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REVIEW

A Comprehensive Review of Natural Fibers: Bio-Based Constituents for Advancing Sustainable Materials Technology

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ABSTRACT

With growing concerns for global warming and environmental issues, the research community has contributed significantly to green technology in the area of material science through the development of natural fiber-reinforced polymer composites (NFRPC). Polymers serve as the matrix in NFRPC, while natural fibers serve as the reinforcing materials. Demand for high-performing materials made with natural resources is growing continuously. Natural fiber-reinforced polymer composites are sustainable biocomposites fabricated with natural fibers embedded with a polymer matrix. They offer a wide range of advantages, including a low weight-to-strength ratio, high flexural strength, damping properties, and resistance to corrosion, wear, and impact. Understanding the basic properties, characteristics, and processing techniques for natural fibers is important to consider their use as raw materials for high-quality biocomposite. Natural fibers come with low density and a high strength-to-weight ratio, allowing them to be a potential reinforcement for low-weight composites. This article attempts to present a comprehensive review of the available natural fibers, their classification, types, structures, physical properties, characteristics, and mechanical properties. Natural fibers are hydrophilic in nature and require physical and chemical treatment prior to their application as reinforcing material. This review will also cover the required physical and chemical treatments of natural fibers for fabricating biocomposites.

KEYWORDS

Natural fibers; biopolymers; natural fiber-reinforced polymer composites; physical and mechanical properties

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Nomenclature

FRPC	Fiber-Reinforced Polymer Composite
NFRPC	Natural Fiber-Reinforced Polymer Composite

1 Introduction

Composite materials are composed of two or more constituents, one being a base matrix reinforced with different types of fibers. Composite materials are widely preferred in industrial applications due to their capability of weight reduction along with high specific strength, high specific modulus, and strong

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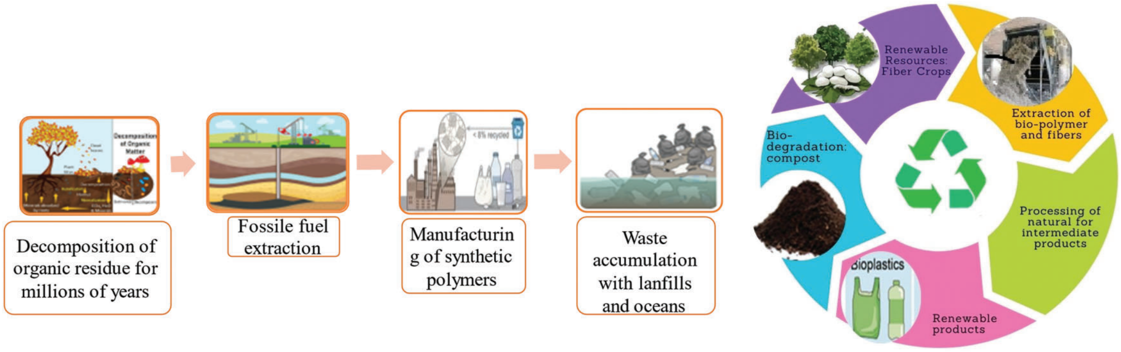
damping properties [1,2]. The evolution of composites begins with the discovery of plastics in the 1900s. Due to the limitation of the load-bearing capacity of plastics, this promoted the development of composite materials with various types of fiber reinforcement. The first fiber-reinforced polymer composite (FRPC) came into the picture in 1935, with major development during World War II in search of lightweight materials [3]. Fiber reinforcement is a major constituent of FRP with load-bearing capacity; it is a thin, long, and intact structure [4]. Depending upon the source, the fibers are classified as natural fibers, synthetic fibers, and semi-synthetic fibers. Glass, carbon, and aramid fibers are the most commonly used synthetic fibers as reinforcement in polymer composites [5].

Growing concern for the environment and the demand for environment-friendly materials boosted the development of materials from natural sources. The use of petroleum-based plastics harms the environment along with the depletion of environmental resources. FRPCs with natural and environmental materials are substituting FRPCs fabricated with synthetic material with environmental advantage and competitive mechanical properties required for industrial, automobile, aircraft, infrastructure, and structural applications [5]. Growing awareness about the environment and regulations related to industrial pollution is forcing the research community to explore sustainable and environment-friendly alternatives to conventional materials [6]. As we are moving towards the circular economy, it is essential to recycle every product for the conservation of the environment. Fig. 1 below presents the life cycle of non-renewable and renewable products. Renewable and sustainable products follow a circular life cycle with complete decomposition and contribute to environmental protection. They are the major contributors to sustainable development.



(a) (b)

Figure 1: Life cycle of non-renewable (a) and renewable products (b)

In the category of renewable materials, the demand for environment-friendly and renewable bio-composite is growing to replace the conventional composites fabricated with synthetic polymers [7,8]. Natural fibers are major constituents used for reinforcing bio-composites satisfying current industrial requirements [9]. The various types of natural fibers extracted from natural resources, including sisal, pineapple, jute, flax, kenaf, hemp, cotton, kapok, coir, elephant grass, etc., are widely used for the preparation of NFRPCs [10,11]. According to one recent survey, the market size for bio-composite is growing at a compound annual growth rate (CAGR) of 11.86% from 2016 to 2024. It is estimated that in 2024, the market size for bio-composite will be \$10.89 billion, up from \$4.46 billion in 2016. So, the utilization of materials from natural resources will rise from 5% in 2004 to 10% in 2010, 18% in 2020, and 25% in 2023.

While biocomposites are an alternative to non-renewable materials, they are not free from drawbacks, including hydrophilic nature, fiber/matrix incompatibility, and processing level difficulty. In addition to being anisotropic, the properties of natural fibers vary, inherently affecting the durability of biocomposites. Natural fibers contain large amounts of cellulose, hemicellulose, lignin, pectin, etc., resulting in hydrophilic material and poor bonding when embedded with hydrophobic polymers. This results in the loss of mechanical and thermal properties of the composites. With rising demand from the global market, the research community is continuously evaluating bio-composites for their improved properties. It is important to know the properties of fibers and matrices and their processing techniques for better performance [12,13].

