional changes in the final composite material. In addition, the irregular geometry of natural fibers poses challenges in modeling and predicting the behavior of green composites. These factors need to be carefully controlled to fully utilize the potential of natural fibers in green composites [7].

Matrices in Green Composites

In green composites, the matrix plays a vital role as a homogeneous phase that determines the overall properties of the composite. It acts as the final component in the composite structure, anchoring the reinforcing fibers in place, forming the structure and uniformly distributing the load throughout the composite [8]. The matrix is important for the mechanical properties of the green composite, which significantly depend on the properties of the polymer matrix. There are two main types of matrices used in green composites: thermoplastics and thermosetting plastics. Thermosetting plastics usually include phenols and polyesters, while polyvinyl chloride, polypropylene and polyethylene are commonly used as thermoplastics. The use of these materials instead of traditional ones is due to the improvement of the specific properties of the composites [9].

In addition to providing structure, the matrix also prevents abrasion and the formation of new surface defects. The matrix maintains the arrangement of the fibers, allowing the composite to deform under load, transmitting and uniformly distributing the stress along the fibers. The choice of matrix materials can vary from petroleum-derived non-biodegradable polymers such as epoxy resins, polyethylene and polypropylene to biopolymers such as epoxy resins, polyhydroxybutyrate and *PLA*. These polymers determine the performance and environmental impact of green composites, among which polyethylene, polypropylene and polylactic acid are widely used [10].

Manufacturing of Green Composites

The manufacturing green composites has evolved along with advances in materials science. Currently, various technologies are used, including hand lay-up, vacuum molding, injection molding, polymer transfer molding, pultrusion, and compression molding. Each method affects the mechanical properties of the composite by changing the integrity of the fiber bond and the surface morphology. Compression molding and hand lay-up are widely used for the production of thermosetting matrices, while injection molding and screw extrusion are widely used for thermoplastic matrices. The chosen manufacturing technology significantly affects the behavior of the material, ensuring that the mechanical properties are optimized without causing damage or cracks [11].

Botanical Description of Sida cordifolia

Sida cordifolia, a member of the *Malvaceae* family and native to India, is an attractive plant due to its constant availability throughout the year. It is an annual or perennial woody subshrub that typically attains a height of 0.5–1.0 m. It features a softly hairy or greyish-green appearance and is characterized by its pubescent texture. The leaves of *Sida cordifolia* are simple, downy, and alternate, measuring 2.5–5 cm×1.8–3 cm as shown in Figure 1. The stipules are arranged linearly on the petioles. The flowers are bisexual, light or sulphur-yellow to creamy white, borne in axils and singly but densely at the tips of the branches. The flowering and fruiting periods are usually from October to February. The plant produces depressed, globular, fractional, disintegrating fruits of 6–8 mm in diameter. Each carpel has two long, erect awns. The seeds are smooth, flattened, kidney-shaped, and range in color from brown to black [12].

Fig. 1. Sida Cordifolia Plant

Sida cordifolia, known by various names such as *Audanika*, *Baladhya*, and *Balini* is native to tropical and subtropical regions of India, at altitudes up to 1,800 m, such as in the states of *Himachal Pradesh*, *Karnataka*, *Maharashtra*, *Uttar Pradesh*, *Assam*, *Andhra Pradesh*, *Gujarat*, *Jammu* and *Kashmir*, *Kerala*, *Madhya Pradesh*, *Tamil Nadu*, *Bengal* and the *Coromandel Coast*. The recent surge in demand for polymer composites in industries such as marine, aerospace, automotive, construction and sports has highlighted the potential of natural fibers such as *Sida cordifolia* as an alternative to synthetic fibers. Despite the durability, light weight and high specific strength of synthetic fibers, its disadvantages include high cost, lack of biodegradability and significant energy absorption during processing, which can lead to environmental pollution and wear and tear of processing equipment. The study of natural fibers is an effort to improve the environmental performance of materials and products, providing a sustainable alternative to traditional synthetic materials [13]. The physical properties of *Sida cordifolia* are listed in Table 1

The present work brings together important results of research on natural fibers and its composites, emphasizing its chemical modifications, mechanical properties and applications. The paper discusses several chemical modifications of natural fibers in composites, such as alkali, silane, acetic acid and other treatments. Such treatments improve the adhesion of the fiber surface to the polymer matrices, improving the mechanical properties of the composite and reducing moisture absorption [14]. The study investigates the viscoelastic properties of sisal fiber-reinforced polyester composites manufactured by polymer transfer molding. The changes in fiber adhesion to the matrix, which are affected by different treatments, were analyzed using *SEM* and *FTIR* spectroscopy to evaluate the changes in the fiber surface morphology [15]. The results of a study on uniaxial natural fabric of *G. tilifolia* are presented, in which approximately parallel

