



Natural Fibers as Reinforcements in Polymer Composites: A Review on Mechanical and Environmental Applications

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ABSTRACT

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Natural fibers, such as leaves, sugarcane, hemp, oil palm, kenaf, pineapple, jute, and flax, among others, are of great interest in the modern world due to their noble mechanical and environmental qualities, affordability, biodegradability, lightweight nature, and superior life cycle. Natural fiber composites have improved impact and flexural attributes, but they might not always be as strong as synthetic fibers in terms of tensile strength. Numerous engineering applications extensively utilize Natural Fiber Reinforced Polymer Composites (NFRPCs), and this field is continually evolving. Both the mechanical and environmental application features of reinforced Polymer of natural fiber-bonded composites are examined in this review paper. Additionally, the techniques used to process reinforced composite materials and the most common uses of natural fibers that make them desirable for use in these applications are compared. It is addressed how natural fiber-based reinforcement polymers are employed in various engineering domains, including the biomedical industry, automotive, aerospace, sports, electrical, chemical, construction, music, and packaging.

1. INTRODUCTION

This review examines the flexural, tensile, and impact properties of polymer composites reinforced with cotton fiber (CF). It also evaluates the role of compatibilizers at two different stages of adhesion. The construction, automotive, and textile industries have increasingly used CF-reinforced composites to achieve desirable mechanical and functional properties. Furthermore, the section highlights the industrial application of CF-based polymers. Cotton fiber (CF) has proven to be an effective reinforcement in hybrid fiber-reinforced polymer composites (FRPCs), particularly when combined with both synthetic and natural fabrics. Hybridization provides high strength at a reasonable cost, making these composites attractive for industrial use. CF-reinforced hybrid composites are now widely applied across various sectors. Environmentally friendly alternatives can also be developed by combining CF with geopolymers, biodegradable polymers, thermoplastics, or thermosetting polymers. Owing to their biodegradability and strong mechanical performance, CF-based hybrid composites are increasingly employed in biomedical, automotive, and textile applications [1]. The fatigue performance of plant-based Natural Fiber Reinforced Polymer Composites (NFPCs) has been evaluated according to ASTM A466 and ISO1099 standards, which define load-controlled tests based on stress ratios and the number of cycles to moisture absorption, reducing fatigue resistance. However, fatigue properties can be improved through chemical modifications

such as are negatively impacted by inadequate fiber-matrix maleic anhydride, silane, and alkaline treatments, as well as by optimizing fiber orientation, hybridization, and stacking configurations. Research indicates that NFPCs have the potential to replace traditional and synthetic composites by providing lightweight materials suitable for load-bearing and structural applications [2]. Industrial application Polyester resin composites reinforced with natural fibers (sisal, hemp, and a mixture) have been developed and tested against standard plastics. Results showed that increasing the fiber weight fraction improved the mechanical performance of these composites. In addition, the flexural and compressive behavior of hemp fiber-reinforced concretes (FRC). Has been evaluating using an orthogonal test strategy. Among the examined parameters, fiber content was found to have the most significant effect. The EMP FRC casting process has been refined. Leading under optimal conditions to a 4% increase in compressive strength, 9% in flexural strength, 144% in flexural toughness, and 21% in the flexural toughness index [3].

Other studies have examined the impact, density, flexural, and thermal properties of polyester hybrid composites reinforced with jute and glass fibers. These properties were analyzed and compared under controlled sintering conditions, with temperatures maintained between 150–200°C using a calibrated digital temperature controller. The results indicated that jute fiber composites exhibited superior performance compared to those reinforced with glass fibers [4].

In a separate study, authors investigated methods for

detecting geomechanical data outliers. Their approach considered four factors: distribution, sensitivity to extreme values, magnitude, and data skewness. The authors found that conventional statistical tests were less effective in identifying outliers, especially with skewed data and small sample sizes. Instead, the boxplot rule and the quasi-interquartile range rule were shown to be the most accurate techniques [5]. Madhu Puttegowda's comprehensive overview of eco-friendly composites reinforced with natural fibers highlights the extraction methods, processing techniques, life cycle assessments, and the increasing importance in industrial applications. This work underscores the rapid transition towards green and sustainable materials in the field of composites [6]. It also has certain drawbacks, such as excessive moisture absorption. Therefore, to control significant moisture absorption, chemical treatments are required. Numerous parameters, including fiber length, fiber aspect ratio, and fiber-matrix adhesion, among others, have a substantial influence on the mechanical properties of natural fibers following chemical processing. Due to their advantages—such as low density, affordability, renewability, recyclability, and CO₂ neutrality—Thermosets, thermoplastics, and natural fiber composites have garnered increased interest. One of the eco-friendly materials is natural fibers. According to estimations conducted between 2011 and 2016, the global natural fiber polymer market was predicted to expand by 10% tough and lightweight natural fibers can be added to polymers (thermoplastics and thermosets) to create composites reinforced with natural fibers that possess a high specific strength and rigidity. Sustainability of the environment and the expanding worldwide garbage problem are increasing annually due to rising environmental awareness [7].

Due to the unsustainable use of petroleum, new environmental restrictions, and growing public awareness of ecological issues, consideration is being devoted to the utilisation of environmentally friendly products. Despite some similarities in general methodology with Chen our work differs in several innovative aspects. It focuses on integrating the mechanical and environmental applications of natural fibers in composites. Introducing additional types of natural fibers, such as bagasse, silk, that were not included in Chen's study. A comprehensive comparison of natural and synthetic fibers in terms of performance and sustainability, which Chen did not include. Recent data 2023, 2024, not included by Chen. A comparison table will be added to show the differences between our methodology and Chen. Natural fiber is regarded as one of the eco-friendly materials when compared to synthetic fiber. Because of their superior qualities and natural fibers—like bananas, bamboo, sugarcane, flax, kenaf, sisal, jute, hemp, and coir—have benefits over synthetic fibers, that involve comparatively light weight, inexpensive, less likely to harm processing machinery, favorable mechanical qualities such as Flexural and tensile moduli, increased composite-molded surface quality components, renewable resources, a lot, processing flexibility, and biodegradability, and many others are becoming more and more common in a variety of applications [8]. This research examines natural fiber and reinforced composites based on natural fiber. The research highlights the type of natural fiber, its mechanical and physical characteristics, and its applications in various contexts, including its benefits and drawbacks, as well as some fundamental issues that need to be addressed to overcome the disadvantages of composites made from natural fiber polymers. All experiments were performed and data reported

using n=3 independent replicates to ensure reproducibility.

