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Review

Natural Fibers Composites: Origin, Importance, Consumption Pattern, and Challenges †

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† Dedicated to the memory of Dimitrios G. Verros (1926–2018) pioneer chemist in the Greek textile industry.

Abstract: This comprehensive review explores the multifaceted world of natural fiber applications within the domain of composite materials. Natural fibers are meticulously examined in detail, considering their diverse origins, which encompass plant-derived fibers (cellulose-based), animal-derived fibers (protein-based), and even mineral-derived variations. This review conducts a profound analysis, not only scrutinizing their chemical compositions, intricate structures, and inherent physical properties but also highlighting their wide-ranging applications across various industries. The investigation extends to composites utilizing mineral or polymer matrices, delving into their synergistic interplay and the resulting material properties. Furthermore, this review does not limit itself to the intrinsic attributes of natural fibers but ventures into the realm of innovative enhancements. The exploration encompasses the augmentation of composites through the integration of natural fibers, including the incorporation of nano-fillers, offering a compelling avenue for further research and technological development. In conclusion, this review synthesizes a comprehensive understanding of the pivotal role of natural fibers in the realm of composite materials. It brings together insights from their diverse origins, intrinsic properties, and practical applications across sectors. As the final curtain is drawn, the discourse transcends the present to outline the trajectories of future work in the dynamic arena of natural fiber composites, shedding light on emerging trends that promise to shape the course of scientific and industrial advancements.

Keywords: nanofillers; polymer matrix; natural fibers; composites; nanocomposites; mineral

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1. Introduction

A fiber is a natural or synthetic material having a sufficiently large length-to-width ratio [1]. Natural fibers are derived from bio-based sources such as plants and animals or exist in nature as minerals in spite of man-made fibers, i.e., synthetic ones.

Natural fibers have been used to make textiles since before the invention of writing. The first indication of the use of fibers is most likely the discovery of flax and wool garments from Swiss lake dweller excavation sites (7th and 6th centuries BCE). People also used many vegetative fibers in prehistoric times. It is believed that hemp, the earliest cultivated fiber plant, originated in Southeast Asia before moving to China, where cultivation is documented as far back as 4500 BCE. Egypt had perfected linen weaving and spinning by 3400 BCE, which shows flax farming had started earlier. India has records of cotton spinning dating back to 3000 BCE. Silk and other products are produced in the highly developed Chinese culture, where sericulture, silkworm cultivation for the production of raw silk, and ways to spin silk date back to 264 BCE [2].

Thinking of these environmentally friendly materials was prompted by the rise in environmental awareness and public interest, new environmental restrictions, and the unsustainable usage of petroleum. Natural fiber is thought to be one of the more environmentally benign materials, outperforming synthetic fiber in many ways [3]. In particular, synthetic fibers show higher mechanical properties than natural fibers, but their sensitivity to heat or moisture is low. However, there are infinite resources for natural fibers compared to the limited resources of synthetic fibers, while the recyclability of natural fibers is higher than that of synthetic fibers. Moreover, natural fibers are low-cost to produce.

Due to their favorable effects on the environment and their lower cost, natural fibers are now favored over synthetic ones. Natural fibers have attracted significant attention due to their non-toxicity, high performance, low cost, ease of processing, abundance, versatility, lack of irritation to the respiratory system, skin, or eyes, and non-corrosive nature as compared with synthetic fibers, in line with the global energy crisis and sustainability. Moreover, the manufacture of natural fibers uses 17% less energy than that of synthetic fibers like glass fibers [4].

In particular, the unique properties of natural fibers have led to important applications in the building and construction industry, transportation, storage devices, electric devices, and everyday applications. The main form of natural fibers used in the above applications is natural fiber—reinforced material composites. Materials such as polymers play the crucial role of matrix phase in these composites.

From the beginning of civilization, natural fibers have been used as a reinforcement material in composite materials. However, mud bricks are generally known as adobe when reinforced with straw, grass, or animal hair. Pharaoh mummies were shielded and strengthened in ancient Egypt by being wrapped in linen cloth that had been soaked with natural resins, Dead Sea salts, and honey. They were most likely the earliest composites of man-made materials known to mankind. Man has copied natural patterns to improve the qualities of materials [5].

Composite materials are defined as heterogeneous substances made up of two or more solid phases that are microscopically in intimate contact with one another [6]. They can also be considered homogeneous materials at the microscopic level because every component in them will have the same physical features. Ceramic matrix composites, polymer matrix composites, and metal matrix composites are three matrix materials.

Natural fibers are divided into animal or protein-based (wool, mohair, avian fiber, and silk), plant or cellulose-based (cotton, sisal, hemp, flax, jute, and coir etc.), and mineral-based, i.e., asbestos.

The major aspects of natural fiber composites, with regard to their manufacture, chemical structure, morphology, characteristics, and applications, are discussed in this article. The aim of this work is to provide an in-depth analysis addressing the varied applications of natural fibers in the field of composite materials. Natural fibers are painstakingly analyzed in great depth, taking into account their different origins, which include fibers generated from plants (cellulose-based), fibers obtained from animals (protein-based), and even fibers derived from minerals.

This article offers a thorough examination, examining not only their chemical make-ups, complex structural details, and innate physical characteristics but also emphasizing their numerous uses in a variety of industries. The inquiry extends to composites made from mineral or polymer matrices, exploring how they work together synergistically and the qualities of the materials they produce. Additionally, this review explores the world of cutting-edge improvements rather than just focusing on the inherent qualities of natural fibers.

The investigation includes the enhancement of composites by the application of natural coatings, including the use of nano-fillers, providing a compelling path for further study and technical advancement. In summary, this review provides a thorough grasp of the crucial position that natural fibers have in the field of composite materials. It combines knowledge from their various historical backgrounds, inherent qualities, and useful applications in various fields. As the discussion comes to a close, it moves beyond the present to define future work in the dynamic field of natural fiber composites, highlighting new themes that could influence how science and industry develop.

The structure of this work is as follows. The cellulosic natural fiber composites are thoroughly explored in the first half. Then, a comprehensive literature review on protein natural fiber composites is made. Finally, the mineral composites and nanocomposites are examined in detail, and then conclusions are drawn, and challenges in the area are presented.

2. Plant (Cellulose Base) Fibers and Composites

2.1. Origin, Physical Properties, and Classification of Plant-Based Fibers

Cellulose-based fibers make up the major plant fibers, such as cotton, ramie, jute, hemp, flax, and sisal. Cellulose-based fibers are used to make cloth and paper. Plant fibers were the subject of extensive investigation [3–13] and may be further classified as in Table 1. Table 1 presents an eloquent classification of these plant-based fibers, unraveling the fascinating intricacies of each category.

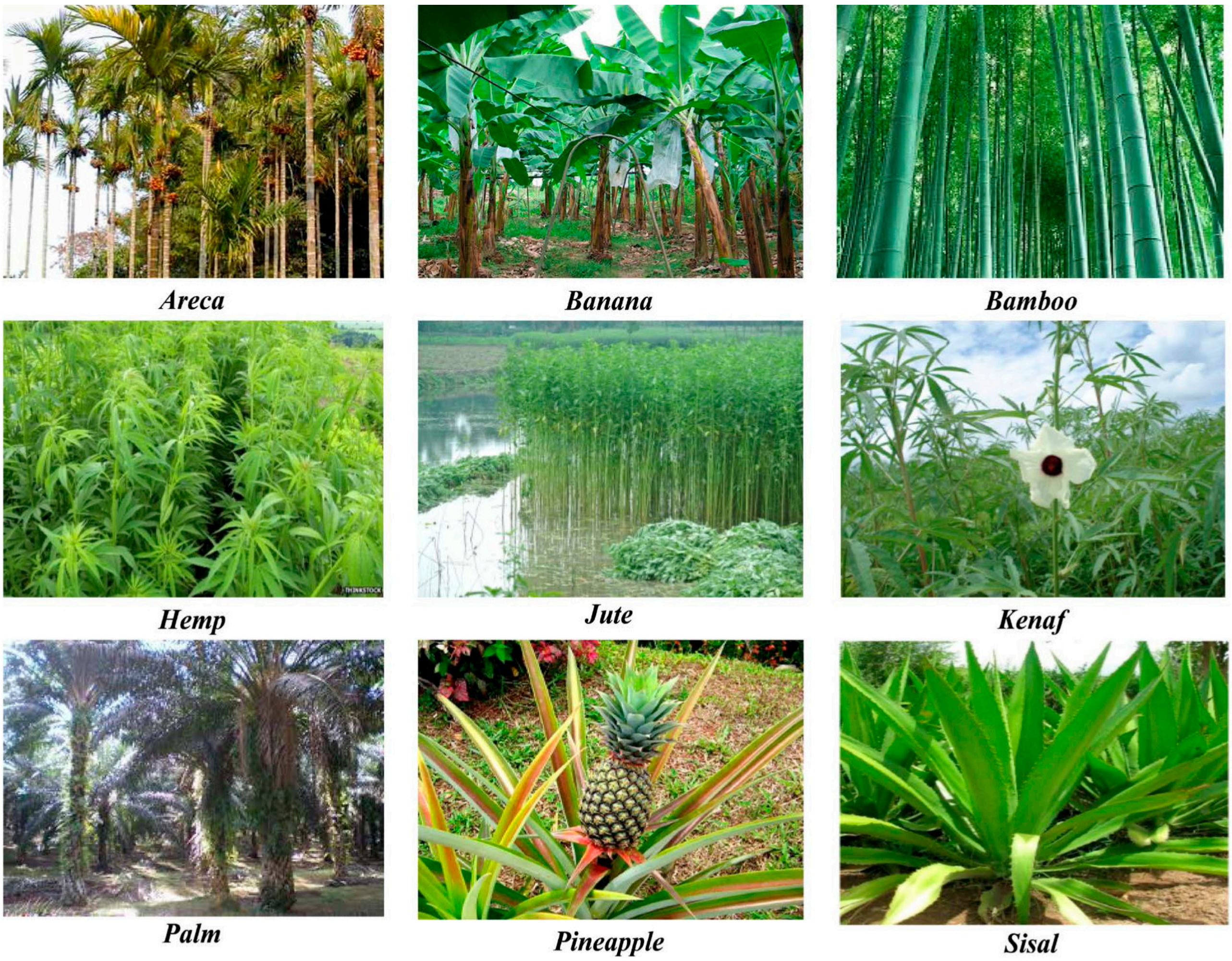


Figure 1. Plants for the production of cellulose base fibers [3].

Table 1. Classification of plant-based fibers [3–14].

Name of Fiber	Detail
Skin fiber or bast fiber	These fibers are gathered from the bast or skin that surrounds the plant's stem. These fibers have very high tensile strength as compared to others. These fibers are used to make strong ramie, fabric, yarn, packaging, and paper. Flax, industrial hemp, soybean fiber, jute, kenaf, rattan, and even vine and banana fibers are a few examples.
Fruit fibers	Coconut (coir) fiber is gathered from the plant's fruit.
Grass or reed fiber	Grass and bamboo fibers are two examples.
Leaf fibers	Fibers gathered from leaves, e.g., abaca and sisal
Seed fibers	Fibers are taken from the seeds or seed casings. The most popular seed fiber is cotton.
Stalk fiber	Plant stalks serve as its natural fiber, like wheat or rice straws.
Wood fiber	Classified either as softwood or hardwood. Such a fiber also exists in tree wood like barley and various plants, such as grass and bamboo. Although kenaf, sisal, jute, and coconut are widely used, cotton, flax, and hemp are the most commonly used natural fibers. Because of their high suppleness and tolerance to a hostile environment, hemp fibers are mostly utilized for ropes and aerofoils. For instance, the heating and sanitary sectors already use hemp fibers as a seal. Figure 1 illustrates the main plants that produce cellulosic base fibers.

Figure 1 offers a visual atlas of the key plants responsible for yielding cellulose-based fibers. This illustrative depiction underscores the rich tapestry of natural resources that humans have harnessed for millennia, culminating in the creation of essential materials that underpin multiple industries.

The natural characteristics of plant fibers are summarized in Table 2. Table 2 stands as a testament to the natural prowess of these fibers, summarizing their inherent characteristics and botanical origins [3–14]. This comprehensive overview delves into the distinctive qualities that set each fiber apart, shedding light on their potential uses and ecological significance.

The plant fibers are made up of lignin, cellulose, and hemicellulose, and their structure is shown in Figure 2. In this figure, a visual representation of the lignocellulosic structure offers a glimpse into the intricate arrangement of cellulose, hemicellulose, and lignin within plant fibers. This illustration elucidates the synergistic interplay between these components, shedding light on their contributions to the fiber's composition and behavior.

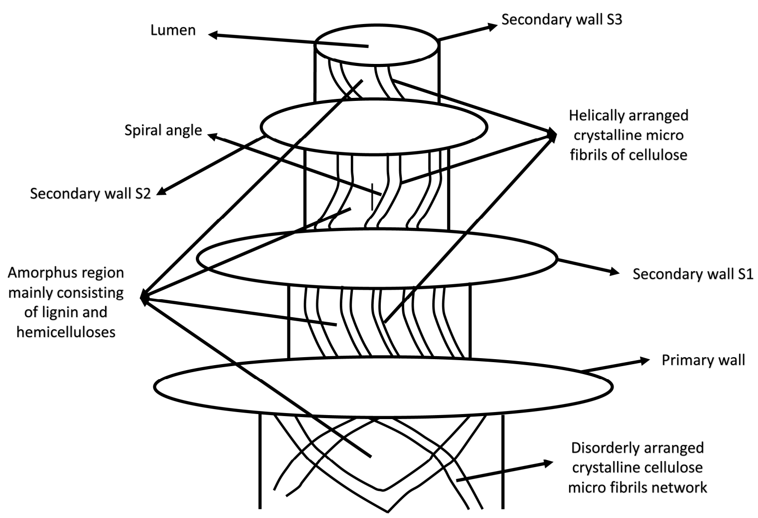


Figure 2. Schematic representation of a lignocellulosic structure [10].