Table 1

Constants of *Sida cordifolia* physical properties [13]

S.NO	Constant	Root (%)	Stem (%)	Leaf (%)
1	Total ash	6.7	9.7	15.6
2	Acid insoluble ash	2.7	2.4	7.6
3	Alcohol Soluble extractive	2.8	2.9	4.5
4	Water soluble Extractive	4.4	6.5	12

fiber surfaces were revealed using SEM analysis [15]. Few authors have focused on the medicinal properties of *Sida cordifolia* used in *Ayurvedic* medicine for its analgesic, anti-inflammatory and other beneficial properties [16]. Authors have described in detail the characteristics of *Cissus quadrangularis* stem fiber, noting its *mechanical* properties *superior* to other fibers [17]. Some papers have highlighted the potential of maize residues (tassel fibers) as a source of cellulose for various applications including its extraction and characterization [18]. A study compares alkali pretreatment with other natural fiber production technologies, noting its environmental benefits and mild conditions despite the longer duration [19].

The author studies the fiber of *Sida Rhombifolia*, emphasizing its high cellulose content and its suitability for composite applications [20]. A new lignocellulosic fiber obtained from *Juncus Effusus L.* is also discussed, focusing on its unique cross-sectional shape [21]. *Dichrostachys Cinerea* fibers, *Heteropogon contortus* plant fibers, and *Epipremnum Aureum* stem fibers have been reported by many authors, each emphasizing the potential of these fibers for the development of lightweight, low-density composite materials due to its favorable mechanical and thermal properties [22]. Previous studies have also focused on the properties of *Perotis Indica* plant fibers, establishing its suitability as a substitute for traditional materials in various industries due to its beneficial mechanical and thermal properties [23]. He even characterized the thermal decomposition of *Sida cordifolia L.*, assessing its potential as an energy source using thermogravimetric analysis [24].

Each of these studies contributes to the ongoing development of natural fibre reinforced composites, providing insight into its potential applications and improvements through various chemical and physical treatments.

Materials and Method

Extraction process of sida cordifolia stem fiber

Sida cordifolia plants, commonly found in tropical southern regions of Asia, were specially obtained for this study from *Krishna* district of *Andhra Pradesh*. These plants generally grow to a height of 1.5 to 2 feet and were about 2 years old at the time of sampling. The fiber preparation process began with cutting the stems to the required length, followed by a 30-day drying period in direct sunlight to reduce the moisture content. After drying, the stems were subjected to a 14-day microbial decay process in fresh water. After this, the fibers were extracted from the stems using a retting method. Finally, these fibers were dried in sunlight to remove residual moisture. The extraction process of *Sida cordifolia* fibers is illustrated in Figure 2.