This article will present a critical review in the area of development of sustainable bio-composites including various matrix and fibers used for the fabrication of NFRPCs. This review will present the chemical composition, physical and mechanical properties, and extraction of fibers and polymers from natural resources for the fabrication of bio-composites. Surface treatment of fibers, their modification, hybridization, the addition of fillers, and advanced manufacturing techniques are also presented.

2 Natural Fiber-Reinforced Polymer Composites

Fiber–reinforced composites comprise two phases: matrix and reinforcement. So, a natural fiber-reinforced polymer composite consists of natural fibers as reinforcement for biopolymers forming NFRPCs. Since 2800 BC, natural fibers have been grown and used for various household and other day-to-day applications. However, attention to global warming and minimizing dependability on petroleum-based products triggered the utilization of biocomposites with natural fibers for industrial applications also. In 1500 BCE, people used bamboo shoots for reinforcing mud walls and laminated glued wood [13]. We can find natural fiber-based NFRPCs in aircraft applications as early as the 1940s. With increasing public awareness about climate, environment, global warming, and dependency on fossil fuel resources, there is a huge demand for biodegradable composites fabricated with natural and sustainable resources. Reinforcing natural fibers with polymer matrix is advantageous due to their biodegradability and easy availability [14]. The mechanical properties like tensile strength, stiffness, stability, and modulus of elasticity of NFRPCs are found to be comparable to synthetic fiber-reinforced polymer composites with due consideration for fiber treatment and fiber proportion with the matrix. NFRPCs are now considered prime alternatives to non-renewable materials, with their advantages in terms of less toxicity, ease of disposal, less energy consumption, and greenhouse gas emissions [15].

NFRPCs are used extensively in various fields as an alternative to conventional synthetic fiber-reinforced polymer composites [16,17]. The comparative property difference between NFRPCs and synthetic fiber-reinforced composites is due to the poor adhesion between natural fibers and polymer matrix. This comes into the picture due to the hydrophilic nature of plant fibers, leading to debonding between fiber and matrix. With poor adhesion and debonding between fiber and matrix, NFRPCs are inferior to synthetic fiber-reinforced polymer composites. Natural fibers are reactive to moisture content; with time, they lose their properties. Improving the bonding between the natural fibers and matrix along with reducing moisture content is possible with the physical and chemical treatment of natural fibers. Therefore, both natural fiber and matrix require modification, which further improves their adhesion and bonding, resulting in improved mechanical properties [18,19].

3 Natural Fibers

Considering origin/source the natural fibers are classified as shown in Fig. 2 below.

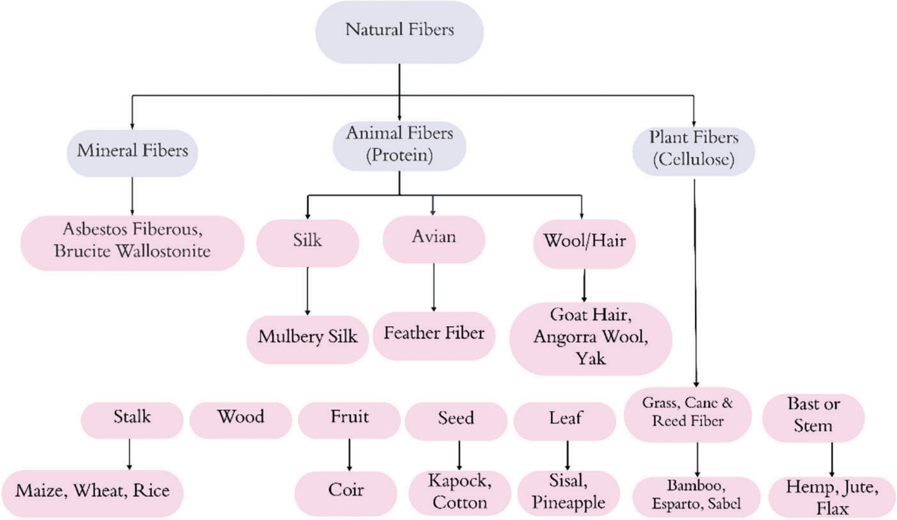


Figure 2: Classification of natural fibers

The major contribution of natural fibers comes from plants, followed by animals. Cellulose is a major constituent of plant fibers, and protein is a major constituent of animal fibers. While asbestos is the main mineral-based fiber used in practice, due to its hazardous nature, it is also banned in most countries.

3.1 Plant Fibers

Plant fibers are a major contributor to the field of sustainable fibers. We further divide them into primary and secondary fibers. The fibers like cotton, sisal, jute, kenaf, hemp, etc., which are cultivated mainly for the production, are known as primary fibers, and secondary fibers are obtained as byproducts after their main use, like banana, coir, oil palm, coconut, etc., [20]. Plant fibers are collected from different parts of plants, including leaf fibers collected from plant leaves, seed fibers from plant seeds, bast fibers from skin and bast around the plant stem, grass fibers from various types of grass, wood pulp fibers, and core fibers from the plant stalks. Plant fibers are major constituents of cellulose, hemicellulose, lignin, wax and pectin. Straw fibers have been used since the early years and proved their applicability in improving composite performance [21]. Fig. 3 below shows the structure of plant fiber with three major components. Generally, plant fibers are constituents of cellulose, hemicellulose, and lignin. The combined structure of plant cells is called lignocellulose. The variation in the chemical composition of plant fiber is also observed depending on the geographical conditions and species of the plants. The microfibril angle and its arrangement inside the side wall affect the properties of the plant fibers.

The different mechanical properties of plant fibers are illustrated in Table 1. Fig. 4 depicts the various plants and respective plant-based natural fibers.