Table 2. Summary of natural characteristics of plant fibers [3–14].

Fiber	Plant Scientific Name	Description
Abaca/ Banana	***Musa textilis/ Musa basjoo***	Abaca is a plant that is related to bananas and is often referred to as Manila hemp. Abaca plants resemble bananas, but unlike bananas, they produce fruit that cannot be commercially produced and is not fit for human eating. Abaca plants, in contrast to bananas, are only grown for their fiber. The abaca fiber has good mechanical properties and resistance to saltwater deterioration. The banana fiber is lightweight and highly strong with strong moisture absorption properties.
Bamboo	**Bambusoideae**	Bamboo has a high strength-to-weight ratio, and it is a fast-growing plant. It has attracted huge attention due to its excellent properties. (good durability, tenacity, flexibility and stability properties, excellent permeability, and ultraviolet resistance behavior) and availability. It consumes less water, and no herbicides or pesticides are used during cultivation and is taken at the base, keeping the root intact. Moreover, the fiber surface is rounded and smooth and has a high length-to-diameter ratio. Compared to glass fiber, it is lighter, stiffer, and stronger. The energy required to produce one mat made of bamboo fiber is just 17% compared to that of a mat made of glass fiber, as per the United States Department of Energy Assessment.
Coir	***Cocos nucifera***	Due to its superior durability compared to most natural fibers, lack of chemical processing, strong resistance to salt water, and availability, coir is very appealing.
Cotton	***Gossypium***	A cotton fiber's absorbency is superb. In terms of natural and synthetic fiber output worldwide, cotton accounts for 46%. It also offers excellent textile strength.
Eucalyptus	***Eucalyptus globulus* Labill**	While being abundantly available, eucalyptus fiber has limited resilience to fire and mold damage. These fibers from bark work well as insulation.
Flax	***Linum usitatissimum***	Comparing flax fiber to glass fiber, flax fiber has a higher specific tensile. It also has high rigidity, high strength, and low density, as well as swift absorption and desorption of water.
Hemp	***Cannabis sativa* L.**	Mechanical strength and Young's modulus of hemp fiber are outstanding, with excellent insulating qualities. Good ultraviolet light blocking and heat-conducting properties, excellent antibacterial properties.
Jute	***Corchronus capsularis***	High length-to-diameter ratio, excellent strength-to-weight ratio, and superior insulating capabilities and antistatic properties, low thermal conductivity are all characteristics of jute fiber.
Kenaf	***Hibiscus cannabinus* L.**	Low density and strong specific mechanical characteristics characterize kenaf fiber.
Pineapple	***Ananas magdalenae***	Excellent mechanical, physical, and thermal qualities can be found in pineapple fiber.
Ramie	***Boehmeria nivea***	Ramie fiber could outperform as compared to glass fiber with respect to strength and modulus. It has low elasticity and easy dying behavior. It also has swift adsorption and desorption of water. However, because it needs pricey pre-treatments, it is less well-liked than the other natural fibers.
Sisal	***Agave sisalana***	Sisal has quick regeneration cycles and is simple to cultivate. The fiber has high tensile strength and tenacity as well as high resistance to alkali, salt water, abrasion, and acid.

A naturally occurring polysaccharide called cellulose is created when the rings of D-glucose-pyranose and the bond of -(1-4)-glycosidic come together. The chemical structure of cellulose can be found in several textbooks. A hemicellulose is a collection of complex polysaccharides, primarily consisting of arabinose, mannose, glucose, and xylose, that act as a bridge between cellulose and lignin. Lignin is entirely amorphous and is composed of hydrocarbon polymers, a complicated group with aromatic and aliphatic components [14].

Natural fibers might have different properties even though they are obtained from the same plant due to differences in chemical makeup, microfibrillar angle, structure, physical characteristics, crystalline cellulose diameter, defects, and isolation process. The mechanical characteristics and properties may also differ significantly. The chemical compositions of various natural fibers are given in Table 3. This table presents an insightful snapshot of the chemical composition of various natural fibers. Hemicellulose, cellulose, and lignin constitute the core components that shape fiber stiffness. The balance between these elements contributes to the fiber's overall characteristics. Notably, hydrogen bonds play a crucial role, linking hemicelluloses and lignin to linear cellulosic macromolecules. These bonds not only bind fibers together but also reinforce the cellulose within the fiber's cell wall.

Table 3. Chemical composition of natural fibers [3–13].

Fiber	Hemicellulose (wt%)	Cellulose (wt%)	Lignin (wt%)
Bamboo	30	26–43	21–31
Coir	0.15–0.25	32–43	40–45
Date palm	18–25	41–46	20–27
Banana	38.54	43.46	9
Bagasse (sugar cane)	16.8	55.2	25.3
Abaca	20–25	56–63	7–9
Jute	14–20	61–71	12–13
Sisal		65	9.9
Hemp	15	68	10
Ramie	13–16	68.6–76.2	0.6–0.7
Flax	18.6–20.6	71	2.2
Kenaf	20.3	72	9
Pineapple	–	81	12.7
Cotton	5.7	82.7–90	<2

Mechanical properties provide a glimpse into the inherent strength and resilience of different plant fibers. Table 4 offers a comprehensive overview of the mechanical attributes of selected natural fibers [8]. The density, diameter, length, tensile strength, Young's modulus, elongation at break, and moisture content collectively define their mechanical behavior. These values reflect the intricate balance between components like cellulose, hemicellulose, and lignin within the fibers.

Table 4. Mechanical properties of some natural fibers adapted from Reference [8]: [a] average value between parenthesis.

Fiber	Density (g/cm^3) [a]	Diameter (µm) [a]	Length (mm) [a]	Tensile Strength (MPa) [a]	Young's Modulus (GPa) [a]	Elongation at Break (%) [a]	Moisture Content (%) [a]
Coir	1.2	7–30 (18.5)	0.3–3 (1.65)	175	6	15–25 (20)	10
Banana	1.35	12–30 (21)	0.4–0.9 (0.65)	529–914 (721.5)	27–32 (29.5)	5–6 (5.5)	10–11 (10.5)
Jute	1.23	5–25 (15)	0.8–6 (3.4)	187–773 (480)	20–55 (37.5)	1.5–3.1 (2.3)	12
Sisal	1.2	7–47 (27)	0.8–8 (4.4)	507–855 (981)	9–22 (15.5)	1.9–3 (2.45)	11
Kenaf	1.2	12–36 (24)	1.4–11 (6.2)	295–930 (612.5)	22–60 (41)	2.7–6.9 (4.8)	6.2–12 (9.1)
Bamboo	0.6–1.1 (0.85)	25–88 (56.5)	1.5–4 (2.75)	270–862 (566)	18–89 (53)	1.6–8 (4.65)	11–17 (14)
Flax	1.38	5–38 (21.5)	10–65 (37.5)	343–1035 (689)	50–70 (60)	1.2–3 (2.1)	7
Cotton	1.21	12–35 (23.5)	15–56 (35.5)	287–597 (442)	6–10 (8)	2–10 (6)	33–34 (33.5)
Pineapple	1.5	8–41 (24.5)	3–8 (5.5)	170–1627 (898.5)	60–82 (71)	1–3 (2)	14
Abaca	1.5	10–30 (20)	4.6–5.2 (4.9)	430–813 (621.5)	31.1–33.6 (32.35)	2.9	14
Ramie	1.44	18–80 (49)	40–250(145)	400–938 (669)	61.4–128 (94.7)	2–4 (3)	12–17 (14.5)
Hemp	1.47	10–51 (30.5)	5–55 (30)	580–1110 (845)	30–60 (45)	1.6–4.5 (3.05)	8

Figure 3 visually showcases the interrelation between the composition of fibers and their resulting properties [8]. This illustration underscores how the dynamic interplay between cellulose, hemicellulose, and lignin dictates the characteristics that define the performance and application of plant fibers.

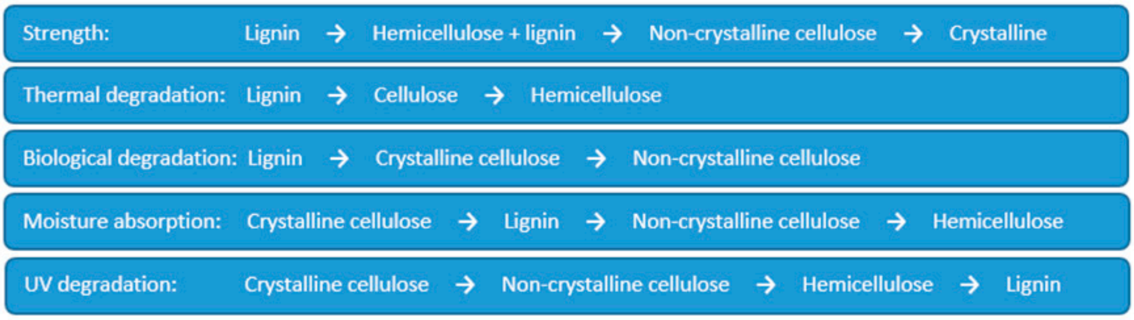


Figure 3. Properties of fiber with their composition [8].

Table 5 unveils the universal production pattern of various fibers, consolidating data from Faruk et al. [15]. This schematic diagram captures the overarching process of fiber production, highlighting the diverse routes followed by different plant fibers in the journey from botanical source to end applications.

Table 5. Universal production pattern of various fibers.

Fiber Source	Percentage (%) in World Production
Bagasse (Sugar cane)	67.8
Bamboo	27.1
Jute	2.1
Kenaf	0.9
Flax	0.73
Grass	0.6
Sisal	0.3
Hemp	0.2
Coir	0.1
Ramie	0.1
Abaca	0.07

A recent detailed overview of plant fibers is given in Reference [16].

2.2. Natural Fiber Processing

The phases of the life cycle of natural fibers generally include extraction, processing, manufacture, usage, disposal, and recycling. Many difficulties prevent the production and usage of fibers on a wide scale. These factors, which include the wide range in soil composition and shape, the hydrophilic character of the fibers, microbial deterioration, service life, and sunlight, have an effect on various stages of the life cycle of natural fibers.

Natural fibers' physical and chemical characteristics are influenced by the plant's origin, the area where it was grown, pesticides, use of genetically modified organisms (GMO), climate, time of harvesting, and fertilizers. Natural fibers typically require multiple treatments to improve fiber-matrix interfacial adhesion and overcome other constraints.

During the processing of the plant fibers, the main issue to be mitigated is the fiber extraction method, which will significantly influence the quality of the fibers. Retting is the method generally used for the separation of fibers from different parts of the plant, and there are four categories of retting extraction processes available. They are biological retting (natural and artificial), mechanical decortication, physical retting (steam explosion and ultrasound methods), and chemical retting processes [3–14].

The hand scraping, mechanical decorticator, raspador, and retting procedures are the most frequently used fiber extraction techniques. While pulling and gathering fibers, the manual extraction method removes 50% of foreign substances from the plant sheath. The quantity of times the fibers are scraped from the sheath determines the grade of the retrieved fiber. This technique works well with fibers that have flat surfaces and longer lengths. Although there are fewer fibers and they are of lower quality and quantity, the extraction procedure might take a longer period. Leaf fibers are often extracted using the hand-scraping technique. Fresh leaves are harvested, preserved, and manually scraped using a stone, ceramic plate, coconut shell, or knife [3–14].

One method of mechanical fiber extraction is decortication. The mechanical decorticator, which has a scrapper roller, plane roller, and squeezing roller, is used for mechanical extraction. The spacing between the rollers is between 3 and 8 mm, and it is used to remove fibers. Under shear, compression, and impact stresses, they squish the fibers. This procedure aids in separating the fiber bundle from the plant stalk's inner core. Following extraction, the decorticated fibers are repeatedly washed and allowed to dry for 48 h in the sun to eliminate the water content [3–14].

Another piece of equipment used to harvest plant fibers is called a raspador. This method of extraction is less expensive and uses less water. The raspador, which works similarly to decorticator rollers, consists of revolving blades that crush leaves and scrape them to remove pulp for fiber extraction [3–14].

Retting extraction is the most popular, cost-effective, and straightforward way to extract plant fibers [3–14]. Chemical, enzymatic, dew, and water retting are only a few of the several types of retting processes. Compared to dew retting and water, enzyme and chemical retting is more manageable and sustainable.

Plant stalk constituents, including lignin, hemicelluloses, and pectin, are broken down by chemical retting. Chemical remediation can be used to extract high-quality fibers by regulating the chemical concentration, reaction time, and temperature. Several climatic factors may have an impact on the fibers' strength and color. Chemicals, including sodium benzoate, mild acids, sodium hydroxide, salts, enzymes, and detergents containing sulfuric acid, are typically used in this procedure [3–14].

The fiber straws are placed in aqueous chemical solutions such as potassium hydroxide, sodium hydroxide, and sulfuric acid during the chemical retting process, which causes the fiber to dissolve and eliminates undesired non-cellulosic elements. The extracted fiber is of excellent quality, but the cost of the finished product is high since chemical retting includes the chemicals utilized and wastewater disposal.

Anaerobic bacteria are responsible for the water retting process, which divides the pectin content in the bundles of plant straw that are immersed in a water bath. This process requires 6–14 days of duration based on environmental parameters. Artificial retting is one of the quick processes to extract high-quality fibers in 4–5 days using a warm water medium [3–14].