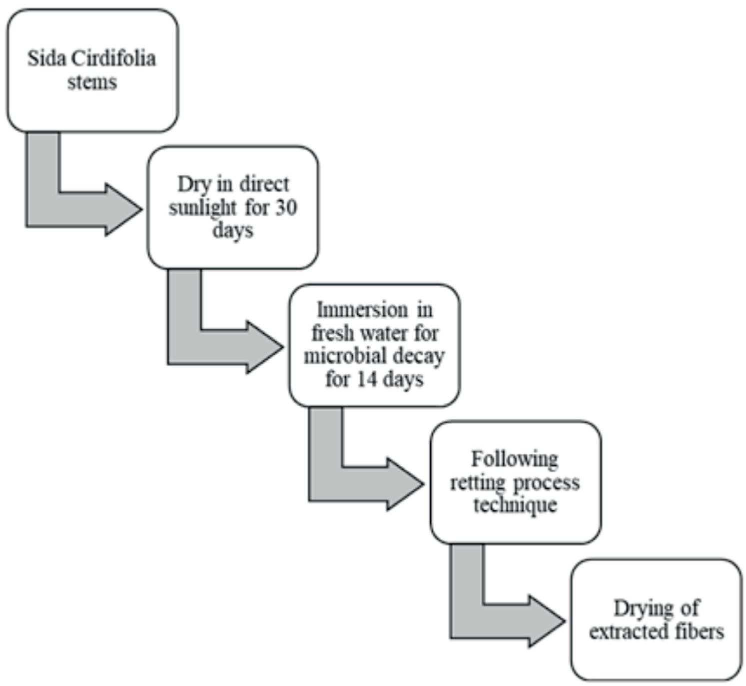


Fig. 2. Schematic flow for the Extraction Process of *Sida Cordifolia* Fibers

Chemical Treatment of fibers

Alkaline Treatment

Treatment of natural fibers with sodium hydroxide (*NaOH*) is a commonly used method for modifying the molecular structure of cellulosic materials. The major transformation caused by alkali treatment is the disruption of hydrogen bonds in the network structure, resulting in increased surface roughness. This process involves the removal of certain components such as lignin, wax, and oils that coat the external surface of the fiber cell wall. It also results in the depolymerization of cellulose, exposing shorter crystallites [25]. Alkali treatment has two main effects on fibers: (1) it increases the surface roughness, promoting increased mechanical cohesion, and (2) it increases the amount of cellulose present on the fiber surface.

$$\text{Fiber-}OH + NaOH \rightarrow \text{Fiber-}O\text{-}Na + H_2. \quad (1)$$

In the alkali treatment process, 10 % solution was applied for 60 minutes as shown in Table 2. After the *NaOH* solution treatment, the fibers were thoroughly washed with distilled water. Then, it was placed in a furnace at 60 °C for 24 hours to facilitate the removal of moisture.

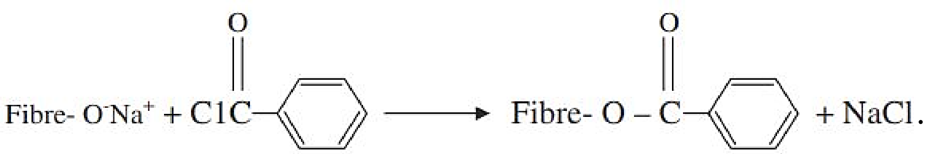
Table 2

Alkaline treatment *NaOH* concentration and time duration

NaOH, %	Time (min)	Furnace drying temperature for 24 hrs
10	60	60 °C

Benzoylation Treatment

Benzoylation treatment involves the use of benzoyl chloride to reduce the hydrophilicity of the fiber, improve interfacial adhesion and subsequently increase the strength of the composite. This process also helps to increase the thermal stability of the fibre [4]. In benzoylation treatment, a salt pre-treatment is first carried out to remove extractables such as lignin, waxes and oil covering substances. This step introduces more reactive hydroxyl (*OH*) groups to the fibre surface. The fibres are then subjected to benzoyl chloride treatment, which replaces the OH groups of the fibres with benzoyl groups attached to the cellulose backbone. This modification increases the hydrophobicity of the fibre and improves adhesion to the matrix [26]:



The *Sida cordifolia* fibers, pre-treated with an alkaline solution, were treated with a *NaOH* solution and stirred with benzoyl chloride for 15 minutes (Table 3). The solutions used were of the following concentrations: 10 % *NaOH* and 50 ml benzoyl chloride (1 % *NaOH* per 5 ml benzoyl chloride for benzoylation treatment). The fibers were then thoroughly rinsed with distilled water and immersed in ethanol for 1 hour to remove excess benzoyl chloride. After this, the fibers were subjected to another thorough wash with distilled water and then placed in a furnace for 24 hours at 80 °C to remove residual moisture from the fibers.

Table 3

Benzoylation treatment *NaOH* concentration and time duration

NaOH and Benzoyl chloride suspended Time (min)	Placed in Ethanol (min)	Furnace drying temperature for 24 hrs
15	60	80 °C

Method

Sida cordifolia fibres possess a number of characteristics that make it particularly suitable for combination with jute fibres in composite materials. *Sida cordifolia* fibres are known for its good tensile strength and flexibility, and when combined with jute fibres, it can improve the overall mechanical properties of the composite. Jute fibres are strong enough, and when combined with the elastic and resilient *Sida cordifolia* fibres, it produces a composite that is both strong and flexible. The chemical composition of *Sida cordifolia* fibres, which contain a significant amount of cellulose, is quite compatible with that of jute fibres. This compatibility can result in improved interfiber adhesion when used in a composite material. Improved bonding promotes better load distribution and increases the overall structural integrity of the composites [27].