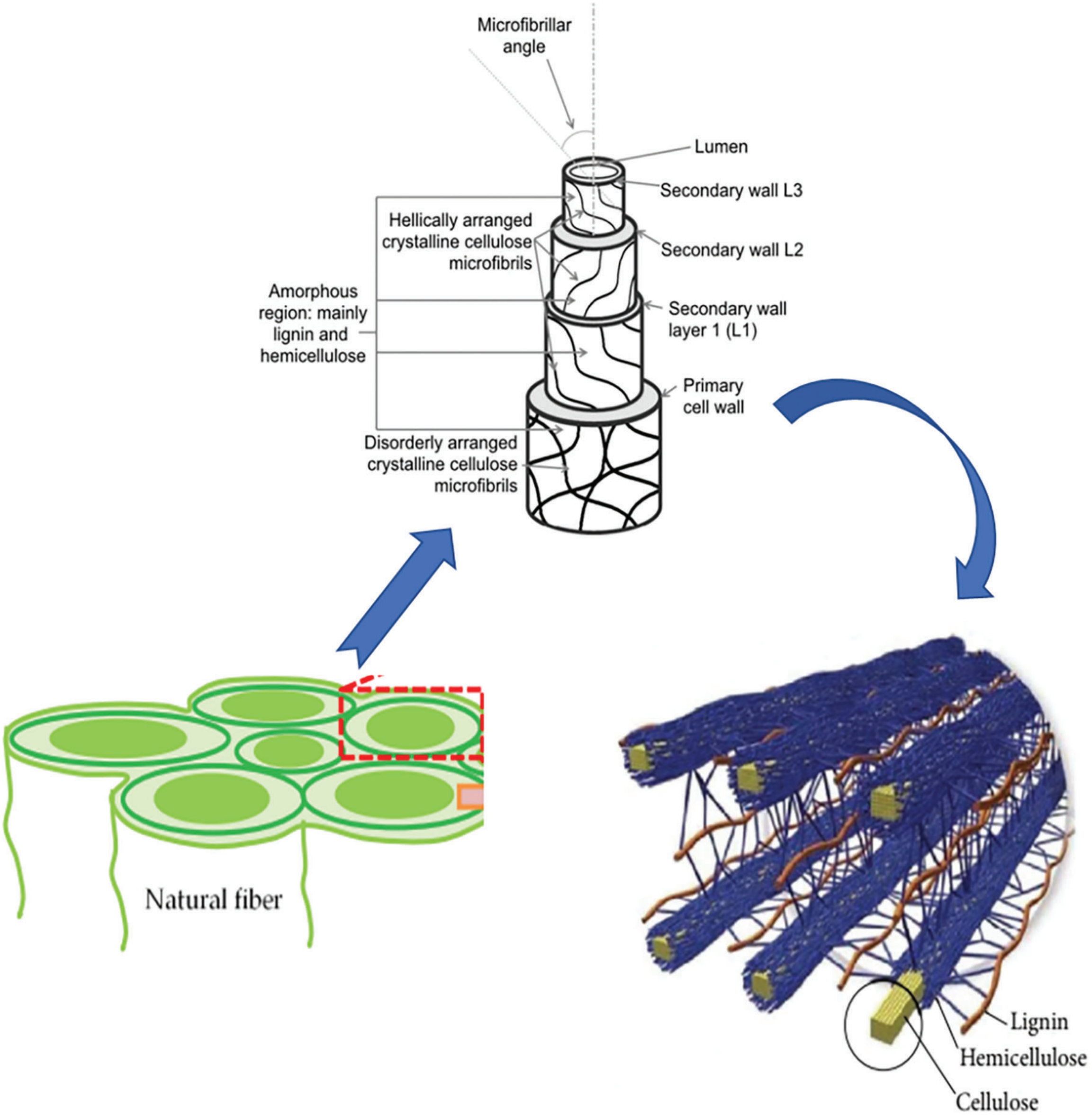


Figure 3: Structure of natural fiber. Adopted with permission from Reference [22], Copyright © 2022, MDPI

Table 1: Mechanical properties of plant fibers [23–26]

Fiber	Tensile strength (MPa)	Sp. strength (MPa.cm^3/gm)	Modulus of elasticity (GPa)	Density (gm/cm^3)	Ref.
Hemp	690	630	35–65	1.2	[23]
Flax	400–1000	300–600	30–70	1.4	[23]
Jute	210–750	320–600	25–50	1.3	[24]
Kenaf	925	640	53	1.4	[25]
Sisal	125–800	350–430	10–20	1.5	[26]
Bamboo	150–220	600	12–16	0.8–1.1	[26]

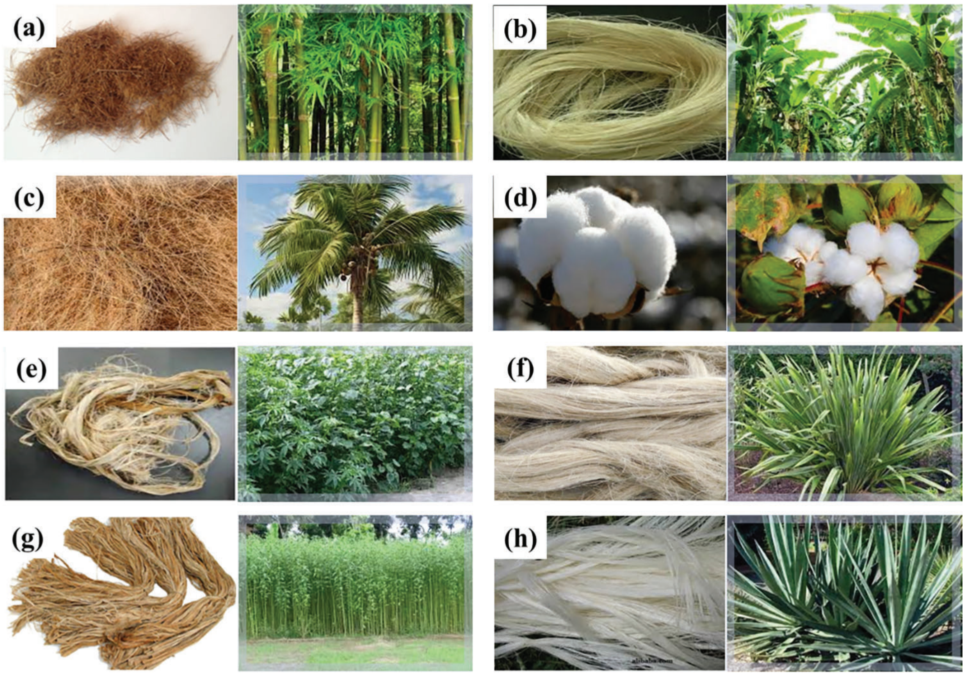


Figure 4: Natural plants and their extracted fibers: (a) bamboo (grass fiber type); (b) banana (leaf type fiber); (c) coir (fruit type fiber); (d) cotton (seed type fiber); (e) kenaf (bast type fiber); (f) flax (bast type fiber); (g) jute (bast type fiber); (h) sisal (leaf type fiber)