Dew retting or field retting is one of the common and oldest extraction methods for fibers. This process has limited constraints regarding temperature and moisture range; hence, it is not being used widely in the world. Harvested plants are left in the countryside during dew retting so they can absorb the dew. In this state, the fiber bundles are separated from the microorganisms and bacteria growing on the plants and fibers. This method of extraction is less expensive and uses less water. Care must be taken at the right time during this process to avoid cellulose degradation by fungi, and this is called over-retting [3–14].

A variety of methods, including coupling agents, water-repellent chemicals, and heat treatments, are used to alter the surface's morphological, topological, roughness, and water absorption index of the fibers. In order to create new solutions and applications, research and technological efforts have been stated to promote the improvement of crop quality and fiber performance from a technical and economic perspective. Table 6 [8,13,14,16–20] provides a summary of the chemical treatment methods and how they affect the characteristics of natural fibers.

Table 6. Functional properties of natural fiber for various chemical treatments. Adapted from [8,13,14,16–20].

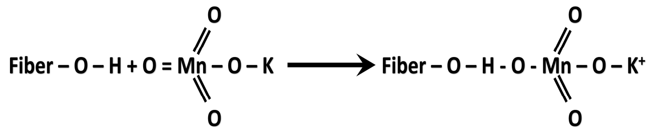
Treatment	Example	Specific Effect	General Effect
Sodium chlorite	Cotton	Bleaching	Improve Young's modulus, tensile strength, and elongation at break
Silane	Kenaf and Pineapple Hemp	Silane treatment removes noncellulosic materials from the fibers. Silane treatment Increases tensile modulus.	Improve mechanical and hydrophobic properties by applying the reactions: $CH_2CHSi(OC_2H_5)_3 + H_20 \rightarrow CH_2CHSi(OH)_3 + 3C_2H_5OH$ $CH_2CHSi(OH)_3 + Fiber - OH \rightarrow CH_2CHSi(OH)_2O - Fiber + H_2O$
Plasma	Jute fibers	Treatment improves the fiber interfacial adhesion and mechanical properties.	Improve hydrophobicity
Peroxides	Sugarcane bagasse fiber: $KMnO_4$ Jute: $KMnO_4$ Kenaf: Peroxide treatment	Thermal properties were enhanced for both fibers and resultant composites. Improvement in tensile properties. Physicomechanical properties were enhanced in treated fibers. Increases crystalline index and surface roughness of the fiber.	Reduce the moisture regain as shown by reactions: 
Ozone	Jute fibers	Changes in physical and chemical properties and also lignin degradation.	Affect contact angle and surface energy
Mercerization	Cotton treated with a caustic (NaOH) solution.	The caustic rearranges the cellulose molecules in the fiber to further improve properties such as fiber strength, shrinkage resistance, luster, and dye affinity.	Improve the mechanical properties and reduce the moisture regain
Isocyanate	Cellulose	Isocyanate treatment increases storage modulus and Young's modulus.	Surface modification
Grafting	Sisal, pineapple	Acrylonitrile (AN) grafting improves tensile strength.	Improve hydrophobicity, UV-protective properties, and mechanical properties
Enzyme	Hemp fiber: fungal and enzymes treatment	Improves moisture resistance. Increases acid-base characteristics of fibers. Good interfacial adhesion.	Reduce the lignin content
Benzoylation	sisal fibers: 10% benzoyl chloride and NaOH for 15 min flax fibers: Pretreatment: 18% wt% NaOH for 30 min, filtration, washing with water. Main treatment: 10% benzoyl chloride and NaOH solutions.	Reduces activation of cellulose and lignin OH groups present in the sisal fiber. Increases the compatibility with the polymer matrices. This treatment also reduces the hydroxyl groups present in the flax fibers and reduces the hydrophilic nature.	Improve hydrophobicity by applying the reaction: 
Alkali	Agave, pine, and coir fibers: 2% NaOH for 15 min Sugar palm fiber: 18% NaOH for 30 min Kenaf fiber:2, 5, and 10 wt% NaOH for 1 h	The uniform fiber distribution and morphology were observed without gaps and voids between the matrix and fiber. The fiber color was changed from black to dark brown, and the fiber diameter was reduced. Formation of glycoside bond and hemicellulose removal due to alkali treatment.	Improve fiber-matrix adhesion, heat resistivity, and thermal stability, and reduce the lignin content. Reaction: $Fiber - OH + NaOH \rightarrow Fiber - O^- Na^+ + H_2O$

Table 6. *Cont.*

Treatment	Example	Specific Effect	General Effect
Acetylation	Jute fibers	Treated fibers show optimum tensile properties and provide effective surface area.	Improve flexural and tensile strength by introducing acetyl groups, as shown by the following reaction: 

This table outlines the impact of different chemical treatments on natural fiber properties, offering insights into their enhancement for specific applications. Treatments include sodium chlorite bleaching, silane treatment, plasma treatment, peroxide treatment, ozone treatment, mercerization, isocyanate treatment, grafting, enzyme treatment, benzoylation, alkali treatment, and acetylation. This table presents the chemical reactions associated with diverse chemical treatments applied to natural fibers, elucidating how treatments influence fiber properties and performance. These treatments contribute to shaping the compatibility and characteristics of natural fiber-based materials for various applications.

A thorough overview of natural fiber extraction, characterization, and processing is given in References [16,21–27]. Vinoth et al. [28] reported in detail the chemical treatments and mechanical characterization of natural fiber-reinforced composites. Pankaj et al. [29] provided a critical review of the chemical treatment of natural fibers to enhance the mechanical properties of composites. Sathishkumar et al. [30] reviewed the characterization of natural fiber and composites in detail.

2.3. Natural Fibers Composites Manufacture, Consumption Pattern and Importance

2.3.1. Classification

In general, natural fiber composites can be categorized as partially environmentally friendly or green, depending on the nature of the ingredients. Green composites are those whose components are all sourced from renewable resources, potentially lowering their dependence on petroleum-derived materials and their carbon dioxide emissions. Partially eco-friendly products are those whose fiber or matrix is derived from non-renewable sources [8]. Natural fiber reinforcement can be divided according to length, dimension, and orientation, as shown in Figure 4. This figure provides an illustration of this classification, indicating the different types of natural fiber reinforcement that can be employed to enhance composite materials. This classification is crucial as it guides the choice of fibers to match the intended application and desired mechanical properties.

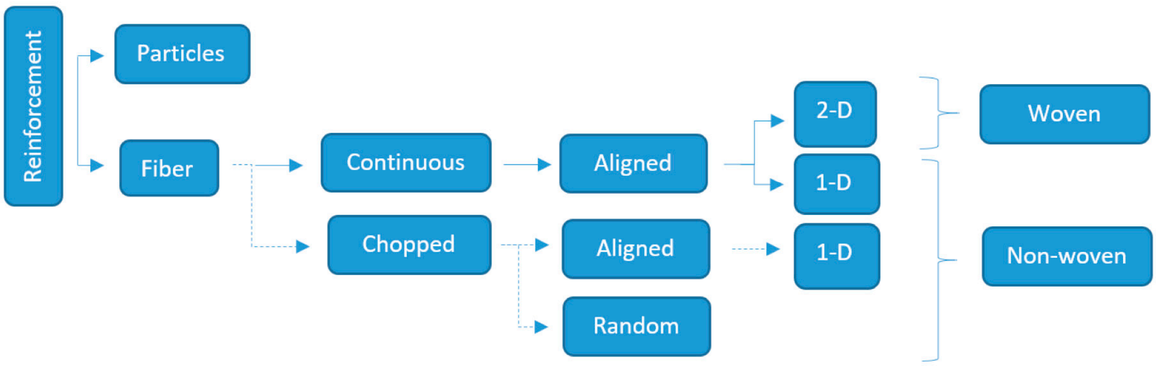


Figure 4. Type of natural fiber reinforcement [8].

Using international ISO standards, transparent conformity evaluations can be performed for commercial and research objectives to accurately label a specific polymeric resin as (a) biobased (ISO 16620:2015), (b) biodegradable (ISO 14852:2018), and (c) compostable (ISO 17088:2012) [8].

- ➢ Biobased (ISO 16620:2015): This label is applied to materials derived from renewable resources, emphasizing their reduced reliance on fossil fuels and their potential positive impact on carbon emissions.
- ➢ Biodegradable (ISO 14852:2018): Composites falling under this category possess the ability to break down naturally through biological processes, minimizing waste accumulation and environmental burden.
- ➢ Compostable (ISO 17088:2012): Materials classified as compostable undergo degradation under specific conditions, ultimately leading to the generation of compost, contributing to sustainable waste management.

2.3.2. Plant Fiber Composites with Polymers

Lignocellulose natural fibers come in a range of lengths and shapes that can be reinforced with polymer matrices, including long fibers, short fibers, woven mats, unidirectional woven fibers, bidirectional woven fibers, and random orientations woven fibers. Natural fiber composites have been produced using a number of fabrication techniques, and in recent years, numerous ways have been developed to address production difficulties.

A pivotal aspect of comprehending the landscape of natural fiber composites is the classification scheme for natural fiber composite polymers (NFCP). This schema, as graphically depicted in Figure 5, serves as a compass to navigate the vast expanse of natural fiber-polymer composites. It segments NFCPs into distinct categories: thermosetting, thermoplastic, rubber, and natural polymers. This classification not only aids in categorizing these composites but also informs the selection of appropriate materials and processing techniques based on the intended application and desired properties.

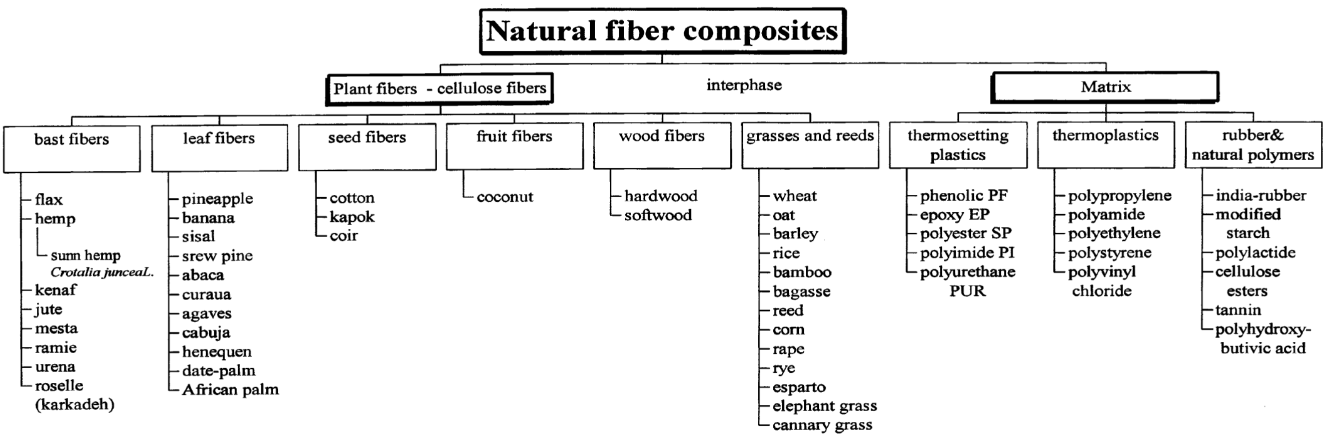


Figure 5. Natural fiber-polymer composites classification [5] (reproduced after permission).

In the orchestration of the manufacturing process, the selection of an optimal technique emerges as a crucial consideration. This selection hinges on a multi-dimensional evaluation encompassing the type of fiber employed, the nature of the matrix material, the desired quality benchmarks, the complexity of the component, the capacity of production, and the cost implications. This intricate balance of factors guides manufacturers toward the most suitable methodology, ensuring the harmonious amalgamation of fibers and polymers to yield robust and functional composites.

The role of polymers in this symbiotic relationship is of paramount significance. The properties of polymers used in natural fiber composites manifest in various attributes that dictate the behavior and performance of the resultant materials. Table 7 stands as a testament to this, showcasing a range of polymer properties, including density, glass transition temperature, melting temperature, thermal conductivity, tensile strength, tensile modulus, and elongation. This tableau of properties provides insights that guide material selection and formulation, driving the tailoring of composites to meet specific performance objectives.

The selection of an appropriate natural fiber to be combined with a polymer matrix composite (PMC) is influenced by a variety of factors, as depicted in Figure 6. These factors encompass a range of considerations, including the type of fiber, the characteristics of the matrix material, the desired quality of the final product, the complexity of the part being manufactured, the production capacity, and the associated costs. This careful selection process ensures that the resulting composite possesses the desired performance characteristics and is suited for its intended application.

Table 7. Properties of the polymers [3–13].