2. NATURAL FIBER

Because they are inexpensive, low-density, and low-processing-cost, as well as their mechanical and physical qualities, natural fibers—which are renewable resources—offer a more sustainable supply option. The primary attributes of biodegradability and non-carcinogenicity that natural fibers possess are what make them popular again, along with their affordability. The primary elements affecting the characteristics of natural fibers are the type of plant and the conditions for growing it, the plant and the condition for growing it, the plants age, and the method of obtaining [9]. The amount of lignin, cellulose, and hemicellulose—the three main constituents of natural fibers—varies depending on the kind. Strong hydrogen bonds, most likely, bind hemicellulose to cellulose fibrils. The molecular weight of hemicellulose polymers is substantially lower than that of cellulose, and they are branched and completely amorphous. Hemicellulose is partially Water-soluble and hygroscopic due to its open structure, which is full of acetyl and hydroxyl groups. Of the components of natural fiber, lignin showed the least amount of water absorption despite being an extremely complicated, amorphous, and mostly units of phenyl propane in aromatic polymer. Helically organized cellulose microfibrils combine with the aid of an amorphous matrix of lignin to produce a composite fiber. The plant fiber's ability to retain water, defend against the pulls of gravity and wind is all made possible by lignin. Plant fibers contain hemicellulose; It is believed to serve as a lignin and cellulose compatibilizer [10].

3. NATURAL FIBER ARCHITECTURE AND CLASSIFICATION

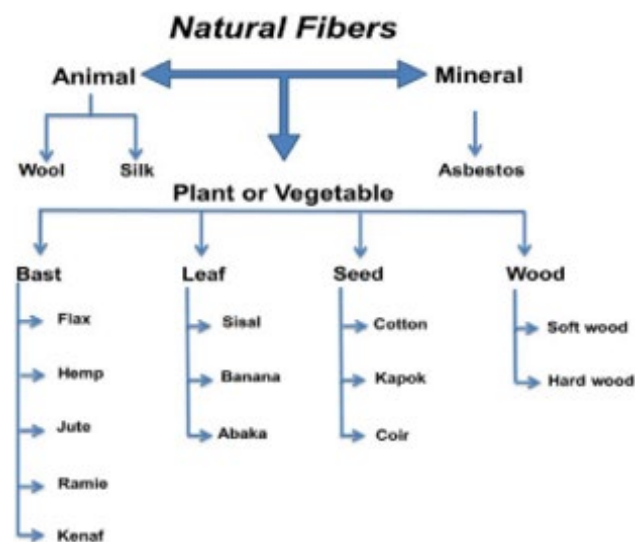


Figure 1. Classification of natural fibers [12]

Fiber architecture refers to the configuration of fibers within a composite, which affects both the composite's processing and its properties. Aspects of the architecture of fibers that might affect the mechanical qualities include fiber continuity, fiber interlocking, fiber crimping, and fiber orienting. The finished composite's characteristics, including the vacant contents, Wetting and dispersion of fibers, dry area, and

additional properties, are determined by matrix movement through the fiber structure during processing, which also influences the composite's performance and attributes [11]. Any hair-like substance that is directly derived from plants and animals, or sources of minerals, is considered a natural fiber. These supplies of raw materials are then transformed into textiles that are not woven, which can be changed into rope, thread, or filaments and ultimately utilized as portions of composite materials. Paper may also be made from them. Thousands of natural fibers have piqued the interest of many scholars. They use natural fibers, explore new applications for them, and strive to enhance the properties of natural fiber composites. Categorization and structure are shown in Figure 1 and Figure 2 [12, 13].

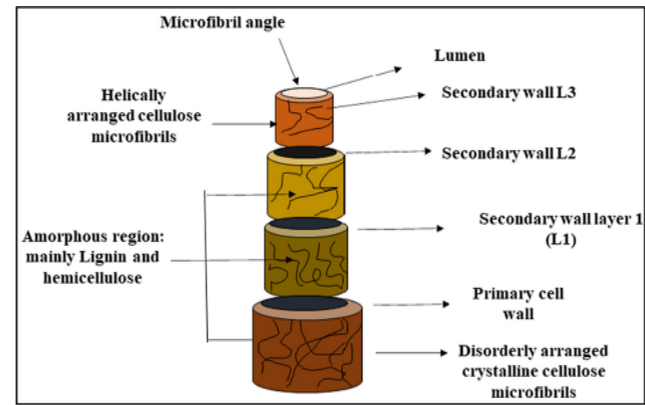


Figure 2. Cell wall structures of natural fibers [13]

4. APPLICATIONS FOR VARIOUS KINDS OF NATURAL FIBERS

Composite materials composed of natural fibers mixed with resins are the focus of numerous researchers. Numerous technical applications already utilize natural fiber composites. Multiple engineering applications use natural fibers. We outline a selection of natural fibers below.

4.1 Hemp fibers

For various technical applications, hemp fibers have been investigated as a significant natural fiber. Usually, the hemp plant's stem is used to remove the fibers. Figure 3 illustrates the texture of a typical hemp plant's leaf. It has been discovered that surface-functionalized hemp fibers improve the formation of the matrix-nanofiller interface and hydrophilicity. Physical, chemical, biological, and other techniques have been employed to modify the surface of hemp fibers. In this context, it has been preferred to utilize environmentally acceptable, non-hazardous approaches. The modified hemp fibers have significantly enhanced the strength and other characteristics of the polymer matrices. Hemp fibers and related materials have been utilized in various uses, including water purification, automotive parts, textiles, radiation shielding, and more [14, 15]. The tensile strength of hemp fiber is exceptionally high, ranging from 550 to 1150 MPa. Hemp fiber's mechanical qualities are found to be similar to those of other fibers. These characteristics of hemp and ramie fibers point to the development of non-asbestos braking composites [16]. Tables 1 and 2, the chemical composition, mechanical characteristics, and physical attributes of raw

hemp fibers, and the p-values in Table 2, are directly indicated as a summary of data from previous studies, because the work is a review article, and there are no actual experiments to analyze the raw data. Data processing includes outlier detection Grubbs test at $\alpha = 0.05$. Outliers identified were excluded, and boxplots were generated to confirm the distribution of the remaining data [17-19].