Both *Sida cordifolia* and jute fibres are biodegradable and environmentally friendly. These fibers are natural, renewable resources that produce less environmental waste during processing and disposal compared to synthetic fibres. Its combined use in composite materials contributes to sustainable development goals by reducing the dependence on non-renewable polymer-based fibres and lowering the carbon footprint of the materials produced. While jute fibers have a relatively high-water absorption rate, which can lead to swelling and subsequent deterioration of mechanical properties, blending with *Sida cordifolia* fibres, which may have different moisture retention properties, can help mitigate this problem. A hybrid fibre composite can be designed to take advantage of the moisture resistance of *Sida cordifolia* and compensate for the hygroscopic disadvantages of jute fibres [28].

Both fibres are cost-effective, especially in regions where it grows naturally. The use of *Sida cordifolia* as a hybrid material with jute can keep the material costs low while providing high performance, making hybrid composites economically viable for various applications. The hybrid composite made from *Sida cordifolia* and jute fibers can be used in various applications including automotive, packaging, and building materials. The combination can be tailored for specific applications requiring mechanical properties or environmental resistance [29].

These synergistic properties make *Sida cordifolia* fibers an excellent candidate for combination with jute fibers, which can potentially result in composites that are strong, durable, and suitable for a wide range of applications. Therefore, in the manufacturing process, *Sida cordifolia* fibers are mixed with a reinforcing material, i.e., jute fibers, and the matrix used in the process is *PLA*, which is a thermoplastic polymer.

Arrangement of polymer composite layers

The hybrid composite of jute and *PLA* with an increased proportion of treated *Sida cordifolia* fibers is shown in Figure 3. All composite materials were preheated at 80 °C for about 4 hours before being placed in the mold. All materials preheated to 80 °C for about 4 hours were layered in the above order in the preheated mold at 170 °C. The mold was sealed at the top and bottom with *Teflon* sheets to prevent the composite from sticking to the mold when a load was applied.

After packing the mold, the load specified in Table 4 was applied to it.

After 15 minutes of successful application of the load to the mould, the heating was stopped. The mold was cooled under a pressure of 150 kN for 120 minutes. As a result of the experiments, 4 different composite specimens were obtained:

Specimen 1: Jute + *PLA*;

Specimen 2: Jute + Untreated *Sida cordifolia* fibers + *PLA*;

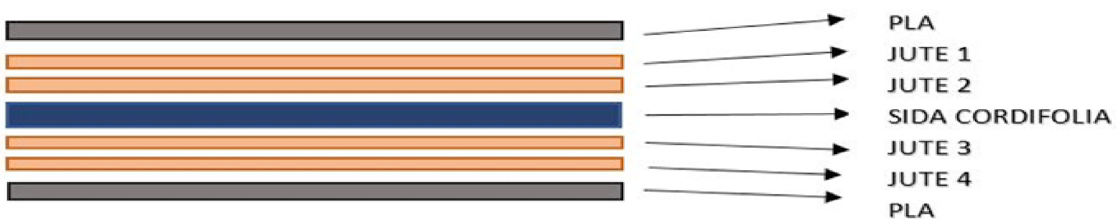


Fig. 3. Arrangement of Fiber layers

Table 4

Load Applying on Mould

S.No.	Load (KN)	Time (min)	Temp (°C)
1	50	01	170
2	100	02	170
3	150	12	170

Specimen 3: Jute + Treated *Sida cordifolia* fibers + *PLA*;
Specimen 4: Jute + Treated *Sida cordifolia* fibers + *PLA*.
Table 5 shows the weight composition of the composite layers.

Table 5

Weight Composition of the Composite layers

Layers Weight (grams)	Specimen-1	Specimen-2	Specimen-3	Specimen-4
Layer – 1	80	80	80	80
Layer – 2	23.5	23.125	23.125	22.375
Layer – 3	23.5	23.125	23.125	22.375
Layer – 4	0	12	12	15
Layer – 5	23.5	23.125	23.125	22.375
Layer – 6	23.5	23.125	23.125	22.375
Layer – 7	80	80	80	80
Total Weight	254	264.5	264.5	264.5

Results and Discussion

Tensile test

Tensile testing was performed on 4 specimens and 3 samples of each specimen. The following tables describe at what peak load in *kg* the fracture occurred and the tensile strength in *MPa* calculated accordingly. Table 6 shows the average tensile strength of the composite specimens made of *Sida cordifolia* reinforced with jute fiber. The biodegradable polymer polylactic acid (*PLA*) was used as the matrix.