Polymer	Density (g/cm^3)	Glass Transition Temperature (°C)	Melting Temperature (°C)	Thermal Conductivity (W/m.°C)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation (%)
Polyurethane	0.8–1.4	−63	240	0.022	10–30	0.2–0.3	100–380
Epoxy	1.1–1.4	50–80	177	0.14	35–100	3–6	1–6
Polylactic acid	1.2–1.4	60–65	150–160	1.13	50	3.5	6.5
Polypropylene	0.92	−20	130	0.1–0.2	40	1.9	15–700
Polyethylene	0.93	−78	105–115	0.33–0.51	15	0.8	90–800
Polystyrene (PS)	1.1	100	240	0.03	40	3	1–2.5
Polyvinyl Acetate	1.19	30–45	200	0.31	40	1.7	1.76
Polycarbonates	1.2	147	157	0.19	70	2.6	80–150
Polyvinyl Chloride	1.4	82	160	0.19	51	2.4	50–80
Starch	1.5	20–60	0	0.38	5–9	0.2–0.3	35–100
Polyglycolic acid	1.53	35–40	225–230	0.35	70	0.3	5.5–6.5

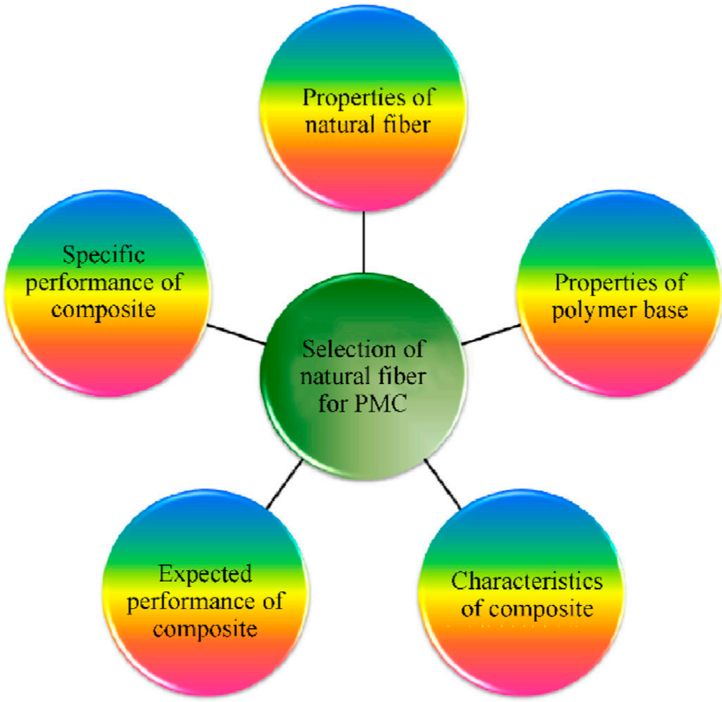


Figure 6. Factors affecting the selection of natural fiber for PMC [10].

Figure 6 illustrates the various factors that impact the choice of natural fiber for integration into a PMC. These factors guide the decision-making process, allowing for informed selections that align with the desired composite properties.

Furthermore, the main manufacturing techniques employed for creating natural fiber composites are outlined in Table 8. This table provides a comprehensive overview of the manufacturing methods associated with specific combinations of fibers and matrices. For instance, it highlights that bamboo and abaca fibers are commonly combined with epoxy using resin transfer molding, while bamboo fiber is often paired with polylactic acid through fused deposition modeling. Various other combinations of fibers, matrices, and manufacturing techniques are also detailed in the table, showcasing the diversity of possibilities for creating composite materials with specific properties and applications. These manufacturing techniques play a crucial role in shaping the final form and properties of the composite, catering to a wide array of industrial and functional needs.

Table 8. Manufacturing techniques for natural fiber composites [3–13].

Fiber	Matrix	Manufacturing Method
Bamboo and abaca	Epoxy	Resin transfer molding
Bamboo fiber	Polylactic acid	Fused deposition modeling
Calotropis gigantean and palmyra	Phenol-formaldehyde	Hand-layup
Coir and sugarcane bagasse	Polyurethane	Extrusion
Flax, hemp, and sisal	Polyurethane	Injection molding
Flax/basalt	Epoxy	Vacuum bagging technique
Hemp and wool	Polyester, vinyl ester, and polyurethane	Pultrusion
Jute	Polyester	Hand-layup fabrication technique
Jute	Polyurethane	Injection molding and extrusion
Jute/glass	Epoxy	Hot press compression molding
Kenaf	Polyester	Vacuum bag resin transfer molding
Glass and kenaf	Epoxy	Filament winding process
Neem, glass, and kenaf	Epoxy	Vacuum-assisted compression molding
Palm leaf stalk, glass, and jute	Polyester	Compression molding
Pineapple	Epoxy	Hand-layup
Sisal and Grewia optiva	Polylactic acid	Hot compression
Sisal/red mud	Polyester	Compression molding
Soybean hull fiber	Thermoplastic copolyester	Fused filament fabrication
Wood fiber	Polyhydroxyalkanoate and polylactic acid	Fused deposition modeling
Wood flour	High-density polyethylene	Extrusion

The diagrams presented in Figures 7 and 8 illustrate the consumption patterns associated with the integration of natural fibers into polymer composites. These figures provide insights into the utilization of natural fibers within polymer-based composite materials. Figure 7 showcases the distribution of natural fibers used in conjunction with polymers in composite applications, highlighting the varying proportions and types of fibers incorporated. This depiction offers a visual representation of the relative prevalence of different natural fibers within the realm of polymer composites, providing valuable information about their usage trends.

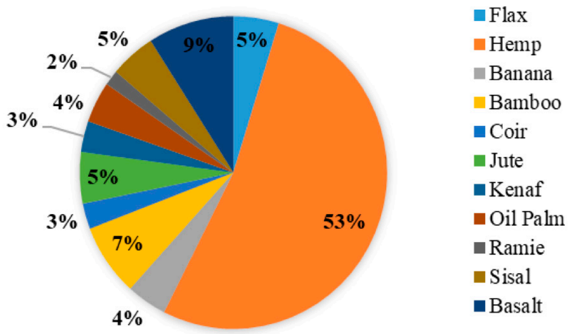


Figure 7. Consumption pattern of natural fibers used in composites with polymers. Adopted from Reference [31].

On the other hand, Figure 8 focuses on the consumption pattern of thermoplastics in the context of composites that incorporate natural fibers. This figure presents an overview of how different thermoplastic materials are employed alongside natural fibers to create composite structures. By illustrating the proportions and preferences for specific thermoplastic matrices, this figure enhances our understanding of the interplay between polymers and natural fibers in composite fabrication.

Collectively, Figures 7 and 8 contribute to a comprehensive understanding of the dynamics and trends in the usage of natural fibers and thermoplastics within the field of composite materials. These visual representations serve as valuable tools for researchers, practitioners, and stakeholders in assessing the evolving landscape of polymer composites and their integration with natural fibers. The figures offer insights into the relative significance of different materials, aiding in the strategic design and development of composite materials with enhanced properties and performance. The adoption of these figures from Reference [31] underscores the significance of this work in the broader context of research and development within the domain of natural fiber-polymer composites.

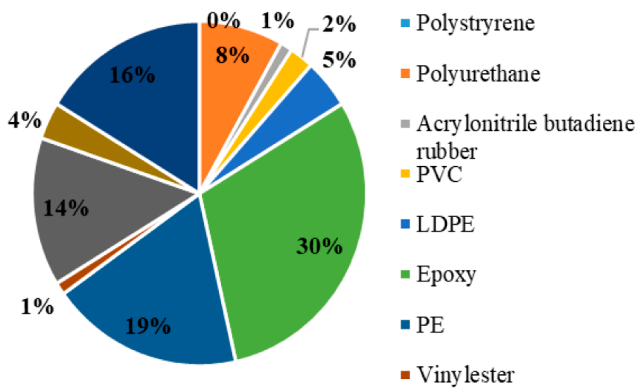


Figure 8. Consumption pattern of thermoplastics used in composites with natural fibers. Adopted from Reference [31].

The wide-ranging applications of natural fiber composites with polymers (NFCP) span across various industries, with a significant focus on the automotive sector. These applications are comprehensively outlined and categorized in Tables 9 and 10.

Table 9. Applications of natural fibers composites with polymers in the automotive industry [8].

Natural Fibers	Component Description	Other Constituents
Bast fibers (flax, sisal, kenaf, hemp, jute, etc.)	Carrier for soft amuses and hard, headliners, seat back panels, sear deck trays, door fosters, center consoles, side and back walls, seat backs, pillars, load floor, and trunk trim. Carrier for covered door panels, covered inserts, covered instrument panel components, and carrier for covered inserts	Polypropylene (PP) and polyester
Coconut	Seat bachnest /surfaces, headrests, interior trim, back rests, seat cushioning, and seat bottoms	Natural rubber
Cotton	Insulation, soundproofing a trunk panel	PP/PEY
Fiberwood recycled	Plastic container and seat back panel	PP granules, thermoplastic
Flax	Pillar panels, floor trays, rear parcel shelves, seatbacks, control consoles, covers, floor panels, and additional interior trim	Mat with PP (floor panels)
Flax or hemp	Carrier for door panels with coverings	Epoxy resin
Flax/sisal	Door frames, interior door linings, and door panels	Thermoset resin
Kenaf	Internal door panel	PP
Wood	Fiber in the seat back cushion, carriers for covered door panels, foamed instrument panels, covered inserts and components, spare tire, covered seat back panels, covered inserts, and covers	Acrylic fibers and synthetic fiber
Wood flour	Carrier for covered door panels, carrier for covered inserts, and carrier for armrest	PP or polyolefin (POE)

Table 9 presents a detailed overview of the utilization of natural fiber composites with polymers in the automotive industry, referencing an open-access source [8]. Within this table, different types of natural fibers, including bast fibers like flax, social, kenaf, hemp, and jute, find use in diverse automotive components. These fibers serve as carriers for both soft and hard materials, contributing to headliners, seat back panels, door fosters, center consoles, side and back walls, seat backs, pillars, load floors, and trunk trims. Additionally, they are employed for covered door panels, inserts, instrument panel components, and other applications. The incorporation of natural fibers is often paired with materials like polypropylene (PP) and polyester to achieve desired properties. Coconut fibers, on the other hand, are employed in areas such as seat backrests, headrests, interior trim, seat cushioning, and seat bottoms, often used alongside natural rubber. Cotton fibers contribute to insulation and soundproofing, often paired with PP/PEY materials. The versatile application of natural fiber composites is also evident in the use of recycled fiberwood, flex, and hemp, each catering to specific automotive components and enhancing their performance. These examples showcase the effectiveness of combining natural fibers with different polymer matrices to achieve desirable properties for diverse automotive applications.

Table 10. Other applications of NFC [3–13].

Sector	Parts Made of NFC	Materials
	Door panel	Bamboo mat composite
	Roof	Jute coir composite
	Wardrobes	Natural fiber-reinforced boards
	Bicycle frame	Flax fiber composite
	Table	Oil palm-based biocomposite
	Container for perfume	Curaua fiber wood flour-based composites
Acoustic	Acoustic absorber	Cotton fiber-rubber granulate composites
Building materials	Panel	Sisal jute sandwich composites
Furniture	Chair	Coir fiber polyester composite
Packaging	Food packaging	Wood fibers with polylactic acid
Sport	Tennis racket	hemp epoxy composite and flax

Table 10 further expands the horizons of NFCP applications beyond the automotive sector. Various sectors benefit from the integration of natural fiber composites. These applications include components like door panels made from bamboo mat composites, roofs incorporating jute coir composites, wardrobes reinforced with natural fibers, bicycle frames using flax fiber composites, tables featuring oil palm-based biocomposites, containers for perfume utilizing Curaua fiber wood flour composites, and acoustic absorbers composed of cotton fiber-rubber granulate composites. The utility of NFCP extends to building materials like panels constructed from sisal jute sandwich composites, furniture items such as chairs composed of coir fiber-polyester composites, and even sport-related products like tennis rackets made from hemp epoxy composites and flax. This array of applications highlights the versatility and broad potential of natural fiber composites with polymers across diverse industries.

In summary, Tables 9 and 10 provide a comprehensive overview of the multifaceted applications of NFCP in both the automotive industry and other sectors. These tables serve as valuable references, illustrating the diverse ways in which natural fiber composites are harnessed in combination with polymer matrices to create functional and performance-enhanced products across a wide range of applications.

Figure 9 graphically represents the distribution of different application categories for natural fiber composites with polymers. The data presented in this figure is derived from a referenced source [31], emphasizing the open accessibility of the information used for analysis.

This figure provides a visual representation of the allocation of natural fiber composite applications across various categories. It serves as a useful reference to understand the prevalence and significance of these composites in different sectors. By presenting this information in a graphical format, the figure enhances the comprehension of how natural fiber composites are contributing to diverse industries and applications.

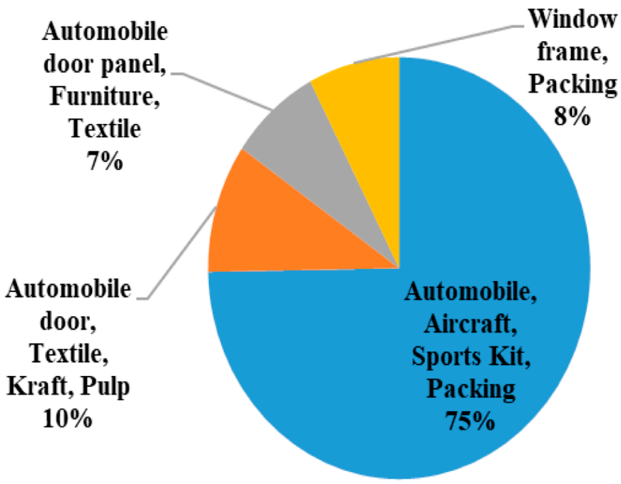


Figure 9. Different application categories in %. Adopted from Reference [31].

A detailed review of natural fiber composite materials in automotive applications was given by Naik et al. [32]. Other important applications include fire retardant materials [33], ballistic applications [34], food packaging [35], etc.

There are numerous published works dealing with natural fiber composites with polymers (NFCP). Sinha et al. [36] examined the abaca fiber-reinforced polymer composites in detail. The review in Reference [37] describes several banana fiber extraction techniques, fiber's biochemical and mechanical characteristics, and applications. Badanayak et al. [38] also reviewed banana pseudostem fiber extraction, characterization, and surface modification. Mousavi et al. [39] deals with the mechanical properties of bamboo fiber-reinforced polymer composites.