Figure 3. A standard illustration [19]

Table 1. Chemical components found in hemp fibers [17]

Elements	The Range
Weight percentage of cellulose	55–90
The weight percentage of hemicellulose	15–22.4
Lignin (weight percentage)	4–13
Pectin (weight percentage)	0.8–1.6
Waxes (weight percentage)	0.8
Moisture (weight percentage)	9–12
Biomass (Mg DM/ha/y)	7–34.0
Ash percentage	0.8

Table 2. Raw hemp fibers mechanical and physical properties [16, 18, 19]

Property	Value
Density ($\text{g}\cdot\text{cm}^{-3}$)	68–81
Particular apparent density	1500
Tensile characteristic (MPa)	310–1235
MPa, specific tensile strength	210–510
GPa, elastic modulus	20–70
Specific Young's modulus (GPa)	20–41
Strain of failure (%)	0.9–4.2
Particular modulus ($\text{GPa}\cdot\text{cm}^3\cdot\text{g}^{-1}$)	0.8
The diameter [μm]	17–24
Length (mm)	8.3–14
The aspect ratio (l/d)	549
angle of the microfibril (Θ)	6.2

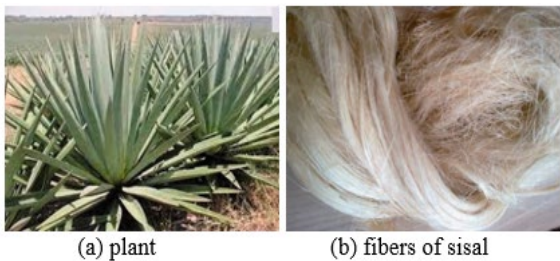


Figure 4. Displays the (a) plant and (b) fibers of sisal

4.2 Sisal fibers

Since sisal fiber has the lowest bulk density and thermal conductivity, it is the most intriguing product. The heat conductivity of the composite specimens was decreased,

resulting in a lightweight product when plant fiber was added to the sisal plant. An intriguing substitute that addresses environmental and energy concerns is the creation of composite materials for buildings utilizing natural fibers like Sisal, which has low thermal conductivity. Sisal is a cheap, renewable, biodegradable, and plentiful fiber that may be used to make a wide range of goods. Additionally, Sisal has been tested in various composite materials as reinforcement or filler [17]. Sisal grows quickly and is easy to cultivate. The fiber is resistant to abrasion, Alkali, acid, and salt water, and it exhibits high tensile strength and tenacity. Table 3 displays

several characteristics of sisal fibers, as depicted in Figure 3 and Figure 4, along with the plant and its fibers. The results in Figure 4 indicate a significant improvement compared to the reference group, although the difference did not reach statistical significance ($p = 0.062$). Note also that Table 3 includes direct numerical comparisons of tensile strength (MPa) and modulus (GPa) for natural and synthetic fiber composites, illustrating the relative performance differences. Today, Sisal is grown worldwide in a sustainable manner. The largest are Brazil and Tanzania, which are closely followed [18].

Table 3. Selected characteristics of sisal fibers [18]

Fibers	Density (g/cm ³)	Diameter (μm)	Length (mm)	Strength in Tensile (MPa)	Young's Modulus (GPa)	Stretching at the Break (%)
Sisal	1.2	7-47 (27)	0.8-8 (4.4)	507-855 (681)	9-22 (15.5)	1.9-3 (2.45)

4.3 Jute fibers

Jute fiber is yellowish-brown in color, glossy, and reasonably robust. It has little elasticity and dissolves easily in water. But this inflexibility turns into virtue. Moisture absorption is a major drawback of jute fiber value up to 13.75% indicating higher hydrophobicity than other natural fibers. The fiber's staple length ranges from 60 to 120 inches. Hessian bagging, rug bac, king, carpets, wall coverings, hammocks, beltings, matting, canvas, thread, and webbing are all made of jute. Table 4 lists some of the fibers' characteristics [19]. The various jute fiber shapes shown in Figure 5 will affect the composite material's characteristics. After reviewing the caption for Figure 5 to determine the statistical representation of the error bars, we note that the error bars represent the mean $\pm$ SD (standard deviation) or SEM/CI (depending on the data). Additionally, therefore, it presents summary values rather than original experimental results, and

the SD/SEM values are not applicable [20].

4.4 Bamboo fibers

One of the first building materials ever employed by humans is bamboo. The bamboo stem, also known as the culm, has been utilized to produce a diverse assortment of goods for both industrial and domestic purposes. Bamboo is widely used in Asia for homes, scaffolding, and bridges [21]. One such inexpensive and mechanically robust natural fiber is bamboo. Bamboo, a long, nonwoven forest product, has replaced Wood and metal. Bamboo is particularly suitable for various uses, including structural boards that can support loads in a single direction. Bamboo is a highly versatile and amiable material that has garnered widespread praise in multiple fields; Figure 6 illustrates the processing of natural bamboo fiber [22]. The average features of wild bamboo are displayed in Table 5 [23].