Flexural test

The three-point bending test was performed with 4 specimens and 3 samples of each specimen. Table 6 describes the bending point at which the peak point load occurred in *kg* and the bending strength in *MPa* calculated accordingly. The ultimate bending strength was calculated using the formula below.

Table 6

Mechanical Strengths of tensile and flexural

Specimen no	Tensile strength (MPa)	Flexural strength (MPa)
1	27.029	3.326
2	25.084	3.290
3	32.297	4.226
4	43.658	6.650

$$\sigma_u = \frac{3FL}{2wd^2}, \quad (2)$$

where *F* is the maximum force applied; *L* is the length of the sample; *w* is the width of the sample; *d* is the depth of the sample.

Table 6 shows the average flexural strength of four composite specimens made *Sida cordifolia* reinforced with jute fiber with biodegradable *PLA* polymer as the matrix.

To optimize the performance of a hybrid composite made from jute, *PLA* and *Sida cordifolia* fibers, several parameters need to be carefully considered.

– Uniform temperature distribution within composite materials to reduce internal stresses and prevent thermal cracking during moulding. Analysis of the effects of different preheating temperatures and durations on *PLA* viscosity and natural fiber integrity can provide insight into the optimal processing conditions that minimize fiber damage and improve the mechanical properties of the composite. To ensure good wetting and bonding, complete melting of PLA and proper flow around jute and *Sida cordifolia* fibers should be achieved. It is very important to adjust the mold temperature to ensure uniform flow of PLA without destroying the natural fibers. A balance should be found where the temperature is high enough to ensure *PLA* flow, but low enough to prevent thermal degradation of jute and *Sida cordifolia* fibers.

– Proper compression of composites to reduce voids and improve fiber-matrix adhesion. The applied load (as listed in Table 4) should be optimized depending on the composite thickness and fiber arrangement. Increasing the load can help achieve better compaction and homogeneity. The time under load, especially at high temperatures, should be minimized to prevent thermal degradation. This will allow the *PLA* matrix to solidify under pressure, ensuring good mechanical bonding and adhesion between the matrix and fibers. Cooling rate and curing pressure are critical; too rapid cooling can cause residual stresses, while insufficient pressure can lead to delamination or void formation. Optimizing these parameters can improve the dimensional stability and mechanical properties of the composite.

– Uniform distribution of fibers within the matrix and between the layers of the composite to ensure isotropic properties. It is important to control the weight and distribution of each layer (as shown in Table 5) to optimize the mechanical properties. The increase in the amount of treated *Sida cordifolia* fibers in subsequent specimens suggests that a strategy was developed to improve certain mechanical properties such as tensile strength and flexural strength. Adhesion between the fibers and the *PLA* matrix is improved for effective stress transfer.

For a visual presentation of the results obtained, the data from the table are graphically presented in Figures 4 and 5. Figure 4 shows the peak loads obtained for different samples of 4 specimens:

– the first specimen with four layers of jute (94 g) and *PLA* matrix (160 g) used to make the composite achieved a tensile strength of 27.029 MPa;

– the second specimen with four layers of jute (92.5 g), untreated *Sida cordifolia* fibers (12 g) and *PLA* matrix (160 g) achieved a tensile strength of 25.0844 MPa;

– the third specimen with four layers of jute (92.5 g), treated *Sida cordifolia* fibers (12 g) and *PLA* matrix (160 g) achieved a tensile strength of 32.297 MPa;

– the fourth specimen with four layers of jute (89.5 g) treated *Sida cordifolia* fibres (15 g) and *PLA* matrix (160 g) achieved a tensile strength of 43.658 MPa.

According to the obtained results, the weight of *Sida cordifolia* fibers increased with a decrease in the weight of jute fiber; keeping weight fraction constant the tensile strength of the composite increased to an optimal value. The use of untreated *Sida cordifolia* fibers shows low tensile strength compared to treated *Sida cordifolia* stem fibers.

Figure 5 shows the peak loads obtained for different samples from 4 specimens:

– the first specimen with four layers of jute (94 g) and *PLA* matrix (160 g) used to make the composite achieved a flexural strength of 3.326 MPa;

– the second specimen with four layers of jute (92.5 g), untreated *Sida cordifolia* fibers (12 g) and *PLA* matrix (160 g) achieved a flexural strength of 3.290 MPa;