Hasan et al. [40] conducted a state-of-the-art review on coir fiber-reinforced biocomposites. Wankhede et al. [41] reviewed the cotton fiber-reinforced polymer composites and their applications. Li et al. [42] reported the recent progress in flax fiber-based functional composites. Yan et al. [43] also reviewed the flax fiber and its composites. Dahal et al. [44] reported in detail the mechanical, thermal, and acoustic properties of hemp and biocomposite materials. Sepe et al. [45] reported in full detail the influence of chemical treatments on the mechanical properties of hemp fiber-reinforced composites. The work of Palanikumar et al. [46] deals with the targeted pre-treatment of hemp fibers and the effect on the mechanical properties of polymer composites.

Pokharel et al. [47] thoroughly reviewed biobased polymer composites. Shahinur et al. [48] reported the current development and future perspective on natural jute fibers and their biocomposites. Devarajan et al. [49] examined in detail the additive manufacturing of jute fiber-reinforced polymer composites.

The mechanical and thermal properties of pineapple leaf fiber (PALF) reinforced composite were the subject of the review conducted by Joshi and Patel [50]. Sahu and Gupta [51] reviewed the sisal fiber and its polymer-based composites. Imraan et al. [52] reported on the properties of sugar palm (arenga pinnata) fibers.

The flexural properties of wood-polymer composites were examined in detail by Jian et al. [53]. Ahmad et al. [54] provided detailed information on the construction applications and life cycle sustainability of natural fiber biocomposites. Rabbi et al. [55] reviewed the injection-molded natural fiber-reinforced polymer composites in detail. Other interesting reviews can be found in References [56–59]. The reader interested in further reading also has to resort to standard books in the area [60–63].

2.3.3. Plant Fiber-Mineral Composites

The inorganic-bonded wood composites, which have a lengthy history, are another significant class. They fall into the following categories [5]:

- Gypsum-bonded composites;
- Cement-bonded composites (made of Portland and magnesia cement);
- Mineral adhesive bonded composites (made of sodium glass and lime);
- Organic resin-bonded composites made up of mineral particles and lignocellulosic;
- Gypsum boards covered in paper and other lignocellulosic materials.

The building materials known as cement-bound lignocellulosic composites can be used both inside and outside. After a particular application of fungicides to THE lignocellulosic material, they can be made more rot-resistant and more fire-resistant. They also have excellent sound-dampening qualities. Asbestos is typically replaced by lignocellulosic fibers in construction. Its use includes asbestos-cement boards, which were formerly often used for roofing. Asbestos can be replaced with paper scraps and short fibers [5].

Gypsum-bonded composites can be made using lignocellulosic waste, wood waste, and gypsum [64]. Although widely used in the building sector, gypsum-bonded composites are not water-resistant [5].

Investigations were conducted into the impact of cement hydration on the resilience of natural fiber-reinforced cement composites and the degradation of the embedded natural fibers [65]. The utilization of coir fibers as reinforcement materials for polymer and cementitious composites was investigated in this work. On the microstructure and mechanical characteristics of coir fiber, coir fiber reinforced epoxy (CFRE), and coir fiber reinforced cementitious (CFRC) composites, the effects of fiber treatment were examined by Yan et al. [66].

The recent advancements in cellulosic fiber fabric-reinforced cementitious (FRC), fabric-reinforced geopolymer (FRG), and cellulosic fabric-reinforced polymer (FRP) composites as reinforcement for concrete, masonry, and wood structures for civil engineering applications are summarized in the review of Yan et al. [67].

The geopolymer matrix can also be reinforced with natural fibers like bamboo, flax, hemp, and jute, which has additional advantages like better tensile and flexural strength, lower density, and improved thermal and acoustic insulation qualities. In order to better understand the raw materials and manufacturing processes used to create compact and porous geopolymer materials, the review paper by Moujoud et al. [68] examined them. de Lima et al. [69] examined the potential of using Amazon natural fibers to reinforce cementitious composites.

Ahmad et al. [70] provided a comprehensive overview of the mechanical and physical properties of concrete reinforced with sisal fibers (SSF). A detailed review of coir fiber and coir fiber-reinforced cement-based composite materials from 2000 to 2021 was performed by Wang et al. [71].

Shah et al. examined the chemical modification using sodium hydroxide (NaOH) in detail and its effect on the mechanical properties of sisal, coir, and hemp fiber-reinforced concrete composites [72]. Abbas et al. [73] reviewed the Kenaf fiber-reinforced cementitious composites. Marvila et al. [74] examined the utilization of natural vegetable fibers in cementitious composites. Martinelli et al. [75] examined the use of coconut fiber in cement composites.

Lv et al. [76] reviewed the alkaline degradation of plant fiber reinforcements in geopolymers. They also examined the properties of 3D printing fiber-reinforced geopolymers [77] and the mechanical properties of plant fiber-reinforced geopolymers [78].

Labib [79] and Hasan et al. [80] investigated in detail the applications of plant fibers in composites with cement. Finally, Li et al. [81] examined the treatment methods for plant fibers for use as reinforcement in cement-based materials.

2.3.4. Hybrid Cellulosic Composites

Hybrid composites are defined as materials that consist of two or more types of fibers embedded in a single matrix. Natural/glass fiber-reinforced polymer composites have been undergoing development to expand their engineering and technological uses. The study by Sanjay and Yogesha [82] focuses on recent advancements in hand-lay-up and compression-molded natural fiber-reinforced polymer hybrid composites. The goal of this study was to comprehend a summary of the findings related to the use of natural fiber in composites made of glass fiber-reinforced polymers [82].

There are two evaluations that go into deeper detail about the natural fiber hybrids that are currently available: Jawaid and Abdul Khalil [83] and Nunna et al. [84]. The decrease in moisture absorption and limiting the variability in characteristics are two themes that appear frequently in many of these works. All natural fibers are prone to absorbing moisture, which results in swelling problems and changes to their mechanical qualities. Normal moisture absorption increases strength and failure strain while decreasing the modulus. Malik et al. [85] provided a detailed review of the physical and mechanical properties of kenaf/flax hybrid composites. Nurazzi et al. [86] reviewed in detail the mechanical performance of hybrid natural fiber polymer composites for structural applications. Suriani et al. [87] thoroughly examined the natural fiber-reinforced hybrid composites in terms of their processing, properties, applications, and cost. Neto et al. [88] reported the thermal characterization of these fibers in detail.

The reader interested in specific applications of natural fiber hybrid composites, such as aerospace applications or their properties, has to resort to References [89–92].

3. Animal (Protein Base) Fibers and Composites

3.1. Origin, Classification, and Physical Properties of Animal Fibers

Animal fibers, also known as protein fibers, are largely used in the textile industry. These are the second most widely used fibers after plant-based fibers. They are generated from alpacas, silk, sheep, cashmere, chickens, and ducks [93–99]. Animal fibers are typically employed as particles or chopped fibers when creating biocomposites. The protein fibers have remarkable qualities like built-in thermal stability and fire resistance. However, because protein fibers are more expensive than plant fibers, animal fibers are not frequently employed in the commercial production of naturally reinforced fiber composites NFRCs [93]. Table 11 provides a comprehensive overview of natural fibers sourced from animals, elucidating their distinct properties and applications. These fibers, originating from diverse animals such as silkworms, yaks, and llamas, exhibit a wide range of qualities, including warmth, softness, tensile strength, and elasticity. These attributes are instrumental in determining the suitability of fibers for various applications across industries, particularly in textiles and materials. The table underscores the versatility and unique characteristics of animal-derived fibers, shedding light on their potential contributions to the realm of natural reinforced fiber composites.

In addition to acting as guardians for cells, organisms, and tissues, animal fibers are protein-rich and contribute to qualities like elasticity, stability, and scaffolding. The type and order of the polypeptide chain made up of amino acids determines how these fibers behave. Animal fibers include a significant amount of keratin, which has a complicated structure and an uneven chemical composition. The three primary components of mammalian fiber are the cortex, cuticle, and medulla. The cortex builds the bulk of the main fiber and determines its mechanical qualities. The cuticle serves as a protective outer layer and prevents water from penetrating the fiber with its wax coating. The medulla degeneration results in lesser fiber strength and lower quality. Due to their chemical makeup, animal fibers interact well with polymer matrices and increase tolerance to alkaline environments [14].

Moreover, animal fibers are superior to plant fibers at absorbing moisture. Animal fibers, including silk, wool, fur, and feathers, come in second place among all the natural fiber sources for composite reinforcing because of their broad availability and lack of toxicity. Also, animal fibers are eco-friendly biodegradable composites that provide a technique to get rid of huge volumes of solid waste. Many varieties of animal fiber, including wool, have their beginnings in sheep, alpacas, bison, cashmere, muskox, and other species. Several publications claim that silk, fur, and feathers are typical choices. Chicken feathers are wastes that are used for the reinforcement of fibers. However, wool is routinely used in the textile industry for various purposes [93].

Table 11. Properties of natural fibers derived from animals [93].

Fiber	Properties	Diameter (μm)	Tensile Strength (MPa)	Elongation at Break (in μm)	Young Modulus (GPa)	Density (g/cm^3)
Wool	Warmth	16–40	120–174	25–35	2.3–3.4	–
Mulberry silkworm fiber	White-tined and more reproducible	10	208.45	19.55	6.10	1.33
Eild (Tussah) silkworm fiber	Beige to brownish-tined	25	165.27	20.57	3.82	1.32
Twisted B. mori silk		10	248.77	33.48	5.79	–
Catgut fiber		790	100	–		
Yak fiber	Warmth, odor-resistant softness, breathability	15–19	270.05	14.53	45.0943	3.42
Bison	Soft and red-brown	59				
Llama	Soft, Fine	30–40				
Qiviut	Smooth, long, 8 times warmer than sheep	15–20				
Camel hair	Warmth, softness,	20.04	212.15	37.05	3.87	–
Spider silk	Smooth fabric finish with high shine	10–13	875–972	17–18	11–13	–
Angora wool	Thin fibers, softness	12–16				
Alpaca	Luxurious, fine, lightweight, soft, glossy	12–29	53.5	42.3		1.38

Wool, sourced from sheep's fleece, boasts a distinct structure consisting of a cortex and a protective cuticle layer. This intricate arrangement makes it one of the most complex textile fibers, as illustrated in Figure 10. The exceptional properties and versatile applications of wool highlight the significance of animal fibers and composite materials in various industries.

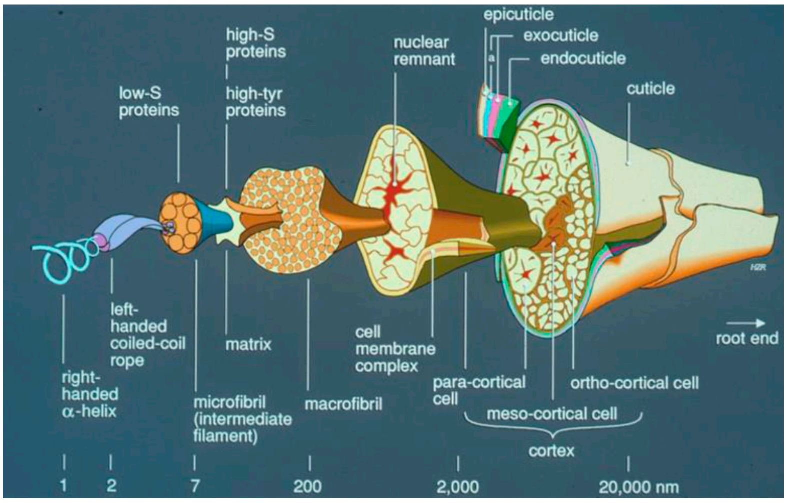


Figure 10. Schematic representation of wool fiber structure [96].

The structural composition of wool fibers is intricate, consisting of distinct components, each comprised of unique morphological elements. Within the cortex, one finds the cell membrane complex and cortical cells collectively responsible for mechanical behavior. The cortex, exhibiting bilateral symmetry, plays a vital role in housing the mechanical attributes of wool, such as elasticity, ductility, and swelling characteristics. On the other hand, cuticle cells possess a specialized surface structure that secures the fiber within the sheep's skin. Notably, wool fibers exhibit a markedly different surface compared to conventional man-made fibers, featuring a relatively uneven texture [94].

The chemical constitution of wool is succinctly presented in Table 12, shedding light on the amino acid composition of cashmere, wool, and yak fibers. This composition significantly influences the properties and performance of wool in various applications. Likewise, the mechanical properties of wool fibers, outlined in Table 13, provide valuable insights. At 22 °C, wool fibers exhibit distinct behavior under varying conditions. For instance, their breaking stress ranges from 250 to 350 MPa when dry and 100 to 200 MPa when wet, with a corresponding strength loss of approximately 20% in wet conditions. Similarly, the breaking strain, elasticity modulus, recovery at different strains, bending modulus, stretching modulus, torsion modulus, and shear modulus showcase the mechanical response of wool fibers under specific conditions. These properties underscore the versatile and unique attributes of wool fibers, highlighting their significance in various industrial and composite applications [93].

Table 12. Amino acid composition of cashmere, wool, and yak fibers [93].