Apart from this, various plant fibers are explored nowadays. Different plant fibers explored by researchers are *Phaseolus vulgaris*, *Axadirachta indica* bark, *Carica papaya* bark, *Pithecellobium dulce*, *Elettaria cardamomum* stem, *Albizia amara* bark, *Eleusine indica* grass, Ripe Bulrush, *Sterculia urens* bark, *Leucas aspera* stem, Kigelia Africana fruit fiber, *Citrullus lanatus* climbers, *Parthenium hysterophorous* [27–31].

Date palm leaves are abundantly available in Middle Eastern countries and North Africa. Date palm leaves have the potential for various applications, including cement reinforcing, the paper industry, energy production, and soil fertilizing [32]. Dhakal et al. [33] evaluated the impact and tensile properties of date palm fiber-reinforced polycaprolactone bio-composite fabricated with an extrusion process. They found that tensile and impact strength increased by 28% and 101.42% for date palm fiber-reinforced biocomposite. The addition of luffa fibers improved the impact energy absorption capacity, and mechanical and acoustic properties of the composite [34,35]. Faheed et al. [36] evaluated the sisal and cotton fibers for fabricating biocomposite for prosthetic applications. Ghalme [37] in his study attempted to optimize the proportion of rice husk and straw fiber to improve the mechanical properties of rice husk and straw fiber-reinforced bio-composite. Various applications of plant fibers are illustrated in Table 2.

Table 2: Applications of plant-based natural fibers

Fibers	Applications	Ref.
Banana	Art/handicraft, currency note paper, rope, tea bags, place mats, paper cardboard, table cloth, string yarn, high-quality textile/fabric fabrics, cordage, cushion cover, curtain, natural absorbent in colored wastewater, oil absorber, light weight composites, and bio-fertilizer.	[38]
Hemp, sisal, coir	Orthoses materials, bags, tarpaulins, carpets, rope, furniture materials, fabric, textile, garden mulch, fleeces, and needle felts, light weight	[38,39]

(Continued)

Table 2 (continued)

Fibers	Applications	Ref.
	composites, composites, geotextiles/geotextile insulation industry, filler, reinforcement in composite materials, light weight composites.	
Jute	Biomedical and pharmaceutical, winter overcoat, bags, sacks, carpets, carpet upholstery, transportation or geotextile, electrical insulation and ropes, tarpaulins, packaging, furniture materials, fabric, lightweight composites.	[40]
Sugarcane, flax, cotton, kenaf, bamboo	Biomedical nanoparticles, antibiotics, fabric, clothes, yarn, furniture industry as coating materials, lactic acid, construction, vinegar, charcoal, methane, composite reinforcement, shoes, food, textiles, pulp and paper production, shocks, and bioenergy sources.	[41]
Kenaf	Ceiling, ballistic armor materials, aerospace, pulp and paper products.	[42]
Pineapple,	Bags, table linens, mats, ropes, pulping material, handbags, composites, lightweight duck cloth, conveyor belt cord, coasters, and many other interior design products, and livestock and agriculture.	[43]
Ramie	Textile, paper, pulp, yarn, biofuel, fabric, oil, resin, wax, seed food, composites, livestock, and agriculture.	[42]
Sorghum bagasse	Particle board, sugar production sources, pulp, and paper.	[44,45]
Abaca	Textiles, clothes, and useful papers such as money, journal, and check paper, as well as composites.	[41]

With wide applicability has promoted the demand for plant-based natural fibers. Table 3 depicts the worldwide production of plant fibers.

Table 3: Worldwide production of plant-based natural fibers

Fibers	World production ($*10^3$ ton)	Country	Ref.
Bamboo	30,000	India, China, Indonesia, Malaysia, Philippines	[46–50]
Jute	2300	India, China, Bangladesh	[46–50,51]
Kenaf	970	India, Bangladesh, United States	[47–51]
Sugarcane bagasse	75,000	India, Brazil, China	[46–50]
Flax	830	Canada, France, Belgium	[47–51]
Grass	700		[47]
Sisal	378	Tanzania, Brazil, Kenya	[46–50,52,53]
Hemp	214	China, France, Philippines	[53,54]

(Continued)

Table 3 (continued)

Fibers	World production (*10^3 ton)	Country	Ref.
Coir	100	India, Sri Lanka, Philippines, Malaysia	[46–50]
Ramie	100	India, China, Brazil, Philippines	[46–52]
Abaca	70	Philippines, Ecuador, Costa Rica	[45–49]
Oil palm	40	Malaysia, Indonesia	[46–50,55,56]
Pineapple	74	Philippines, Thailand, Indonesia	[46–50]
Rice husk	160,000	China, India, Indonesia, Malaysia, Bangladesh	[57,58]
Rice straw	579	China, India, Indonesia, Malaysia, Bangladesh	[48,49,59]
Wood fiber	1,750,000	Canada, United States, China	[48–50]
Palm date	4200		[47,48]

3.2 Animal Fibers

Animal fibers are the second most important and preferable source of natural fibers after plant fibers for biocomposite reinforcement with their promising mechanical and physicochemical properties, easy availability, and non-toxic nature. Animal fibers are obtained from three different sources, namely hair, avian feather, and secretions [60,61].