Table 4. Characteristics of jute fibers [20]

Fibers	Density (g/cm ³)	Viscosity Cp	Monomer Ratio	Sour Type	Glycol Type
Jute	1.15 – 1.2	350-500	31 – 36	orthophthalic	glycol standard

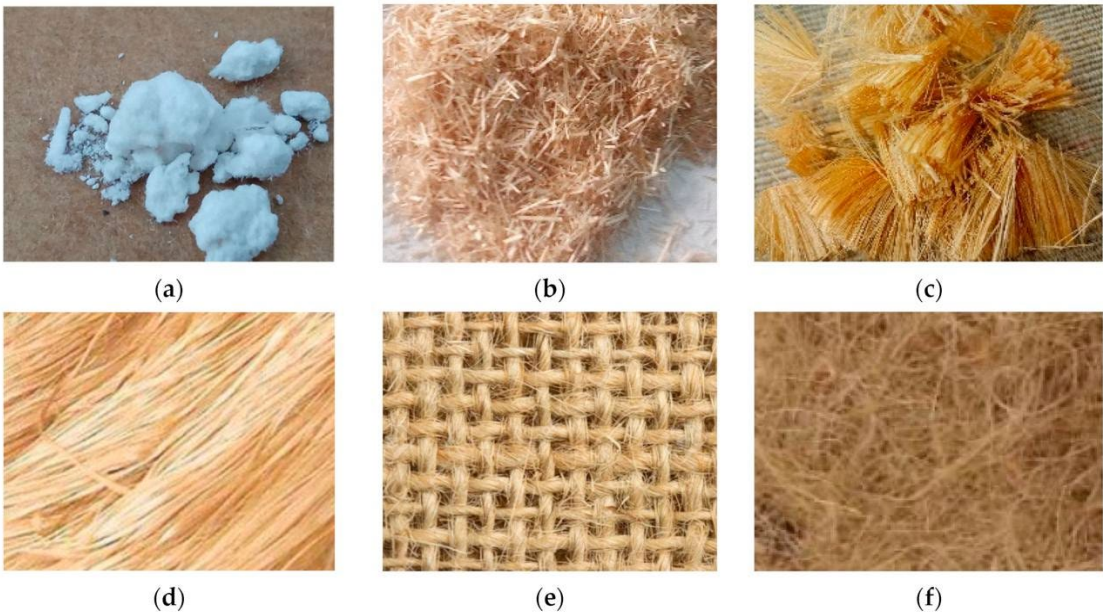


Figure 5. Jute fiber comes in several forms, including particles, short, semi-long, long, fabrics, and nonwoven [20]



Figure 6. Genuinely processing bamboo fibers in a natural way [22]

Table 5. Normal characteristics of natural bamboo [23]

Fibers	Density (g/cm ³)	Tensile strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Flexural Strength (MPa)
Bamboo	0.66	206.2	20.1	78.7	210.3

4.5 Cotton fibers

The finest form of cellulose, the most prevalent polymer in nature, is found in cotton fibers. Cellulose makes up around 90% of the cotton fibers. Cotton fibers contain cellulose, which has the most significant structural and molecular weight of any plant fiber. A-cellulose makes up the majority of cotton fibers (88.0–96.5%). Cotton is a natural fiber that is long-lasting. Among its many benefits are its exceptional strength and durability, absorbency, and ease of combining with other fibers. Given all of its characteristics, Cotton fibers (CF) have the potential to be combined with other natural or synthetic fibers to form a unique, environmentally beneficial composite [24]. There are between 150 and 400 convolutions per inch in a single cotton fiber. Table 6 lists several characteristics of cotton fibers. Convolutions play a crucial role in the cohesiveness of yarns, which is essential for strength. Figure 7 shows cotton fiber in both longitudinal and cross-sectional views [25].

Table 6 Properties of cotton fibers [25]

Fibers	Density (g/cm ³)	Length (%)	Strength in Tensile (MPa)	Young Modulus (Gpa)
Cotton	1.54	7.0-8.0	287-597	5.5-12.6

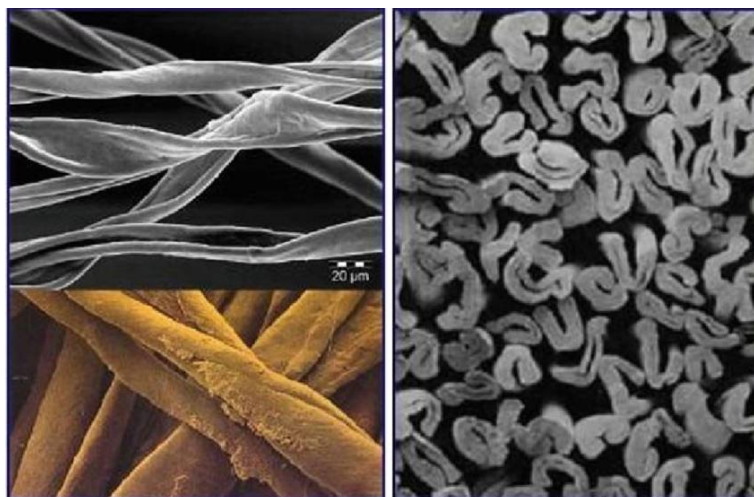


Figure 7. A longitudinal and cross-sectional image of cotton fiber [25]

Table 7. Wool fibers' mechanical characteristics [26]

The Fibers	Density (g/cm ³)	Elongation (%)	Strength in Tensile (MPa)	The Young Modulus (GPa)
Wool	1.32	0.9–1.1	180–240	2.7–17

WOOL FIBRE STRUCTURE AND PROPERTIES

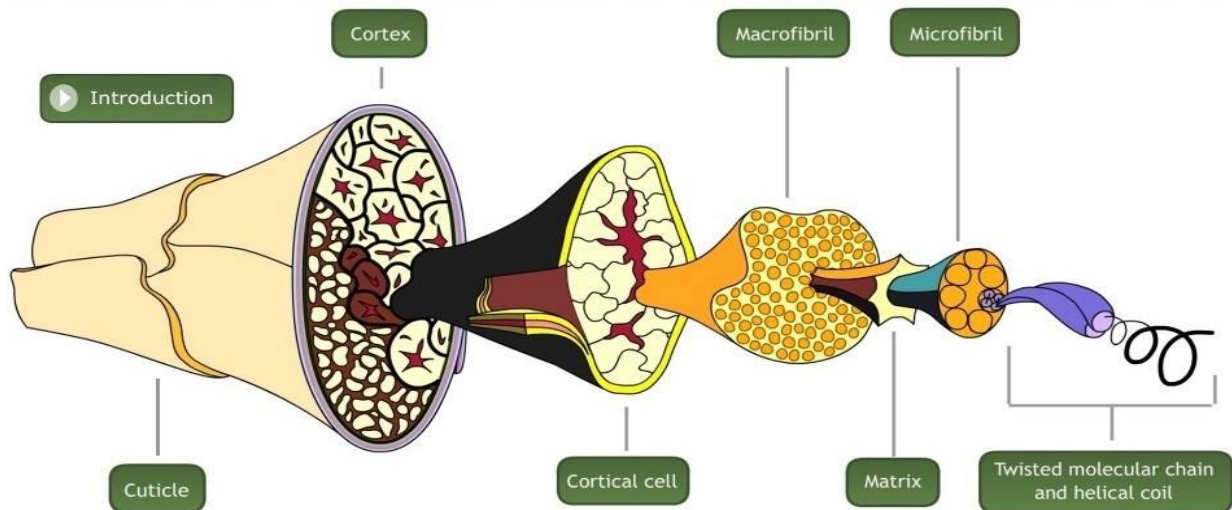


Figure 8. Structure of wool [27]