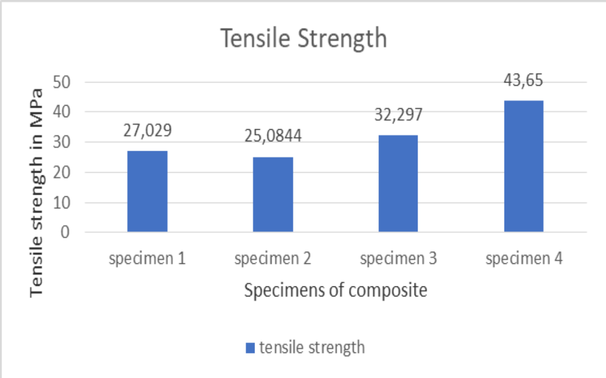


Fig. 4. Tensile strength Graph

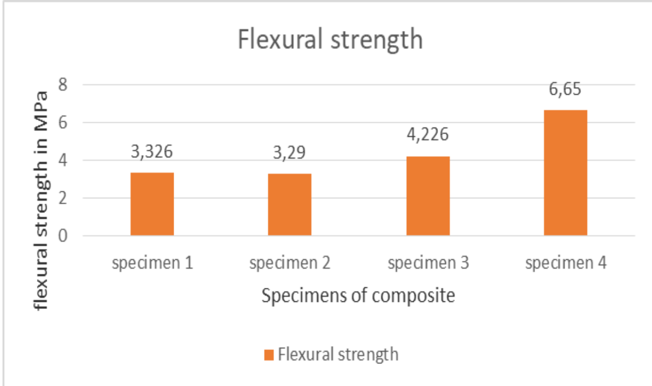


Fig. 5. Flexural strength Graph

– the third specimen with four layers of jute (92.5 g), treated *Sida cordifolia* fibers (12 g) and *PLA* matrix (160 g) achieved a flexural strength of 4.226 MPa;

– the fourth specimen with four layers of jute (89.5 g) treated *Sida cordifolia* fibres (15 g) and *PLA* matrix (160 g) achieved a flexural strength of 6.650 MPa.

According to the obtained results, the weight of cordifolia fibers increased with a decrease in the weight of jute fiber, and keeping weight fraction constant the flexural strength of the composite increased to the optimal value.

Scanning electron microscopy

The mention of hemicellulose on the surface of untreated *Sida cordifolia* fibers does not mean that it has been intentionally fixed or coated onto the fibers. Rather, hemicellulose is a natural component of plant fibers, including *Sida cordifolia* fibers. In this context, the statement means that the hemicellulose layer remains intact and present on the fibers because these fibers have not been treated. When plant fibers are harvested and treated, these fibers naturally contain several biochemical components, including cellulose, hemicellulose, and lignin. These components contribute to the physical and chemical properties of the fibers.

Generally, when natural fibers are treated for use in composites, the natural fibers retain its original biochemical composition, including hemicellulose. Hemicellulose in this state can affect the interaction of the fibers with the matrix material (e.g. *PLA*) because it can be hydrophilic (water-attracting), which can interfere with adhesion to hydrophobic (water-repelling) matrix materials. Treatment processes such as alkali treatment, bleaching or benzoylation are often used to remove or modify hemicellulose and other components. Such treatments improve the compatibility of the fibers with synthetic polymers by changing its surface chemistry and reducing its moisture absorption capabilities.

For a more detailed visual representation, microscopic imaging techniques such as scanning electron microscopy (*SEM*) are commonly used to illustrate the presence of hemicellulose or the effects of treatment on the fiber surface. These images show the surface morphology of the fibers, highlighting the differences between treated and untreated fibers.

Therefore, the surface morphology of the developed composite was analyzed by *SEM*. The surface treatment of the fibers (as shown in Figures 6–9) can be further optimized. Treatment methods such as alkali, silane, acetic acid treatment can be systematically varied and tested to find the best conditions to improve wettability and chemical bonding at the interface.

The properties of the composite are improved by post-treatment methods such as annealing or conditioning. Post-treatment conditions such as environment (humidity and temperature), time and methods can be tailored to reduce residual stresses and improve the composite's resistance to environmental influences. Through carefully managing and controlling these parameters, the performance of the hybrid composite can be maximized, resulting in a material that is not only stronger and more durable, but also more suitable for specific applications where the combination of natural and synthetic components is beneficial.