In the category of wool (hair) fiber is obtained from mammalian hair like sheep, alpaca, goat, camel, llama, etc.; silk (secretion) fiber is obtained from silkworms, butterflies, spiders, etc.; and avian fibers are obtained from bird feathers. Protein is the main constituent for animal fibers formed by combining amino acids with long-chain molecules of polypeptide [62]. Silk fiber consists of fibroin-type protein molecules with 140 nm long and another 70 nm long composed of tyrosine and other side groups. Silk constitutes two fibroins in triangular shape covered with sericin gum, as shown in Fig. 5 [63].

Hair/wool and feather constituents are mainly α-keratin types of proteins. α-Keratin fiber is structured with an inner part known as the cortex and medulla while the outer layer is known as the cuticle [64,65]. The thickness of the cuticle ranges from 1 to 2 scales for fine wool fibers and 8 to 10 cuticle cells for goat hair coarse fiber. Cuticle contributes to 10% to 20% weight of fiber and provides a protective layer for 80% to 90% of the bulk fiber in the form of spindle-shaped cortical cells. Microfibril embedded in the matrix contributes mainly to the mechanical strength of the wool fiber. Cortical cells in the cortex are polyhedral, spindle-shaped, and 100 nm long. Fig. 6 shows the morphological and chemical structure of wool fiber [66]. The cuticle is again overlapped with the epicuticle, with a few nanometers in thickness. It has protein and high chemical resistance and is important for all surface properties. Epicuticle is again covered with a thin layer of fatty acid and is responsible for the water-repellency of mammal fibers [67].

The various mechanical properties of animal fibers are presented in Table 4.

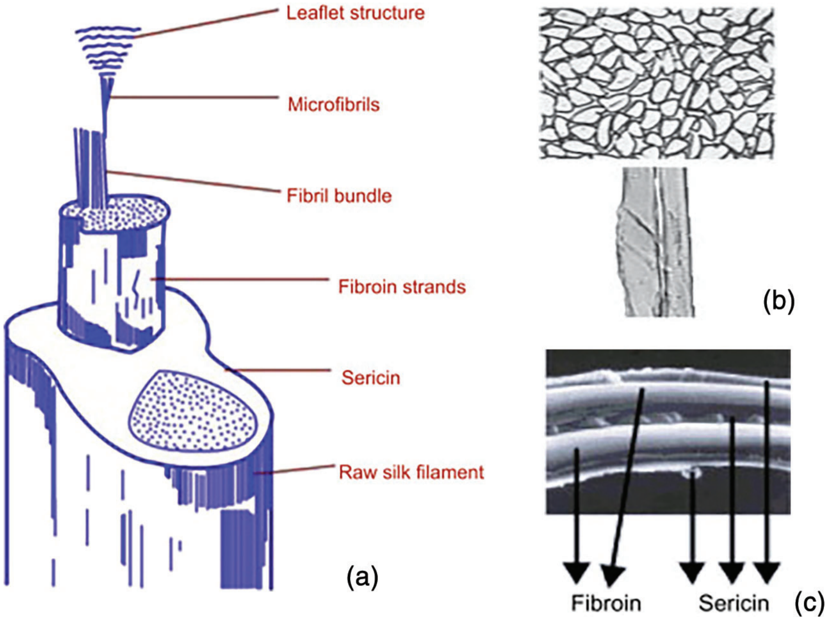


Figure 5: (a) Structural image of silk fiber; (b) longitudinal and cross-sectional image of silk fiber; (c) morphological side view of silk fiber

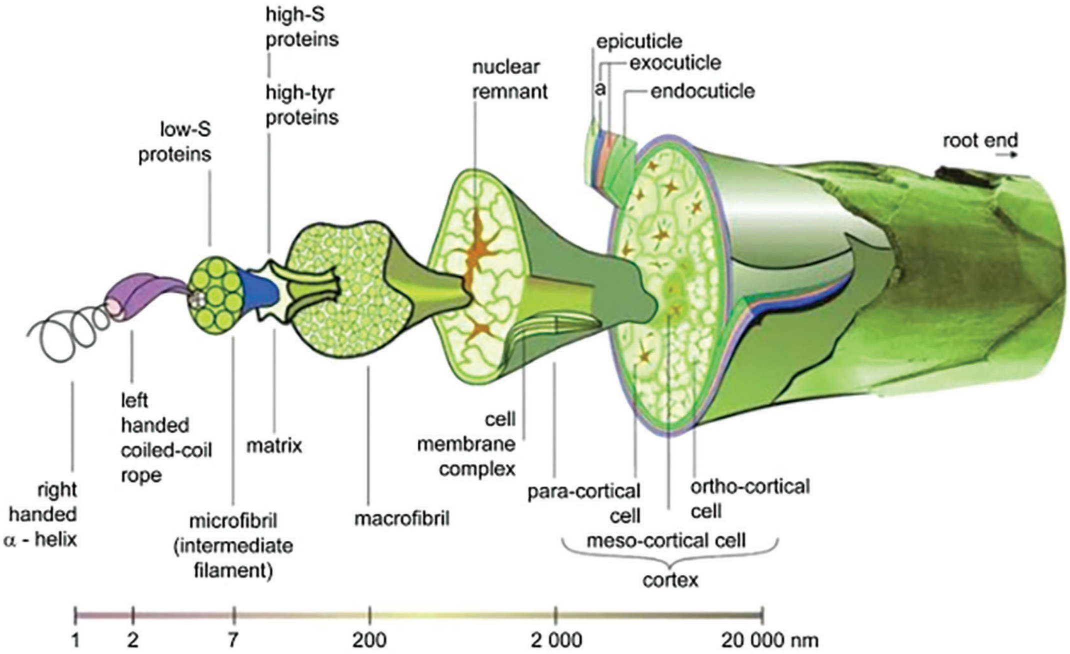


Figure 6: Morphological and chemical structure of wool fiber

Table 4: Mechanical properties of animal fibers

Fiber	Density (gm/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Sp. modulus	Elongation (%)	Absorption (%)	Ref.
Sheep wool	1.5–2.0	120–174	1–4.8	–	25–30	NR	[68]
Chicken feather	0.8–0.89	187	4.6	NR	8	85	[69]
Human hair	NR	300–600	3–4	NR	20–30	30–40	[70]
Pig hair	NR	44.5–155.1	3.93–8.08	NR	3–8	95	[71]
Silk	1.34–1.38	25–50	2–6	15–44	10–40	10–12	[72]
Dog hair	1.31–1.34	NR	2–3	NR	43.7	NR	[73]