4.7 Abaca fibers

The abaca is found on the plant's robust, seawater-resistant stalk. Collected. Low density, suitable stiffness, and mechanical properties, in addition to strong biodegradability, recyclability, and renewability, are just a few of the many benefits of abaca fiber. Abaca fiber, one of the most robust cellulose fibers, is used in marine applications and can withstand exposure to saltwater. It is frequently used for producing tea bags, meat casings, and fishing nets.

Additionally, it serves as an untreated substance for the production of premium paper, hospital linens, electrical conductors, and machinery filters. Figure 9(a) and (b), respectively, show abaca bananas and abaca fibers [12, 28].



Figure 9. Displays the fibers and the plant [12]

4.8 Flax fibers

Together with its outstanding mechanical characteristics, flax's ecological benefits stem from its recyclability, biodegradability, renewability, and low specific gravity. Many businesses employ flax fibers for structural purposes. Flax fibers are utilised as the foundation for parts like door liners, boots, and parcel shelves (found in Models of Mercedes and BMW) in the automobile industry, as seen in the door panels of the Opel Vectra [29]. Numerous writers have observed that flax fiber includes different proportions of cellulose, hemicellulose, wax, lignin, and pectin [28, 29]. Figure 10 depicts natural flax fibers, and Table 8 lists the flax fibers'

mechanical characteristics [30]. The plant variety and agricultural variables, like the amount of soil, weathering circumstances, maturity of the plant level, and the retting quality procedure, cause these variations in the proportions of constituents in flax fibers.



Figure 10. Flax fibers that are natural [30]

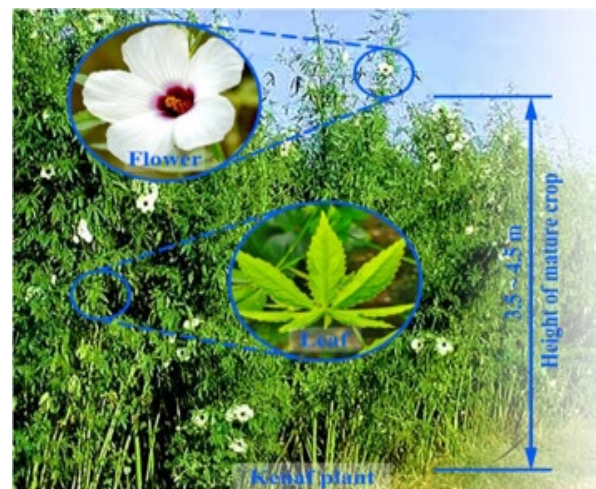


Figure 11. An established kenaf plant [34]

4.9 Kenaf fibers

The annual herbaceous plant known as kenaf (*Hibiscus cannabinus* L.) belongs to the group Malvaceae family. The plant has been widely dispersed and effectively grown in many Asian and American countries, particularly in certain regions such as China, Malaysia, Thailand, and India, which have abundant solar radiation and heavy rainfall. Figure 11 depicts

a fully grown kenaf plant. The kenaf fiber's higher cellulose content gives it better mechanical properties, making it preferred over other fibers utilized in composites, as well as for further industrial uses. Furthermore, when it comes to creating composites, kenaf fiber exhibits exceptional synergistic and hybrid properties with synthetic and other natural fibers [31, 32]. Table 9 lists the usual Kenaf fibers' mechanical and physical properties [33].

Table 8. The flax fibers' mechanical characteristics [30]

Fibers	Density (g/cm ³)	Specific Tensile Strength (MPa/ (g/cm ³))	MPa for Tensile Strength	Young Modulus (GPa)	Specified Young's Modulus (GPa/ (g/cm ³))
Flax	1.40–1.50	245–1334	343–2000	15–80	11–53

Table 9. The kenaf fibers mechanical characteristics [33]

Fibers	Density (g/cm ³)	Tensile Module (GPa)	Strength in Tensile (Mpa)	Elongation throughout a Break (%)	Diameter (μm)	Specific Strength (N·m/g)	Specific Stiffness (N·m/g)
Flax	1.2–1.5	11–60	223–1191	1.6–5.7	50–144.8	148.7–794	1066.7–2916.7

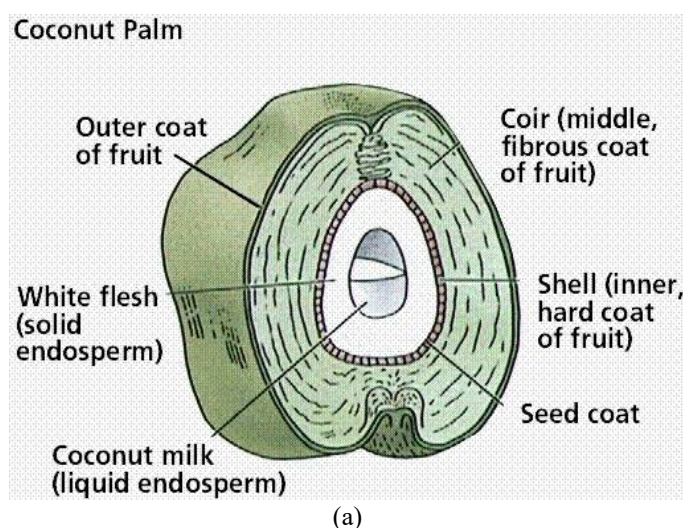


Figure 12. (a) The coconut's structure and (b) coconut fibers [34]

4.10 Coconut fibers

The coconut tree (*Cocos nucifera*) yields coconut fiber, also known as coir fiber, a firm and coarse fiber. To reinforce polymer composites, the husks and shells of trees are being processed into natural fibers. Coir fibers have several advantages, including low degradation, low thermal conductivity, good insulating properties, low cost, stiffness, high strength, corrosion resistance, light weight, durability, minimal environmental impact, and ease of manufacturing. Additionally, compared to other natural fibers, coir fibers absorb water less due to their lower cellulose content. Figure 12(a) shows the structure of the coconut, which contains the coir. Figure 12(b) shows the coconut fibers [34, 35].