Amino Acid (mol %)	Cashmere	Wool	Yak
Glutamine + glutamic acid	12.4	12.1	12.5
Serine	12.2	10.2	10
Glycine	9.9	8.1	9.8
Leucine	7.5	6.9	8.3
Arginine	7	7.2	7.1
Proline	6.7	7.5	6.6
Threonine	6.6	6.5	6.6
Asparagine + aspartic acid	6.2	6	6.7
Cystine	6	11.2	6.4
Alamine	5.8	5	5.6
Valine	5.5	5.1	5.9
Tyrosine	3.5	4.2	3.4
Isoleucine	3.2	2.8	3.5
Phenylalanine	2.8	2.5	3
Lysine	2.8	2.3	3
Histidine	1.2	0.7	1
Methionine	0.5	0.5	0.5
Tryptophan	–	1.2	–

Table 13. Mechanical properties of wool fiber at 22 °C [93].

Property	Condition	Value
Breaking stress	Dry	250–350 MPa
	Wet	100–200 MPa
	Strength loss when wet	20%
Breaking strain	Dry	28–48%
	Wet	40–61%
Elasticity modulus	Dry	4.0–5.0 GPa
	Wet	2.0–3.0 GPa
Recovery at strain	2%	95–99%
	5%	60–70%
	10%	40–50%
	Bending modulus	4.0–5.5 GPa
	Stretching modulus	5.0–6.0 GPa
	Torsion modulus parallel	1.1–1.3 GPa
	Stretching modulus in torsion	3.0–4.0 GPa
Shear modulus in torsion	Dry	1.2 GPa
	Wet	0.1 GPa

Due to its unique blend of attributes and cost, natural silk is a desirable raw material. It has excellent levels of chemical resistance, elongation at break, and breaking strength and is composed of well-organized proteins. Silk has a wide range of qualities because it is produced by several sources. Bombyx mori silkworms are the principal producers of natural silk. Spider silk, made from the fibroins produced by spiders (such as the Nephila spider), comes in second place.

Table 14 offers a breakdown of the amino acid composition in two key components of Bombyx mori silk: fibroin and sericin. These amino acids are the fundamental building blocks of proteins, which form the structural foundation of silk fibers. Glycine is the most abundant amino acid in fibroin, comprising around 42.75% of the total. This high glycine content contributes to the silk's remarkable flexibility and tensile strength. Sericin, which surrounds fibroin, has a different amino acid profile, including higher amounts of serine and aspartic acid. This diversity in amino acid composition influences the overall properties of the silk, including its elasticity, strength, and affinity for moisture.

Table 14. Amino acid composition of sericin and fibroin in natural silk *Bombix mori* [97].

Amino Acids	Fibroin (%)	Sericin (%)
Glycine	42.75 ± 2.75	11.0 ± 3.0
Alanine	25.0 ± 9.0	4.0 ± 1.0
Serine	13.0 ± 3.0	29.0 ± 8.0
Tyrosine	9.0 ± 4.0	4.25 ± 1.75
Valin	3.0 ± 1.0	3.5 ± 0.5
Aspartic acid	1.9 ± 0.9	15.75 ± 1.75
Glutamic acid	1.35 ± 0.35	4.75 ± 1.25
Threonine	1.45 ± 0.45	8.25 ± 1.75
Arginine	0.9 ± 0.6	4.75 ± 1.25
Lysine	0.9 ± 0.6	3.25 ± 0.75

Table 15 outlines a comparison between two types of silk: Nephila dragline silk and mulberry silk. One key aspect highlighted is the degree of crystallinity, which indicates the extent of molecular order within the silk fibers. Nephila silk has a lower degree of crystallinity (20–45%) compared to mulberry silk (38–66%). This difference influences the mechanical properties of the silk, such as its tensile strength and flexibility. The density of mulberry silk falls between 1.35 and 1.42 g/cm^3, indicating its lightweight nature. Maximum application temperatures and thermal degradation points also provide insights into the silk's heat resistance and stability. The data emphasize how the silk's origin and composition affect its characteristics and suitability for different applications.

Table 15. Properties of Nephila dragline silk and mulberry [93].

Property	Bombyx Mori	Nephila Dragline
Degree of crystallinity in %	38–66	20–45
Density in g/cm^3	1.35–1.42	
Crystallite size in nm	1.0–2.5	$4.7 \times 5.3 \times 6.0$
Index of refraction	1.591 parallel to fiber	1.538 perpendicular to the fiber
Maximum application temperature, °C	170	150
Thermal degradation, °C	250	234
Heat capacity, J/g K	1.38	
Glass transition temperature	178 °C at 0% RH	39 °C at 75% RH
Supercontraction in water	No	~50%

Table 16 presents a comparative analysis of the mechanical properties of various materials, including rubber, nylon, silk, and high-strength steel. One crucial parameter is elongation at break, indicating how much a material can stretch before breaking. Rubber exhibits impressive elasticity, stretching up to 600% at the break, while silk shows an elongation of 18%. Breaking strength, another crucial aspect, showcases the material's ability to withstand stress. Silk demonstrates a significant breaking strength of 1500 MPa, indicating its robustness. Comparing these values with those of other materials like high-strength steel, which has much higher breaking strength but limited elongation, provides valuable insights into how different materials can be selected for diverse applications based on their mechanical performance.

Table 16. Mechanical properties of various polymers, silk, and steel [97].

Material	Elongation at Break. %	Breaking Strength, MPa	Fracture Toughness, J/m^3
Rubber	600	100	100
Artificial web	35	4000	160
Nylon	20	3000	80
Silk	18	1500	70
Revlar	5	4000	50
High-strength steel	1	5500	6

By examining these tables in detail, researchers and engineers gain a comprehensive understanding of the molecular composition, physical characteristics, and mechanical behavior of various natural fibers, helping them make informed decisions when designing and using these materials in a wide range of applications.

The center shaft and the vanes make up most of a feather. The rachis and calamus are the two components of the shaft. The medulla is a hollow tube-shaped cortex that is filled with honeycomb-structured foam. Interconnected hooks from the barbules, which make up the vanes, create them. Similar to this, the barbules' connection to the central shaft creates the barb, which connects to the vanes' characteristics and prevents them from collapsing. The structure resembles hooklets, which improves the bulking.

Feathers from chickens have hollow interiors. They can effectively adsorb heavy metals such as strontium, lead, mercury, copper, chromium, uranium, nickel, and cesium thanks to internal holes. When the phenolic content, temperature, and pH rise, so do the adsorption characteristics of feathers. Moreover, the properties of being hydrophilic, hydrophobic, and hygroscopic aid in adsorption and biosorption.

A chicken feather's typical length is 135 mm, and its aspect ratio ranges from 400 to 2200. The diameter of a feather is between 5 and 6 μm, making it the smallest available natural fiber. The fiber weight has a higher surface area due to its small diameter and high aspect ratio, which make it suitable for lightweight applications. The chemical makeup of several avian feathers, including those of ducks, pigeons, and chickens, has been documented. Chicken feathers include 82–91% protein (keratin), 1% lipids, and 2.2–2.5% crude fiber, while final examination reveals carbon levels of 62–65, nitrogen levels of 16–17, and sulfur levels of 2–3%. The quantities of glutamic acid, aspartic acid, arginine, glycine, proline, alanines, cysteine, valine, serine, leucines, and other amino acids in keratin fiber are 7, 5, 5, 11, 12, 8, 7, 9, 4, 11, and 16%, respectively. Around 60% of the amino acids in chicken feathers are hygroscopic, with the remaining 40% being hydrophilic [97].

3.2. Applications and Importance of Animal Fibers

Because the primary protein in animal fibers is biocompatible, they exhibit cross-linking properties. Two forms of fibers made from animals, silk and wool, are valuable for use in many eco-friendly applications. Also, because hydrogen bonds exist and the protein has a hydrophobic shape, these strands are more stable than spherical proteins. Silk from silkworms is employed in biomedicine to regenerate tissues. The automobile sector can benefit from these renewable fibers because they can be used as reinforcement in composite interior parts for commercial and passenger vehicles. A review providing a summary of recent research initiatives in the area of cement-based composites with sheep wool reinforcing is also available [95].

In order to generate a new type of composites known as "green composites," renewable fibers and polymers (matrix) must be combined. Paulraj et al. [98] reviewed the research on the mechanical properties of natural fiber-reinforced polymer (NFRP) materials.

Silk is utilized as a reinforcing material during the manufacturing of composites such as polyethylene and natural rubber. A paradigm shift in materials science is being brought about by contemporary smart gadgets used in biomedical applications. Silk fibroin films have high permeability to dissolved oxygen when they are wet despite being too delicate to be employed in dry conditions. The mechanical properties of silk fibroin composites are enhanced using polysaccharides. Crystallinity and tensile characteristics are significantly increased by increasing the concentration of silk fibroin composites with chitosan, which were later applied in biomedical applications. Silk is used in tissue engineering as a biomaterial to help with the repair of ligaments, tendons, and bones.

Life has become simpler because of tremendous advancements in electronics and communication technologies. Wireless electronics is one such development, where devices work at gigahertz frequencies while sending and receiving signals in the form of electromagnetic (EM) waves. EM pollution is a result of the increased amount of EM waves in the atmosphere. During operation, "electromagnetic interference" (EMI), which is caused by an increase in the amount of sophisticated circuitry in a constrained space as a result of device shrinking, occurs. As they are viewed as serious dangers to electronics and their functionality, EMI worries are growing. Flexible and lightweight EMI shielding materials are essential to address this problem. Due to their exceptional flexibility, functional textiles are regarded as viable options and are receiving more attention. Jagadeshvaran and Bose [100] reviewed the recent advance of surface engineering in the development of textile-based EMI shields.

The use of neutral aqueous zinc ion batteries (ZIBs) for wearable electronics and grid-level energy storage is incredibly promising. However, the use of ZIBs in actual applications has been constrained by specific component performance flaws. In order to overcome the existing issues in ZIBs, a variety of pure materials and their composites with fiber-based structures have recently been employed to create more effective cathodes, anodes, current collectors, and separators. To achieve diverse electrochemical performances and mechanical flexibility, many functional materials can be produced into various fiber forms that can then be transformed into various yarn structures or interlaced into various 2D and 3D fabric-like constructions. In the review by Jia et al. [101], the ideas and fundamentals behind fiber-based materials for ZIBs as well as the use of various materials, are discussed.

Other important applications of silk-based composites include the remediation of toxic contaminants from wastewater [102] and sensors for humidity and gas sensing [103]. Hardy and Scheibel gave a detailed review of silk protein applications [104]. Finally, the formation of all-silk composites and the time-temperature superposition were reviewed by King et al. [105].

Figure 11 provides an illustrative depiction of the manufacturing process involving chicken feather composites. The process begins with the collection of chicken feathers, which are abundant due to the large-scale poultry industry. These feathers, often considered waste, offer an eco-friendly and sustainable raw material for composite fabrication. The feathers undergo a series of treatment steps, including cleaning and sterilization, to prepare them for integration into composite materials. The cleaned feathers are then processed, possibly involving grinding or cutting to achieve a suitable form for composite incorporation. These feather particles are mixed with a polymer matrix material, which may be a biodegradable polymer, to create the composite mixture. This mixture is then shaped into the desired form, such as sheets or panels, using molding or extrusion techniques. The resulting chicken feather composite products exhibit qualities like robustness, water resistance, and thermal and acoustic insulation, making them suitable for a wide range of applications. The depicted manufacturing process showcases how a seemingly unconventional material like chicken feathers can be transformed into valuable composite materials, contributing to sustainability and resource optimization.

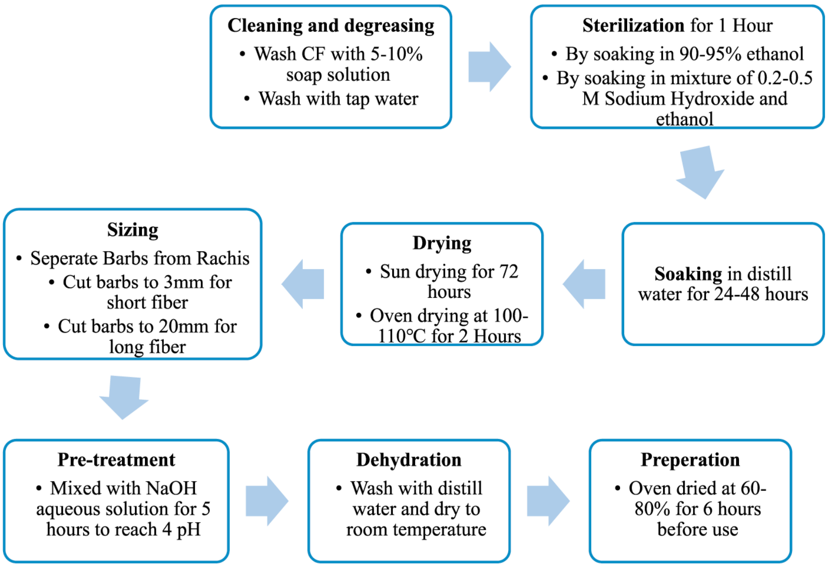


Figure 11. Commonly used chicken feather composite manufacturing process [106] (reproduced after permission).