Animal fibers are mainly used in the textile industry for different products like clothes and textile goods. Demand for organic, sustainable, eco-friendly, and lightweight products for the automobile industry is driving the market growth for animal fibers. Bird feathers, human hair, and animal hair/wool are all waste by-products and can be used for the production of sustainable composites for use in various sectors. Huge production of wool and feather fiber is expected in the coming days. On average, a single sheep can produce 4.5 kg of wool, and in 2022 the number of sheeps have risen to 1.296 billion, generating a significant amount of wool [74]. It is estimated that of the total weight of chicken, the 6% weight goes to the feathers [75]. In 2022, about 138.8 million tons of chicken meat were produced, generating 8.32 million tons of chicken feathers as waste by-products [76,77]. 124.6 million tons of pig meat was also produced in 2022, generating waste of pig hairs, which are difficult to decompose, providing an opportunity for the use of pig hair fibers [76]. Human hairs also have protein filaments available naturally and non-biodegradable [78]. It has been expected that the total population will grow up to 2 billion by 2053 from the current population, making the availability of a huge amount of human hair fibers. Manjunatha et al. [70] and Bheel et al. [78] evaluated the applicability of human hairs as reinforcement for construction materials. Human hairs have wide applications including wigs, fertilizer, clay reinforcement, fabric making, artwork, oven lining, cosmetic brushes, etc. [79]. Silk is the oldest fiber known to human beings and has been in use for 5000 years. Silk is recognized for its unique luster, glamour, and unique mechanical properties, along with offering warmth in the cold season and comfort in the warm season [80]. It is produced through the secretion of animals and insects to prepare their cocoons and webs. The textile industry uses silk for commercial purposes produced by silkmoth, mulberry, *Bombyx mori*, and some other genera [81]. Silk produced by other insects like spiders is used rarely for commercial applications like in weapons and telescope cross-hair [82]. Silk is the lustrous fabric used in the textile and apparel industry, biomedical applications, construction, and silk non-woven fabric preparation [80]. Bird feathers are also found suitable for biomedical and automobile applications [83].

4 Natural Fiber Treatments and Modifications

Natural fibers are considered as reinforcement for polymer matrix, but adhesion and compatibility of fibers with matrix affect the properties of NFRPCs. Bonding between matrix and natural fiber is affected by various factors like chemical compatibility, fiber surface roughness, humidity, and surface treatment. As well, natural fibers are hydrophilic in nature and matrix are generally hydrophobic in nature, resulting in poor adhesion and bonding leading to poor mechanical properties of the reinforced composite. To improve the compatibility and adhesion between natural fiber and matrix, along with reducing the hydrophilicity of natural fibers, the fiber treatment is essential [60,84].

4.1 Chemical Treatment

To improve the fiber/matrix adhesion and improve moisture resistance, fibers are chemically treated. Chemical treatment helps to improve the bonding between fiber and matrix.

4.1.1 Alkalization

Alkalization was initially developed in 1844, is still commonly used in textile industries, and is also known as mercerization. In this process, fibers are exposed to a saturated aqueous solution of NaOH. This leads to dilatation and changes in cell structure, size, morphology, and mechanical properties. Alkalization removes the oil, and wax from the surface and lignin and hemicellulose from fibers before its fabrication process [85]. Alkalization improves the surface roughness of fiber, thereby improving the adhesion and bonding between matrix and fiber. Excess alkalization leads to excess removal of lignin and hemicellulose, thereby damaging the cell walls of fiber and affecting mechanical strength [86]. Alkalization also contributes to the thermal stability of fibers. The schematic representation of alkalization is presented in Fig. 7, and the reaction of cellulose with NaOH is presented below reaction [86].

$$cellulose - OH + NaOH \rightarrow (cellulose - O) + Na^{+} + H_2O + impurity \tag{1}$$

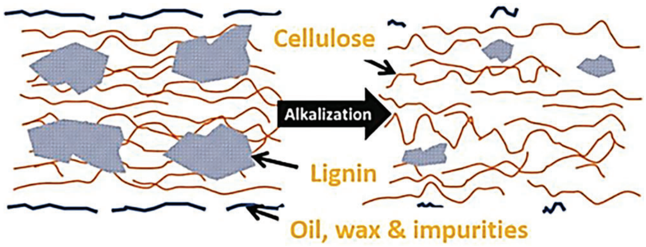


Figure 7: Alkalization treatment and variation in fiber structure

4.1.2 Silane Treatment

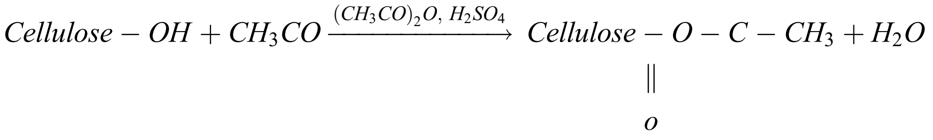
Silane is a coupling agent, and it acts as a mediator between the hydrogen bond of the polymer and the hydroxyl group of the fiber [87–89]. Silane is a multifunctional compound of silicon oxide with a chemical formula of Si_nH_{2n+2} and bi-functional group that reacts with fiber and polymer matrix. By means of the siloxane element, silane forms a chemical link between fiber and matrix. Natural fibers undergo three different stages when treated with silane.

a) *Hydrolysis*: during this stage, silane monomers are released and silanols are formed due to hydrolysis in the presence of moisture and hydrolysable alkoxy groups [89].
b) *Self-condensation*: during this stage the silanols formed are allowed to be absorbed with hydroxyl groups present with natural fibers.
c) *Adsorption*: during this stage, silanol monomers are adsorbed with the surface of natural fibers or in the cell walls. The free silanols react with each other and form polysiloxane with a stable bond of -Si-O-Si- [90].
d) *Grafting*: during this stage, at high temperatures a hydrogen bond between the hydroxyl group of natural fibers and silanol forms a covalent bond of -Si-OC- with the evaporation of water [90].