4.11 Bagasse fibers

One is bagasse, a type of lignocellulose that is cheap, lightweight, renewable, and commonly obtainable. Figure 13 illustrates bagasse fibers. The durability over time among these natural Fabre-reinforced composites can be regarded as a breakthrough in the fields of polymers and biocomposites. Glass-reinforced composites may eventually be replaced with bagasse fibers as the main component. NFRP Composites'

excellent mechanical strength, wide availability, environmental friendliness, recyclable nature, and biodegradability make them a viable alternative to synthetic fiber-reinforced polymeric composites [36]. The chemical makeup of bagasse fibers is displayed in Table 10 [36]. The mechanical and physical characteristics of bagasse fiber are shown in Table 11 [37].



Figure 13. Bagasse fibers [36]

Table 10. Bagasse fibers of chemical components [37]

The Components	The Range
Cellulose (wt%)	32–45
Hemicellulose (wt%)	20–32
The lignin (wt%)	17–32
Pectin (wt%)	NA
Ash	1.0-9.0
The moisture (wt%)	NA

4.12 Silk fibers

Silk is a natural protein fiber with a moderate modulus and stiffness, as well as outstanding biodegradability and excellent biocompatibility. Silk fibers have exceptional mechanical toughness because they can both absorb and release energy during deformation [38, 39]. Many insects and spiders spin the fibrous proteins into yarn. Two filaments of structural fibroin covered in glue-like proteins called sericin make up the cocoon silk filament of *Bombyx mori*. High amounts of amino acids, including serine, glycine, and alanine, are found in fibroin. Natural polymers with reactive functional groups, such as silk

proteins, are biodegradable. Silk fiber is very extensible and strong. Because of these characteristics, composites reinforced with silk fibers take the place of those reinforced with synthetic fibers [40]. The term "queen of the fibers" is typically used to describe silk. It is a byproduct of the silk cocoon's life cycle. There are two primary types of silk: wild silk and cultured silk. Table 12 lists the economic, technical, and ecological characteristics of silk, while Figure 14 depicts silk fibers [41].

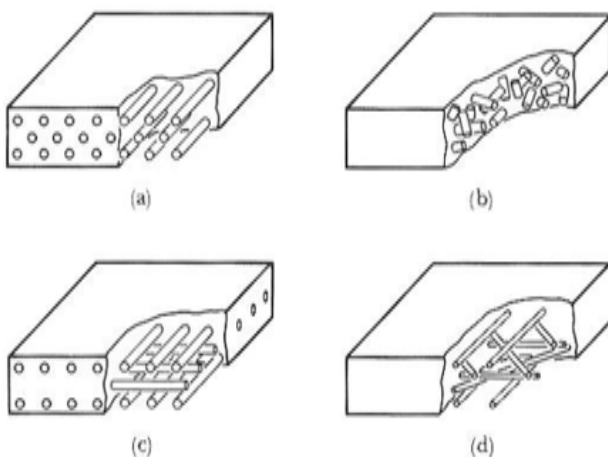
**Figure 14.** Silk fibers [42]**Table 11.** Bagasse fiber's mechanical and physicochemical characteristics [38]

Fibers	Density (g/cm ³)	Modulus of Young (GPa)	Strength in Tensile (MPa)	Elongation at Break (%)	Microfibrillar Angle (°)
Baggas	0.55–0.70	15–19	170-290	3-7	10-22

Table 12. Characteristics of silk fibers: technological, ecological, and economic aspects [41]

Properties	Silk Fibers
Density	1.25-1.35
Moisture absorption (%)	5-35
Tensile stiffness (GPa)	5-25
Strength in tensile (GPa)	0.2-1.8
Specific Strength in tensile (GPa/g cm ⁻³)	0.1-1.5
Toughness (MJ m ⁻³)	25-250
Fiber diameter (apparent) (Lm)	1-15
Chemical nature	Proteinaceous
Cost of commercial raw fiber (≤/kg)	2.0-30.0
The annual manufacturing of fibers worldwide (in tons)	150,000

5. EFFECT OF FIBER ORIENTATION ON MATERIAL PROPERTIES

**Figure 15.** Fiber orientation in composites can be classified as either (a) a single direction, (b) arbitrary, (c) mutual, or (d) multidirectional for various planes [43]

An essential factor in regulating the mechanical characteristics of the composite is fiber orientation. It was observed that the mechanical characteristics change as the angle of orientation is varied from 0 to 90 degrees [42]. The angle of orientation also effects on the damping behavior of composite materials. Variations in tensile and flexural strength if fiber natural are strongly influenced by geometrical parameters such as fiber length and orientation [27]. For example, the tensile strength of unidirectional natural fiber reinforced composites aligned at 0° with the load direction can reach ~250 MPa, but at 90° the strength drops to ~80-120 MPa depending on the fiber matrix system [43]. Figure 15 shows different orientations fiber, while Figure 16 illustrates how composite behavior change when the load is applied in different direction. Unidirectional composites aligned with the loading axis exhibit a 40–60% reduction in tensile strength when misaligned. Bidirectional composites demonstrate more homogeneous mechanical responses in multiple directions; however, their ultimate strength is 20–30% lower than that of unidirectional composites. Randomly arranged fibers behave anisotropically, and their tensile strength is reduced by 15–25% compared to aligned fiber systems. The fiber dispersion

also influences the composite's final properties. The observed deviations from the classical Hall-Petch relationship are due to several factors related to natural fibers, non-uniform fiber size distribution, structural defects, moisture sensitivity, and variable fiber matrix adhesion. These factors disrupt the expected inverse relationship between grain size and mechanical strength. The composite's strength rises with the uniformity of the chopped fiber distribution [44].