The findings of the analysis of the thermoplastic films from the characteristics showed that the feather films were robust and water resistant. This might be used to create biomaterials for many biomedical uses. The advantage of feathers is their low relative bulk and superior thermal and acoustic insulation. Figure 11 depicts the handling of feathers [106]. Since billions of chickens are harvested each year, a variety of uses are possible, as can be seen in Table 17. Table 17 outlines the diverse range of potential applications for chicken feather fiber (CFF) composites. These composites, derived from a readily available waste material, hold promise across various sectors. In the architectural and civil domain, CFF composites can find utility in wall panels and roofs, enhancing insulation and structural properties. The transport industry can benefit from their integration into automotive inner insulation parts and aircraft body components, potentially reducing weight and enhancing efficiency. In the biomedical field, CFF composites exhibit potential for hydrogels, scaffolds, and hydrofilms in tissue engineering, as well as orthopedic and dental implants and replacements. In the electrical sector, they can serve as base materials for printed circuit boards (PCBs), electrical insulators, and sensor applications. Thermal applications include flame resistance and thermal insulation, catering to safety and energy-efficiency needs. Filtration applications encompass the removal of heavy metals, phenols, and air filtration mats, addressing environmental concerns. CFF composites also contribute to food packaging as bio-degradable thin films, aligning with sustainability goals. Finally, in fire safety, they can play a role as protective housing parts, smoke retardants, flame retardants, and even carbon monoxide absorbents, enhancing safety standards. The table highlights the versatility of CFF composites and underscores their potential to meet multifaceted industry requirements while offering a sustainable solution to waste management.

The effect of chemical treatments and additives on the properties of chicken feathers thermoplastic biocomposites were reported in full detail by Casadesús et al. [107].

Human hair is strong enough to be used as sutures in the majority of surgical procedures. Research has demonstrated the potential of using human hair sutures in general surgeries on both people and animals, as well as in the treatment of conjunctival wounds and cataracts [93,106]. There is a wealth of information available regarding biomedical devices made from animal fibers [108–117]. Cutting-edge methods for extracting keratin from feathers to create biomaterials were also disclosed [118]. Innovative methods like 3D printing were also used to produce biomaterials [119].

Table 17. Suggested applications of CFF composites [106].

Area of Application	Application Form
Architectural and civil	Wall panels and roofs
Transport industry	Automotive inner insulation parts and aircraft body parts
Biomedical	Hydrogels, scaffolds, and hydrofilms in tissue engineering, orthopedic and dental implants, and replacements
Electrical	PCB base materials, electrical insulators, sensor base materials
Thermal	Flame resistance applications and thermal insulations
Filtration	Removal of heavy metals, phenols, and mats for air filtration
Food packaging	Bio-degradable thin films for foods
Fire safety	protective housing parts, smoke retardant, flame retardant, carbon monoxide absorbent

4. Mineral Fibers: Origin and Applications

Due to their advantages over other fibers, natural mineral fiber composites are widely used in a range of industries. Natural mineral fibers have demonstrated their efficacy in a number of fields, including electronics, aviation, medicine, seafaring, automobiles, and structural components for concrete. Natural mineral fibers could be classified as toxic (e.g., asbestos) and non-toxic [120,121]. The name "asbestos" is used in commerce to describe a group of amphibole minerals and fibrous serpentine with exceptional tensile strength, moderate chemical resistance, and low heat conductivity. The use of asbestos was abandoned since it is carcinogenic [122]. The most often used natural mineral fibers in composites are basalt and wollastonite.

Among all igneous rocks, basalt is the most prevalent; it makes up more than 90% of all volcanic materials. The pace at which molten lava cools has a significant impact on the microstructural components of basalt rock. Basalt microstructure shows a potentially crystalline atomic arrangement when the solidification rate is sluggish, whereas a quicker solidification rate results in an amorphous structure [121].

For the creation of materials for a variety of applications, nature continuously offers a variety of resources. Although many natural textile fibers are fibrous in character, there are other raw materials that can be transformed and turned into a filament in a manner akin to melting and solution spinning of other textile fibers. Igneous basalt is composed of hardened volcanic lava. Basalt has drawn interest as an alternative to asbestos fibers. Basalt has become a contender in the field of composite fiber reinforcing [123].

Basalt fiber (BF) has a low energy need, a low carbon footprint, strong mechanical strength, excellent temperature resistance, good chemical stability, and good temperature stability. The application requirements of electrical equipment, such as new conductors, insulated pull rods, and composite cross-arms, are met by BF-reinforced polymers (BFRPs), which also offer good corrosion resistance and designability. Basalt fiber (BF) can be employed in high high-performance applications and can tolerate very high temperatures.

Table 18 provides insight into the chemical compositions of three types of fibers: basalt, wollastonite, and synthetic e-glass. Basalt fibers are primarily composed of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), which are common minerals found in volcanic rocks. Wollastonite fibers are dominated by calcium oxide (CaO) and silica (SiO_2), making them primarily composed of calcium silicate. In contrast, synthetic e-glass fibers consist of silica (SiO_2) as the major component, along with alumina (Al_2O_3), boron oxide (B_2O_3), and sodium oxide (Na_2O) as additives to improve the glass-forming process.

Tables 19 and 20 compare the thermal and mechanical properties of different fiber types, including basalt, e-glass, s-glass, carbon, and aramid fibers. When we examine the tensile strength and modulus of elasticity, we find that basalt fibers generally exhibit higher values than e-glass fibers. This means that basalt fibers possess a greater ability to resist stretching and deformation under load, making them suitable for applications demanding structural integrity and strength.

Table 18. Chemical composition of e-glass fibers, wollastonite, and basalt [120,121].

Oxides Content (wt. %)	Basalt	Wollastonite	E-Glass
$Na_2O + K_2O$	2.5–6.0	0.364	0.29
MgO	3.5–5.0	0.47	3.3
TiO_2	0.2–3.5	0.49	0.14
Fe_2O_3	7.0–14.0	0.17	0.28
MnO	0.17–0.22	-	N/A
B_2O_3	0.8	-	10.3
ZrO_2	0.0	-	0.8
Al_2O_3	13.3–18.0	0.83	14.3
CaO	8.0–11.0	44.55	19.0
SiO_2	47.5–53.0	50.78	53.4
SO_3	-	0.04	N/A

Table 19. Comparison of properties of fibers commonly used in fiber-reinforced polymer composites [121].

Fiber	Fiber Diameter (μm)	Density (g/cm^3)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Elongation at Break (%)
Basalt	9–23	2.8–3.0	3000–4840	79.3–93.1	3.1
E-glass	9–13	2.5–2.6	3100–3800	72.5–75.5	4.7
S-glass	9–13	2.46–2.5	4590–4830	88–91	5.6
Carbon	4–7.5	1.75–1.9	3500–6000	230–600	1.5–2.0
Aramid	5–18	1.44	2900–3400	70–112	2.8–3.6

Table 20. Thermal stability of different fibers [121].

Fiber	Working Temperature Range, ΔT (°C)	Thermal Conductivity (W m^{-1} K^{-1})	Thermal Expansion Co-Efficient (10^{-6} °C^{-1})
Carbon	−50 to 700	5–185 (axial only)	0.05 (axial only)
E-glass	−50 to 380	0.034–0.040	5.40
S-glass	−50 to 300	0.034–0.040	29.00
Basalt	−260 to 700	0.031–0.038	8.00

In terms of thermal conductivity, basalt fibers have a lower value compared to e-glass fibers. This implies that basalt fibers offer better insulation properties, which is advantageous for applications requiring heat resistance and thermal insulation.

Table 21 outlines the environmental impact comparison between basalt and glass fibers. Basalt fibers typically have a lower energy requirement and carbon footprint during manufacturing compared to e-glass fibers. This lower environmental impact can be attributed to the natural abundance of basaltic minerals and the lower processing temperatures needed for basalt fiber production.

Moreover, the recyclability of basalt fibers contributes to their reduced environmental footprint, aligning with sustainable practices. Recycling basalt fibers can help minimize waste and resource consumption, which is becoming increasingly important in the context of environmental sustainability.

The comprehensive analysis of these tables underscores the potential benefits of basalt fibers over synthetic e-glass fibers. Basalt fibers exhibit superior mechanical properties, including higher tensile strength and modulus of elasticity, which are critical for applications demanding strength and durability. Additionally, the better insulation capabilities of basalt fibers make them attractive for applications involving thermal management. From an environmental perspective, basalt fibers' lower carbon footprint, energy consumption, and recyclability position them as a more sustainable option compared to e-glass fibers.

As industries increasingly prioritize sustainability and eco-friendly practices, the characteristics highlighted in these tables can guide material selection for various applications, considering both performance and environmental considerations.

Table 21. Environmental externalities associated with the production of 1 ton of basalt and glass fiber [121].

Category	Unit	Basalt Fiber	Glass Fiber
Source			
Carcinogens	kg C_2H_3Cl eq	15.2	—
Non-carcinogens	kg C_2H_3Cl eq	12.1	—
Respiratory inorganics	kg PM2.5 eq	0.320	—
Ionizing radiation	Bq C14 eq	2.30×10^3	—
Ozone layer depletion	kg CFC11 eq	35.1×10^{-6}	483×10^{-10}
Respiratory organics	kg C_2H_4 eq	0.175	—
Photochemical oxidant	kg NMVOC	—	5.26
Human toxicity	kg 1.4-DB eg.	—	20.8
Aquatic ecotoxicity	kg TEG water	256×10^3	—
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	—	0.461
Terrestrial ecotoxicity terrestrial	kg TEG soil	57.4×10^3	—
Acidification/nutrification	kg SO_2 eq	6.56	10.3
Land occupation	m^2 organic arable	8.05	—
Aquatic acidification	kg SO_2 eq	1.34	—
Aquatic eutrophication	kg PO_4 P-lim	40.3×10^{-3}	5.25×10^{-3}
Global warming	kg CO_2 eq	398	1740
Non-renewable energy	MJ primary	6630	—
Fossil depletion	kg oil eq	—	578
Mineral extraction	MJ surplus	6.55	—

The use of basalt as reinforcement of a polymer matrix was reviewed by Tao et al. [124]. The chemical, thermal, and additive treatment of the mechanical properties of basalt fiber and their composites was examined in detail by Jain et al. [125]. To transfer stress and improve the composite's mechanical properties, the matrix and BF must adhere to one another. This was the subject of [126]. The characterization of basalt fibers in relation to basalt fiber-reinforced composites was investigated by Yang et al. [127].

Uses of the basalt-reinforced polymer matrix include the strengthening of concrete structures [128]. A comprehensive review of the effects of different simulated environmental conditions and hybridization processes on the mechanical behavior of different FRP bars was given by Mirdarsoltany et al. [129].

Industrial applications of basalt fibers include the oil and gas industry [130], the clean energy sector and power grids [131], the automotive industry [132,133], and ballistic applications [134]. An overview of basalt fiber industrial applications was given in [135]. One of the most important applications of basalt is the construction industry as a composite with cement, geopolymers, etc. A detailed review of basalt composites with other minerals is given in [136–144]. The use of basalt in hybrid composites with carbon particles or nanotubes was examined in [145,146].

Mortar is composed of cement, water, and fine gravel, whereas cement paste is composed of cement and water. Studies on cement slurry or mortar were carried out by replacing sand and/or cement with wollastonite, as given in Table 22.

Wong et al. [147] and Chan et al. [148] reviewed the thermal-flammability and mechanical properties of wollastonite-filled thermoplastic composites. Other important applications of wollastonite composites include the bioengineering [149].

Table 22. Usage and different effects of wollastonite in the cement [120].

Wollastonite Replacement Instead of Cement	Effect of Wollastonite
5–10%	Fracture toughness increases up to 34%.
0–15%	Compressive and flexural strength increases to 12% and 6%, respectively.
0–50%	Cement hydration increases and workability decreases.
5–15%	Ductility and crack growth resistance increase.
10–30%	Drying shrinkage decreases up to 47%, and initial setting time increases.
0–12%	Flexural and compress strengths increase up to 11% and 8%, respectively; water sorptivity coefficient decreases up to 15%; gas permeability and rapid chloride permeability decrease up to 25% and 4%, respectively.
0–25%	Water permeability, carbonation depth, chloride diffusion, and porosity decrease.
0–25% instead of cement	Corrosion resistance enhanced.

5. Natural Fibers and Nanomaterials: Importance and Applications

5.1. Introduction

With its numerous applications, spanning from industrial advancements to influencing our daily lives, nanotechnology has changed the planet. It can be used in a variety of financial sectors and promotes the advancement of research endeavors with significant economic potential. The science of nanotechnology has expanded in new directions thanks to nanomaterials, particularly those that have demonstrated biological and other health-related features. Recently, the scientific community has paid close attention to the use of bioresources in nanotechnology because of its availability, complete environmental friendliness, and affordable price.

Nearly every industry is using nanomaterials. It has a vast array of uses in biological, electrical, and sensing applications. Nanomaterials such as nanoparticles, nanofibers, nanotubes, and polymeric nanocomposites are widely used in these sectors.

Researchers have been drawn to discover innovative techniques to manufacture these nanomaterials in a more efficient and regulated manner, which can further enhance the desired qualities of the material due to the growing use of nanomaterials in various industries.

Natural fibers might be strengthened by adding some elements, like nanomaterials. Nano-bio composites and natural or biofiber-reinforced bio-composites are thought to be superior to traditional composites. Materials in the category of polymer nanocomposites utilize nanoparticles as one of their reinforcements. The category of materials known as "nanofillers" or "nanoparticles" includes all substances with at least one dimension in the nanoscale range (less than 100 nm) [150,151].

The fascinating qualities provided by nanocomposites are a result of the particle size. Based on their size, nano-fillers are often divided into three categories. The first class of nanoparticles are sheet-like particles, such as graphene, which have a thickness of only a few nanometers and a length of 100–1000 nanometers. They fall within the category of multilayer polymer nanocomposites. The second sort of particle has two dimensions: a nanoscale and an elongated third dimension that is a few thousand nanometers long. This category includes nanofibers and nanotubes, such as carbon nanofibers, carbon nanotubes, and halloyte nanotubes [150,151].