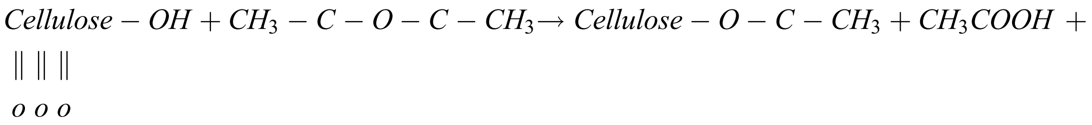
Aminopropyltriethoxysilane (APS) is the most commonly used silane for natural fiber treatment [90]. A recent investigation of silane-treated NFRPC presented improved mechanical properties in comparison to alkaline-treated NFRPC [91–95].

4.1.3 Acetylation Treatment

Acetylation is also known as esterification and is used for the plasticization of natural fibers, which helps to treat the surface of fibers and modify them to be less hydrophilic and thermally stable. The acetyl group reacts with the hydroxyl group of natural fibers and removes existing moisture present with natural fibers. The hydroxyl group (-OH) of natural fibers gets replaced with an acetyl group (CH_3CO-), making them hydrophobic in nature and dimensionally stable [96,97]. During acetylation, fibers are soaked with acetic acid and then treated with acetic anhydride for 60–180 min at high temperature. Two chemical reactions with acid and without acid catalysts are presented below:



$$Cellulose - OH + CH_3CO \xrightarrow{(CH_3CO)_2O,\ H_2SO_4} Cellulose - O - \underset{\underset{o}{\|}}{C} - CH_3 + H_2O \tag{2}$$



$$\begin{array}{l} Cellulose - OH + CH_3 - C - O - C - CH_3 \rightarrow Cellulose - O - C - CH_3 + CH_3COOH + \\ \|\ \|\ \| \\ o\ o\ o \end{array} \tag{3}$$

Acetyl treated fibers show rough surface roughness with improved mechanical properties, thermal stability, and bio-resistance [98–101].

4.1.4 Benzoylation Treatment

Pretreated natural fibers are again treated with benzoyl chloride, thereby reducing the hydrophilic nature of fibers, improving interfacial adhesion, and thermal stability with improved mechanical properties of NFRPCs. Pretreated fibers with alkaline remove wax and lignin and give more exposure to the hydroxyl group with fiber surface. These pretreated fibers, when treated with benzoyl chloride, lead to the replacement the hydroxyl group from the fiber surface with the benzoyl group, leading to more hydrophobic nature and improving adhesion and bonding between fiber and matrix [102–106].

4.1.5 Permanganate Treatment

During this treatment, alkaline-pretreated fibers are immersed with potassium permanganate ($KMnO_4$) and different concentrations of acetone for a duration of 1−3 min [107]. $KMnO_4$ reacts with plant fibers and forms reactive permanganate ions (Mn^{3+}); these ions react with a hydroxyl group to form cellulose permanganate. This cellulose permanganate removes non-cellulose constituents like lignin from the fiber cell wall. Removal of these non-cellulose constituents improves the thermal stability and moisture resistance of natural fiber [31,108–111].

4.2 Physical Treatment

Physical treatment of modification techniques helps to increase the fiber strength, thereby improving the bonding of natural fiber and matrix. These methods modify the fiber's surface and structure without affecting the chemical composition, leading to improved adhesion between fiber and matrix [112].

4.2.1 Plasma Treatment

Plasma treatment is a widely used physical fiber surface treatment technique in industrial applications specifically used for etching and cleaning the surface of the food processing industry. Plasma treatment helps to remove surface contaminants and improves surface properties like wettability, dyeability, flammability, etc. Due to plasma treatment, surface roughness increases and helps to improve the mechanical bonding between matrix and polymer. Fig. 8 shows a schematic representation of plasma treatment for natural fibers. Due to plasma treatment polar groups are generated with the surface and improve significantly adhesion and hydrophilicity of the fiber surface [113,114]. Plasma-treated fibers show improvement in Young's modulus, tensile strength, flexural strength, stiffness, and fracture toughness also [115–119].

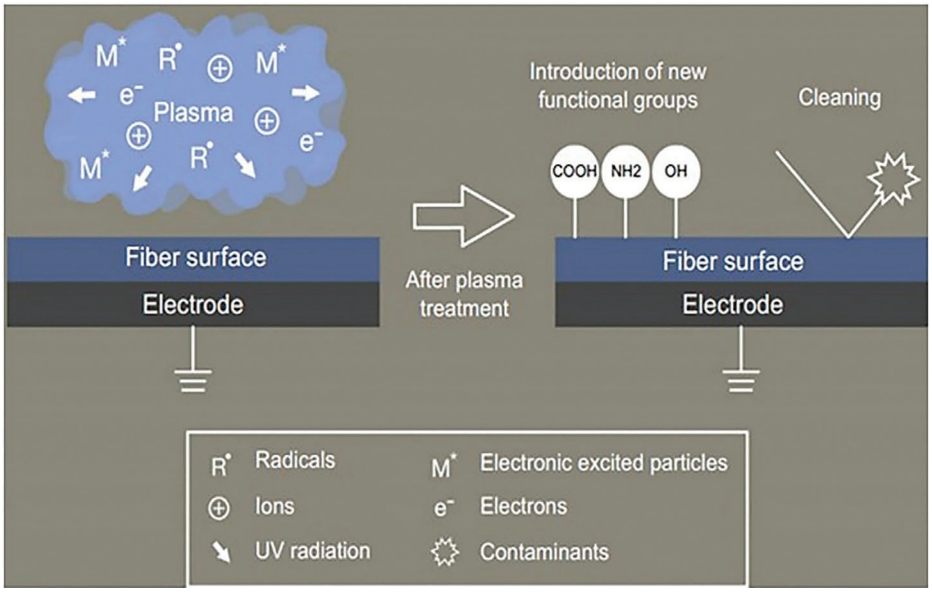


Figure 8: Plasma surface treatment. Adopted with permission from Reference [120], Copyright © 2019, Elsevier Ltd

4.2.2 Ozone Treatment

Treating natural fiber surface with ozone (O_3) or oxygen-fluorine contributes to the improving natural fiber surface. Ozone gas is a powerful oxidizing agent with significant oxidation potential. Ozone treatment helps to improve the surface energy and contact angle between polymer and matrix. Improvements in mechanical properties were observed for jute fiber [121,122] and rice husk fiber [123,124] after ozone treatment.