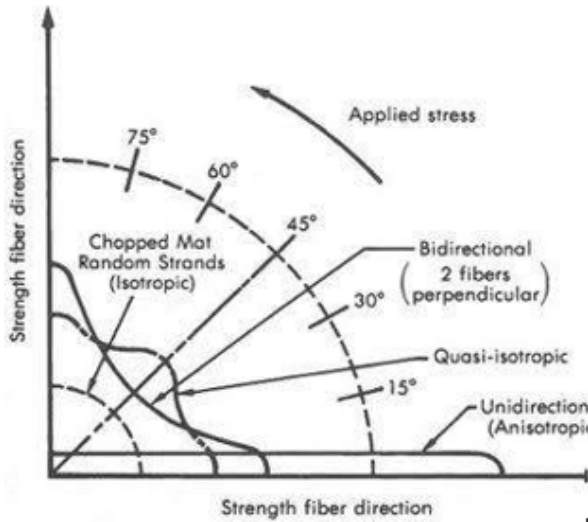


Figure 16. Composite characteristics' reliance on loads and fiber orientations [46]

6. COMPOSITE'S MECHANICAL AND PHYSICAL CHARACTERISTICS MATERIALS COMPOSED OF NATURAL FIBER POLYMERS

In addition to mechanical testing, phase analysis of natural fiber composites is often performed using X-ray diffraction (XRD). These patterns are compared to JCPDS standard cards to determine phase and ensure purity. The most commonly investigated physical and mechanical characteristics of Flexural and tensile strength, impact resistance, beyond water absorption, are characteristics of natural fiber composites (NFCs). The influence of the NFC determines whether natural fiber is best for a given application [45]. Matrix choice, production, orientation, strength, dispersion method, and porosity of the polymer contact are the elements that affect the mechanical characteristics of NFC [46]. The strength and stiffness properties of fibers are greater than those of the matrices; consequently, adding them to the polymer matrix improves the tensile characteristics. Better tensile strength is revealed when the proportion of weight approaches the ideal values (For example, maximum loading of fibers), thereby increasing the distribution of load that is firmly attached to the resin and matrix. For short-reinforced polymer composites to achieve good performance, more fiber loading is necessary. The specimen's flexural strength properties are entirely influenced by its upper and bottom surfaces. One criterion for assessing the flexural stiffness of the sample is what determines its deformability. Two essential characteristics that influence the stress per unit strain are the material structure's flexural stiffness, also known as the elastic modulus. And the material's moment of inertia is in the area of its geometry of the cross section [47]. The material's most crucial characteristic is its ability to withstand fractures. The energy

required to cause harm impact strength refers to the composite's ability to accelerate its failure. The inherent stress and strain behavior is what gives the composite its resilience. The most robust fibers are those with the best mechanical qualities. The fiber's hydrophilicity, which allows it to absorb the most water when there are holes and spaces, is demonstrated by its water absorption behavior.

The heat stability of natural fiber polymer composites is a significant issue, including moisture content, biodegradation, and photodegradation of natural fibers [46].

7. USE OF COMPOSITE MATERIALS MADE OF NATURAL FIBERS AND POLYMERS

Organic fiber-reinforced composites are rapidly becoming a viable alternative to ceramic or metal- Utilizing materials in a variety of applications, like electronics, sporting goods, the marine, automotive, and aerospace [48]. Regarding the application of composites made of natural fibers, Germany is a leader. Natural fiber composites have been introduced for both external and interior applications by the German automakers Volkswagen, Audi, BMW, and Mercedes. The 1999 Mercedes-Benz S-Class's interior door panel, manufactured in Germany, is the first commercial example. It is composed of 65% flax, hemp, and sisal blend and Bayer's 35% semi-rigid Baypreg F (PUR) elastomer [49]. When Audi released the A2, an intermediate car, in 2000, another example of the commercial use of natural fiber composites was demonstrated. The panels for the door trim were made of polyurethane reinforced with a mixture of sisal and flax. Toyota intends to line the interior of its cars with an eco-friendly material that it made from sugar cane. Composite bonded with natural fibers is commonly used for interior components, such as panels for doors, dashboard elements, package cable linings, backrests, seat cushions, and shelves. Because mechanical strength is so important, there are not many applications outside [50].

7.1 The biomedical sector

Present-day developments in composites of polymers based on natural fibers have enhanced their applications in medical devices, generating substantial prospects for improved materials generated by renewable resources while placing a greater emphasis on global sustainability. Human tissues are classified as hard (bones and teeth) and soft (skin, veins, cartilage, and ligaments) [51]. In addition to cellulose nanowhiskers and microfibrillated cellulose, bacteria also produce nanocellulose. One new biomaterial that shows considerable promise as a scaffold for tissue regeneration is bacterial cellulose (BC), a biological implant and a potential wound and burn dressing material. Furthermore, cellulose is appealing for cell im310.

Mobilization and cell support due to its nanostructure and physical resemblance to collagen [52].

7.2 The automotive industry

The automobile and aviation sectors have been actively growing a range of natural fibers, mainly hemp, flax, and sisal, as well as bioresin systems for their interior components. The specific qualities and affordable costs of natural fiber composites make them appealing for a range of uses [52].

Fiber applications are most natural in the automotive sector due to their low weight, cost effectiveness, and mechanical reliability. These applications extend to door and steering panels, trunk components, seat backrests, and roof panels, as documented in numerous industrial case studies, as well as mats (Figures 17 and 18) [53-55].