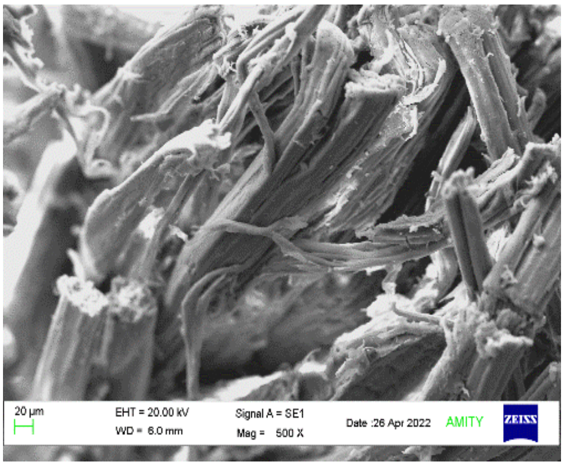


Fig. 6. Untreated fibers (500×)

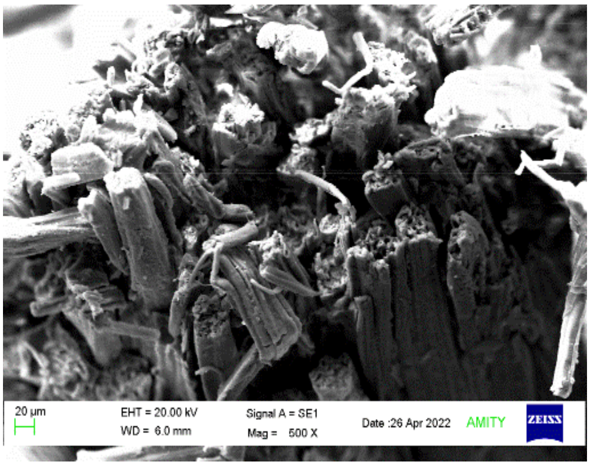


Fig. 7. Treated fibers

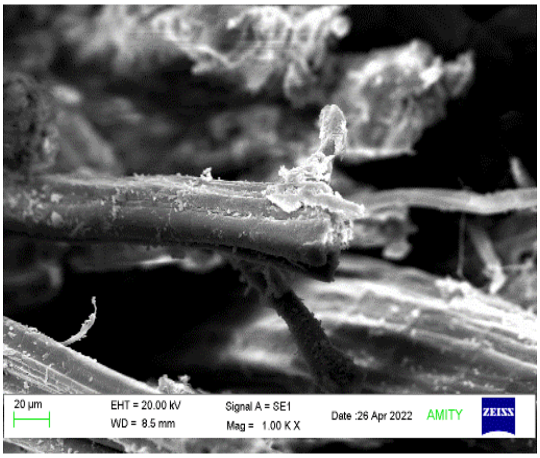


Fig. 8. Untreated fibers (1,000×)

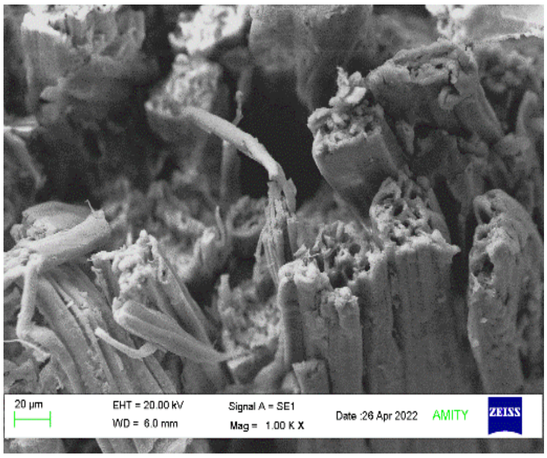


Fig. 9. Treated fibers

Fractured tensile specimens were selected to study the failure mechanisms and interactions between the matrix and fibers in the composites. *SEM* analysis was performed at ×500 and ×1,000 magnification, with four specimens being examined in detail at these two magnification levels.

Figures 6–9 show a comparison of the SEM images of the tensile-tested composites with and without *Sida cordifolia* fibers, both untreated and treated. At ×1,000 magnification, it was observed that the hemicellulose layer was preserved on the surface of the untreated *Sida cordifolia* fibers, which was absent on the fibers subjected to benzoylation treatment. The removal of the hemicellulose layer increases the wettability of the fibers, contributing to the increase in the tensile strength of the benzoylation-treated composites. Notably, the fiber elongation was more pronounced in specimens 3 and 4 containing *Sida cordifolia* fibers treated with benzoylation compared to the untreated variants. This observation highlights the increased tensile strength of the composites with the treated fibers, which is attributed to the stronger fiber-matrix bonding. The increased fiber elongation reflects its increased load-bearing capacity due to its higher wettability after treatment.