4.2.3 Corona Treatment

Corona treatment or electric discharge treatment was found to be effective in reducing fiber surface impurities and increasing surface energy, leading to improved bonding between hydrophilic fiber and hydrophobic matrix [125–127]. Corona treatment activates the surface through oxidation, leading to increasing aldehyde group concentration on the fiber surface and modifying the fiber surface without affecting their properties [128]. During corona treatment, the samples are placed between two electrodes and bombarded with high-speed electrons. These high-energy electrons break the molecule bonding of the substrate surface. This will induce the surface oxidation due to oxidants present during corona discharge. Oxidation will increase the polar groups, leading to improvements in the wettability and adhesion properties of the surface. Corona treatment is very essential in the textile industry. Corona treatment is a low cost process with low energy consumption.

4.2.4 Ultraviolet Irradiation Treatment

UV irradiation is electromagnetic radiation that has an efficient source of energy and the ability to execute photochemical reactions at the molecular level of natural fibers, thereby eliminating surface impurities of the natural fiber surface and improving mechanical properties [129–133]. UV treatment acts as a clean and cost-effective treatment to improve surface properties.

4.3 Evaluation of Natural Fiber Treatment Processes

Chemical and physical treatments for natural fibers improve their compatibility and adhesion between fiber and matrix. Understanding these processes during natural fiber treatment on various criteria is essential. Chemical treatments of natural fibers, such as alkalization, silane, and acetylation, showed 4–54.5, 10–45, and 35%–56% improvement in tensile strength, respectively [134–137]. The tensile strength of banana fiber was found to be increased by 13% and 5%, respectively, after benzoylation and permanganate treatment. These two processes are not effective in comparison to the rest of the chemical treatment processes [138]. Considering the amount of energy consumed per unit of natural fibers during these chemical treatments, silane, acetylation, and alkalization consume about 18, 15, and 10 KW of energy, respectively [139]. Although these figures represent total energy consumption during these processes, the silane and alkaline processes consume more amount of process energy, and the acetylation process consumes more amount of effluent energy due to the additional pretreatment for natural fibers. Whereas, in the case of physical treatments, there is no use of effluents and no valid data available related to energy consumption during these processes. But, in physical treatments, the corona treatment consumes low energy as well it is a low-cost process. The cost of natural fiber treatment also varies depending on the type of fibers, so the data related to cost-wise comparison for these physical and chemical processes is also not available. Overall, the alkaline treatment is simple, eco-friendly, repeatable, and cheap and is extensively applicable for all the natural fibers. In comparison to other processes, silane coupling agents are expensive. Acetic anhydride used during acetylation is a cheap chemical, but at the same time, it is toxic. Acetylation improves the adhesion between fiber and matrix as well as its susceptibility to moisture, thereby improving dimensional stability and resistance to environmental degradation of fibers. The resultant improvement in the mechanical properties of natural fibers and energy consumption during these processes may be considered as a selection parameter.

4.4 Cost of Natural Fibers

In consideration of cost, the natural fibers are also cheaper than the synthetic fibers. The synthetic fibers are 3–4000 times more expensive than the natural fibers. Natural fibers are low density, which makes them cheaper in transportation in comparison to synthetic fibers. Reinforcing natural fibers in matrix leads to cheaper natural fiber reinforced polymer composites than synthetic fiber reinforced polymer composites. The cost comparison for natural and synthetic fibers is presented in Table 5.

Table 5: Cost of natural and synthetic fibers [140]

Categories	Fiber	Market price (USD)
Synthetic fibers	Glass	1.97/kg
	Kevlar	8.5/kg
	Aramid	30/kg
	Nylon	4/kg
	Carbon	3000/kg
Natural fibers	Jute	0.7/kg
	Coir	1.0/kg
	Bamboo	2.25/kg
	Banana	1.0/kg
	Sisal	1.5/kg

5 Conclusion and Future Scope

Fiber-reinforced polymer composites are preferable for various applications due to their lightweight and comparable strength, but growing concerns for environmental issues have suggested an alternative to these FRPCs. Natural fibers derived from natural resources like plants, animals, and minerals are biodegradable, naturally available, low cost, and low weight, making them a fascinating alternative for the fabrication of natural fiber-reinforced polymer composites (NFRPC). The commercialization of NFRPCs is expected to grow on a large scale with growing awareness about the environment among the public. Natural fibers are now widely used in automobile industries, aerospace industries, construction industries, electronic components, sports material, and packaging industries, and even in biomedical fields also due to their advantages:

- Biodegradable, eco-friendly, and minimizing fossil fuel dependency.
- Abundant availability and some fibers are even generated with waste.
- Light in weight, helping to improve the fuel efficiency for automobile and aerospace applications.
- Utilization of agricultural waste creates more job opportunities.
- Comparable acoustic properties for sound absorption.
- Significant mechanical properties.

Along with these advantages, natural fibers come with drawbacks limiting their applicability:

- Limiting capability for water absorption.
- Due to its hydrophilic nature, there is poor adhesion between fiber and matrix.
- Limited resistance to fungi and microorganisms.
- Poor thermal conductivity and poor temperature resistance.
- Crop patterns are responsible for the supply of fibers.

To improve the mechanical performance of NFRPCs through the improved adhesion between fiber and matrix, various chemical and physical techniques are proposed for the treatment of natural fibers. These treatments modify the surface as well as the hydrophilic nature of natural fibers so that they can better adhesion. Moreover, with the growing demand for sustainable materials with improved properties, more research is needed in the area of manufacturing also using these sustainable resources for developing sustainable biocomposites.

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