Figure 17. Door manufacturing using hemp fiber [54]



Figure 18. Door manufacturing using hemp fiber [55]

7.3 The aerospace sector

Generally speaking, Materials used in aerospace are structural materials that sustain aircraft loads throughout different flight phases. Several vital aircraft parts, including the fuselage, rudder, wings, airframe, landing gear, engine, and lift, are vulnerable to structural harm as a consequence of the extreme strain. When choosing materials for an airplane, structural strength is the first consideration due to safety concerns. Since weight has a direct impact on cost and fuel consumption, it is also a crucial design goal for any aerospace vehicle. Reducing the weight of a Boeing 747, which is frequently utilised to transport goods, by 1 kg has been shown to decrease carbon emissions by aircraft fuel and 0.94 kg. usage by approximately 0.3 kg [56]. For aeronautical applications, it is therefore essential to select materials that are both extremely strong and lightweight. The need for advanced composite materials that provide the aerospace industry is seeing a rise in the substantial weight reduction of aircraft without sacrificing structural integrity. Currently, composites made of polymer matrix (PMC) make up a substantial portion of aircraft materials. Because of their excellent strength-to-weight ratio, affordability, and natural fibers being renewable, they are a valuable option. Become a viable alternative to synthetic fibers like carbon fibers, E-glass, and others in the composite material manufacturing process. To identify the best performance characteristics, the selection of natural fibers

for NFRP composites requires thorough statistical analysis and data evaluation. For every kind of statistical analysis, sample size is always crucial. Because the same natural fiber may come from around the globe, its characteristics change based on the temperature, humidity, and the amount of moisture in the climate [57].

7.4 The sports field

As the economy expands and people's quality of life increases, an increasing number of contemporary individuals are unwinding in various sporting venues. Additionally, sports specialists place a high value on the creation of sports equipment and the advancement of modern athletic sports while concentrating on scientific training. Sports equipment has widely used fiber-reinforced composite materials because of their low weight, great strength, vast design freedom, ease of processing, and forming properties [57, 58].

7.5 Applications for electricity

Materials scientists and engineers are interested in composite materials caused of their high ratio of strength to weight. In non-critical applications, thermoplastic materials reinforced with natural fibers offer significant benefits. Additionally, composites can be utilised. In electrical uses, such as shielding cables and insulating wires, in addition to their mechanical engineering applications, the composite's electrical and mechanical qualities are crucial. Because fewer volume fractions are required to reach the desired conductivity, fillers in the form of fibers and flakes are most effective for this purpose. Important electrical characteristics include dielectric strength and dielectric constant. The capacity to tolerate voltage without breaking down is known as dielectric strength [59, 60].

7.6 The chemical sector

Traditional thermoplastic matrices (such as PVC, PP, and PE) have been replaced by recent developments in biopolymers, which have greatly expanded the range of composite materials reinforced with natural fibers. Polylactic acid (PLA), produced from renewable starch sources, and PHAS, is manufactured by microbial fermentation of vegetable oils. Its biodegradability and compatibility with natural fibers make it highly suitable for sustainable composite applications in the packaging, automotive, and biomedical industries [61].

7.7 The instruments of music

The creation of composite materials has resulted in better performance in numerous applications. The evolution of musical instruments has greatly benefited a commonly overlooked use. Bows, string instrument top plates, saxophone reeds, and neck stiffeners are just a few of the musical instrument elements that are increasingly being made from composite materials. There are several stringed instruments with top plates made of composite on the market right now, ranging from mandolins to cellos. For various reasons, including decreased material variability, enhanced resistance to environmental changes, accelerated production schedules, and the depletion of some wood species supplies, String instruments have made use of composites [62].

7.8 The construction materials

Due to the substantial advantages that natural fibers offer, as mentioned above, their applications have expanded to include civil engineering. Plant-based bast fibers are the most extensively researched and utilised natural fibers for construction, out of cotton, both processed cellulosic fibers, and animal fibers (such as wool, silk, etc.) [63]. Using short fibers as internal reinforcements is among the most significant applications of natural fibers in the construction industry, primarily to enhance the materials' tensile and flexural qualities. After cracking, cement concrete exhibited increased durability when reinforced with short, naturally occurring fibers that were dispersed randomly [64]. These findings are summarized in Table 3, which highlights the significant role of short fibers in improving the durability of cement composites.

7.9 The packaging materials

One of the key areas in the food processing sector that improves product shelf life and minimizes waste is packaging. Food packaging has utilized a variety of fiber materials derived from plants as fillers, reinforcements, and packaging matrices. Natural fibers (physical and chemical treatments) have been developed and modified in recent studies and used in packaging through the use of injection molding, compression molding, hot pressing, melt mixing, and casting. The packaging material has a significant impact on product functionality, environmental sustainability, processing parameters, and consumer satisfaction [65, 66]. Table 13 lists several areas examined when researching the characteristics of packing materials, including mechanical strength (folding endurance, tensile strength, puncture resistance), barrier properties (permeability to water vapor and O₂), and sustainability factors such as safety, compostability, and biodegradability [67].

Table 13. Characteristics of the materials used for packaging [67]

Property	Examples
Properties of structures	Bending stiffness, delamination, folding endurance, wet strength, burst strength, puncture resistance, edge crush resistance, tensile strength, rip qualities, and compression properties.
Absorption and barrier characteristics	Water absorption capacity, the permeability of water vapour (wvp), oxygen (op), and volatile substances.
Quality of manufacturing, along with manufacturing feasibility	Consistency in moisture content, density, and thickness.
Transition to food	Migration studies and toxicology parameters.
Functionality that is not structural	Static and kinetic friction, as well as resistance to abrasion.
Compostability and decomposition	Compostability in tests for disintegration and biodegradation.

7.10 The ecological domain

Numerous researchers and industries are interested in exploring the possible applications of natural fibers due to the need to preserve nature, increase environmental awareness, and improve societal economics. By designing the composite according to the product's specifications, a balance can be achieved between the intended performance and environmental effects [67]. Using eco-friendly materials has become a consideration due to growing community interest and ecological consciousness, as well as new environmental regulations and concerns about unsustainable petroleum usage [68].

8. CONCLUSION

In contrast to items made of synthetic composites, natural fibers. There are benefits to using reinforced polymer composites in commercial settings (automotive industry, buildings, and constructions), due to their advantageous qualities, which include low density, reduced solidity, environmental friendliness, low coefficient of friction, strong thermal and dimensional stability, and ease of availability. Natural fibers are gaining popularity for various reasons, and extensive research and scientific data are being conducted worldwide. The mechanical behavior of polymers is enhanced when polymeric composites are reinforced with natural fibers. This essay gives a summary of natural fibers, their varieties, uses, and mechanical characteristics. In summary, the usage of natural fiber in industrial applications is rapidly growing. Among the emerging fields within materials research that is

gaining recognition for its diverse applications is fiber composites.

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