Conclusion

A study involving the use of four different compositions of a 7-layer polymer composite demonstrated significant improvements in mechanical properties while maintaining a constant amount of fiber material. Tensile, flexural tests and scanning electron microscopy (*SEM*) investigation showed optimum values reflecting the effectiveness of the developed composite.

Deliberate increase in the weight of *Sida cordifolia* fibres combined with decrease in the amount of jute fibres while keeping the total weight of both fibres constant in all specimens containing benzoylated *Sida cordifolia* fibres in *PLA* matrix resulted in significant increase in composite strength. This suggests that inclusion of higher proportion of *Sida cordifolia* fibres contributes significantly to the mechanical robustness of the composite.

SEM analysis of fractured tensile specimens at ×500 magnification provided valuable insight into the fibre bonding characteristics of the fibers. The lignin content observed in untreated fibres correlates with weaker bonding to the matrix. Conversely, chemically treated *Sida cordifolia* fibres are characterised by the absence of lignin in the composite, resulting in superior bonding to the matrix and, consequently, increased strength. The increased fibre elongation in chemically treated *Sida cordifolia* fibres further highlights its improved load-bearing properties, which are attributed to its high wettability.

Based on the successful results of mechanical tests, it is recommended to explore the possibility of hybridizing *Sida cordifolia* fibers with other natural fibers to achieve even more favorable results. The versatility of *Sida cordifolia* fibers makes it suitable for use in combination with various natural fibers, which allows the creation of special composite materials with excellent mechanical properties.

The experimental results of tensile and flexural tests conducted on hybrid composites made from jute, polylactic acid (*PLA*) and *Sida cordifolia* fibres demonstrate important results regarding the mechanical properties of these materials. The main findings of the study can be summarized as follows:

Increase in mechanical strengths with treated fibers. There is a clear trend indicating that the mechanical properties of the composites improve with the addition and increase in weight of the treated *Sida cordifolia* fibers. Specimen 4, which contains the highest amount of treated *Sida cordifolia* fibers (15 g), exhibits the highest tensile strength of 43.658 MPa and flexural strength of 6.650 MPa. This suggests that the treatment process improves the adhesion of the fiber to the matrix, thereby improving the load transfer between the fibers and the *PLA* matrix.

Effect of fiber treatment on composite properties. The treatment of the *Sida cordifolia* fibers plays a crucial role in the performance of the composites. The untreated fibers in Specimen 2 resulted in a slight decrease in tensile and flexural strength compared to the composites with treated fibers. This indicates that the treatment process can modify the surface properties of the fibers, improving compatibility and bonding to the *PLA* matrix.

Overall, the study shows that hybrid composites reinforced with treated *Sida cordifolia* and jute fibers in a *PLA* matrix exhibit promising mechanical properties. Treatment of natural fibers and its optimized incorporation into composites can play a key role in the development of sustainable and high-performance materials for various engineering applications. Further studies on durability, environmental impact and economic feasibility are needed to fully realize the potential of such composite materials in industrial applications.

Future Scope and Potential Developments

A study of hybrid composites consisting of *Sida cordifolia* fibres, *jute* and *PLA* matrix, with particular emphasis on different fibre treating options, has demonstrated promising results in enhancing tensile and flexural strength. However, further research and development is suggested in several key areas to expand the application and improve the performance of these composites:

– Advanced chemical or physical treatment processes for *Sida cordifolia* fibers can further improve its compatibility with the *PLA* matrix, improving mechanical bonding and overall composite performance.

– Modifying the *PLA* matrix by mixing with other biopolymers or adding plasticizers can improve its ductility and processing characteristics, which will allow it to better combine with natural fibers.

– Exploring alternative composite manufacturing methods, such as polymer transfer molding or vacuum forming, may provide more uniform material properties and reduce void content. Using variable pressure and temperature curing cycles can help optimize mechanical properties and minimize internal stresses in the composite. Different stacking sequences and orientations of the fiber layers can be analysed to tailor mechanical properties to specific application conditions.

– Evaluation of the application of these composites in structures such as automotive components, furniture or even in construction as an eco-friendly alternative to traditional materials. Comprehensive studies on the end-of-life options for these composites, including recycling methods and biodegradability assessment, can improve its eco-friendliness. By addressing these challenges, the research and development of hybrid composites using jute, *PLA* and *Sida cordifolia* can be greatly expanded, leading to innovative applications that utilize its biodegradability and mechanical properties for sustainable development.

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Conflicts of Interest

The authors declare no conflict of interest.