The aspect ratio (L/D), indicating the ratio of length to diameter, becomes a pivotal geometric parameter governing the properties of particles within this category. The third category encapsulates nanoparticles wherein all dimensions remain confined within the nanoscale realm. Spherical and cubical nanoparticles like calcite, silica, and alumina exemplify this category. Figure 12 visually encapsulates the different types of nanofillers based on their dimensions, presenting a comprehensive depiction of their classifications. The figure categorizes nanofillers into three distinct classes, each characterized by their dimensional attributes. These categories serve as a fundamental framework for understanding the diverse nature of nanofillers and their applications within nanotechnology [150].

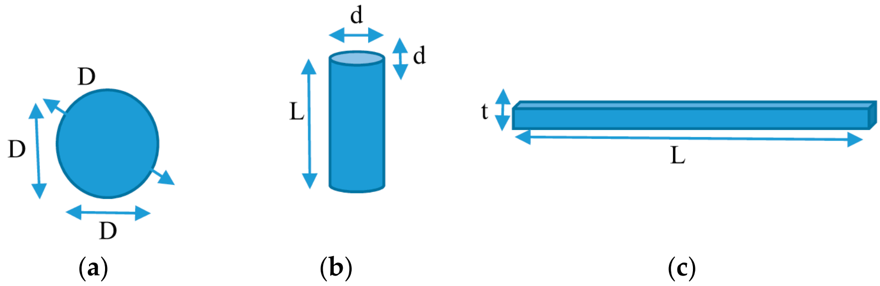


Figure 12. Types of nanofillers according to their dimensions [150] (reproduced after permission). (**a**) 3D, (**b**) 2D, (**c**) 1D.

Table 23 provides an insightful comparison between natural fibers and nanofibers, elucidating their defining characteristics and primary applications. It contrasts the attributes of fibers originating from natural sources with those of nanofibers, showcasing their distinct features and utilization. The table highlights key aspects related to sources, categories, treatments, and applications of both types of fibers, offering a comprehensive understanding of their respective roles and significance.

Table 23. A comparison between nanofiber and natural fibers along with their characterizations and main applications [151].

Natural Fibers	Nanofibers
Definition	
A substrate of natural origin is considered to be a fiber if its length-to-diameter ratio is more than 1:200.	Fibers with nanometric-sized diameters are known as nanofibers.
The main sources	
Compared to fiber composites made of petroleum, natural fiber composites are more environmentally friendly.	Nanofibes are often categorized as metal oxides, polymers, metals, carbon, ceramics, and hybrids, according to their composition.
Main categories of natural fibers	***Main types of nano-lignocellulose fibers***
1–Mineral fibers (asbestos, basalt, and brucite) 2–Animal fibers (hair, silk, and wool) 3–Plant fibers (lignocelluloses)	1–Lignocelluse nanofiber 2–Bacterial nanocellulose 3–Nanocrystalline cellulose 4–Nano-fibrillated cellulose
Main treatments for natural fibers	***Main fabrication techniques of nanofibers***
Chemical (acetylation, alkaline, benzoylation, peroxide, potassium permanganate, silane, and stearic acid) and surface treatments	Hydrothermal, electrospinning, and non-electrospinning methods (such as phase separation drawing, self-assembly, and template synthesis)
The main applications of natural fibers	***The main applications of nanofibers***
Automobile, construction, aerospace, and marine structural industries	Structural applications, 3D printing industry, aerospace, polyurethane matrix, paper, orthopedic, and textile industry

The nanoparticles' vast surface area helps to ensure that they are properly bonded to the matrix. The dispersion of the particles in the matrix is another phenomenon that is crucial to the polymer nanocomposite. Typically, 1 to 10% of the volume of the polymers is filled with nanofillers [150–152].

Due to their abundance and large form factor, nanoclays are the most frequently used category of nanomaterials. Clays are divided into five groups based on their chemical makeup: smectite, chlorite, kaolinite, illite, and halloysite. Nanoclays are layered mineral silicate nanoparticles having layered structural units that, when stacked, can create intricate clay crystallites. There are about 30 different varieties of nanoclays that can be employed for diverse applications, depending on the mineralogical makeup of the nanoclays. Montmorillonite (MMT) clay, also known as smectite, has been the subject of the most research and is the clay that is used most frequently [150,151].

Calcium carbonate, calcium oxide, aluminum dioxide, silicon dioxide (silica), magnesium oxide, tungsten oxide, and zinc oxide are the most often utilized metal nano oxides used as fillers in polymer composites. These metal oxides work more effectively when employed in nano form compared to other sizes. They have been used in a variety of industries, including electronics, optical, pharmaceuticals, cosmetics, and a number of others. Metal oxides are produced using several different synthetic processes. Coprecipitation, microemulsion, thermal breakdown, hydrothermal synthesis, and sonochemical synthesis are the top five methods for making metal oxides.

Agro-waste materials have been harnessed to produce nanofibers with promising applications, contributing to sustainability and resource optimization. In this context, Table 24 compiles notable instances of agro-waste-based nanofiber production, highlighting the versatility and potential of these biodegradable materials across various sectors [152].

Table 24. List of some different agro-wastes that are used in producing nanofibers [151].

S.No.	Nanofibers Obtained from Agro-Wastes and Used Method	Comment on Nanofibers
1.	A starch/ polyvinyl alcohol nanocomposite film reinforced with cellulose nanofiber from sugarcane bagasse was created using alkaline acid treatment and ultrasonication.	Nanocomposite film-reinforced cellulose nanofiber
2.	Using bamboo eaters (Phyllostachus pubescens) as lignocellulosic biomass and producing cellulose nanofiber by microwave-assisted ethanol solvent treatment.	Cellulose nanofibers
3.	Washing the Eucalyptus sawdust with an aqueous surfactant solution will yield lignocellulosic nanofiber.	Bio-nanocomposite films
4.	Waste products from the production of orange juice can be used to create biodegradable films reinforced with cellulose nanofiber.	Nano-nanocomposite films
5.	Combining polyvinylpyrrolidone and polyvinyl alcohol with pomegranate (*Punica granatum* L.) peel extract.	Nanofibers for cosmeceutical purposes
6.	Quinta wastes mixed with multi-walled C-nano tubes and ZnO can be employed to create natural cellulose fibers.	Bio-nanocomposite
7.	The electrospinning process produced cellulose nanofibers made from pomegranate peel ethanolic extract.	Cellulose nanofibers
8.	Pomegranate peel ethanolic extract nanofibers were tested in vitro using the electrospinning process.	Gelatin nanofiber
9.	To create peach branch-cellulose nanofiber, peach branches are employed in a high-pressure homogenous process.	Nanofiber-reinforced gelatin hydrogel
10.	Clysical nanocellulose was produced via hydrolysis disintegration using rice and coconut husks.	Mechanically reinforced polymer composites
11.	Acid hydrolysis was used to create the poly-lactic acid matrix that contains nanocellulose from cotton waste.	Production of nanocellulose
12.	Waste pineapple leaf is used to create cellulose nanofiber, which is then reinforced into a polystyrene substrate.	Cellulose nanofiber-reinforced polystyrene nanocomposites

Sugarcane bagasse, a byproduct of sugarcane processing, was utilized to create cellulose nanofibers that were incorporated into a starch/polyvinyl alcohol nanocomposite film. This approach enhanced the film's mechanical properties, offering a sustainable alternative for biodegradable materials with improved strength.

By employing microwave-assisted ethanol solvent treatment, bamboo eaters' lignocellulosic biomass was converted into cellulose nanofibers. These fibers present unique properties derived from their natural source, showing promise in diverse industries.

Eucalyptus sawdust, often considered waste, was transformed into lignocellulosic nanofibers by washing with an aqueous surfactant solution. The resulting bio-nanocomposite films hold potential in eco-friendly packaging and biodegradable materials.

Waste generated during orange juice production found purpose in the creation of biodegradable films reinforced with cellulose nanofibers. This innovation repurposes waste and simultaneously enhances the mechanical properties of the resulting films.

In the cosmetic and skincare sector, nanofibers with cosmeceutical applications were developed by combining polyvinylpyrrolidone and polyvinyl alcohol with pomegranate peel extract. This aligns with the growing trend of utilizing natural ingredients in personal care products.

Quinoa wastes were repurposed by incorporating them with multi-walled carbon nanotubes and zinc oxide to create natural cellulose fibers. This innovative approach showcases the potential of incorporating agricultural waste into advanced bio-nanocomposites.

Electrospinning techniques were employed to derive cellulose nanofibers from pomegranate peel ethanolic extract. These nanofibers hold promise in wound healing and tissue engineering applications owing to their potential biocompatibility.

Peach branches, through a high-pressure homogenous process, were transformed into natural cellulose fibers that reinforced gelatin hydrogels. This development finds applications in biomedical areas, including tissue engineering and drug delivery.

Hydrolysis disintegration was used to extract crystalline nanocellulose from rice and coconut husks. These nanocellulose materials offer the potential to enhance the mechanical properties of polymer composites, introducing possibilities for eco-friendly materials.

Cotton waste was subjected to acid hydrolysis to create a poly-lactic acid matrix containing nanocellulose. This innovation converts waste into valuable nanocellulose, with prospects for biodegradable materials across various sectors.

Waste pineapple leaves yielded cellulose nanofibers, which were incorporated into polystyrene substrates using a unique process. This resulted in cellulose nanofiber-reinforced polystyrene nanocomposites, showcasing potential in multiple applications.

These instances demonstrate the power of agro-waste integration in nanofiber production, addressing waste management challenges and presenting sustainable alternatives in diverse sectors. Through creative utilization of natural resources, these innovative approaches contribute to the advancement of environmentally friendly materials.

One of the most popular nanofillers for enhancing the performance of polymer composites is carbon-based nanoparticles. The most widely utilized carbon-based nanoparticles include fullerenes, carbon nanotubes, graphene and its numerous derivatives, and graphene oxide. Just trace amounts of naturally occurring carbon-based nanoparticles are known, and the vast majority are created by engineering or synthetic synthesis. Applications for carbon-based nanomaterials include gas storage, manufacturing of conductive materials, and micro- and nanoelectronics.

5.2. Plant Fibers and Nanocomposites

One of the most popular nanomaterials is green nanocomposites. The green nanocomposites have become particularly popular among these nanocomposite materials. These green nanocomposite materials are reasonably priced, lightweight, eco-friendly, and sustainable.

The primary source of the green nanocomposite material is fibers made from various plants [153]. Selecting a good matrix-filler combination and then combining them in the right ratio gives it a highly special ability to modify the properties of the material. It is crucial to use the right synthesis method while creating nanocomposites [153].

On the other hand, plant fibers and sticks mostly consist of cellulose, hemicellulose, and lignin and contain a small amount of ash. Because of this, plants such as jute are now the best source for pure nanocellulose, nanolignin, and nanocarbon preparation. Additionally, it has served as a source in the development of nanomaterials that are used in a variety of applications. Hemicellulose and lignin, which can be extracted from jute fibers and sticks, could also be used as a stabilizer or reductant when creating other nanomaterials [154,155].

Traditional applications of plant fiber nanocomposites include the automotive industry and, in general, the construction sector. Imran and Susan recently reviewed nanocomposite applications in the automotive industry [156]. Balea et al. [157] examined in detail the applications of nanocelluloses for fiber-reinforced cement composites; biodegradable flame retardant materials based on plant fibers nanocomposites were reviewed by Kovačević [158], while Taib et al. [159] reported the recent progress in cellulose-based composites regarding flame retardancy applications. Nanostructured cellulose and its application in the construction industry was the subject of the study by Nasir et al. [160]. Cellulose nanofibers also play an important role in epoxy composites, as reported by Biswas et al. [161]. Another rapidly developing area of plant nanocomposites is the energy storage by phase-changing materials, as reviewed by Shen et al. [162].

One of the most important fields for nanomaterial applications with cellulosic fibers is the textile industry. In particular, as textile materials play a crucial part in the development of human culture, there has been an increase in the quest for novel materials to create smart textiles in order to meet customer expectations and needs. The textile materials' high surface area and moisture-retentive properties also make them ideal growth environments for microorganisms.

Recently, the development of functional smart textiles with self-cleaning, UV protection, insect repellent, waterproof, anti-static, flame resistant, and antimicrobial resistance has greatly benefited from the use of nanoparticles and nanomaterials in the textile industry [163]. A detailed review of the applications of plant fiber nanocomposites in the textile industry is given in [163]

Another important field for the utilization of cellulosic fibers nanocomposites is the biomedical sector. Because they are soluble in both water and common organic solvents, cellulose derivatives are an effective substitute for pure cellulose.

This, along with their affordability, biocompatibility, and biodegradability, makes them a desirable option for use in the biomedical and bioanalytical fields [164]. As films and membranes for osseointegration, hemodialysis and biosensors, smart textile fibers, tissue engineering scaffolds, hydrogels, and nanoparticles for drug delivery, cellulose derivatives-based composites with better characteristics have been extensively studied in the literature [165–169].

Other important applications of cellulosic nanomaterials include fluorescent composites [170], candidate material for 3D printing applications [171], water purification by photocatalysis [172], sustainable packaging systems [173], etc.

The interested reader seeking a detailed review of cellulosic nanomaterials properties and applications has to resort to References [174–179].

5.3. Animal and Mineral Fibers and Nanocomposites

Silk is one of the most promising materials for high-performance nano-composites. Kiseleva et al. [180] and Qin et al. [181] reviewed the recent advance in hybrid spider silk with inorganic nanomaterials for diverse applications. Prakash et al. [182] reported in detail on composites using regenerated silk fibroin loaded with natural additives. Saad et al. [183] examined the sericin biomedical and pharmaceutical applications regarding nanomaterials. Other important biomedical applications of silk fiber or its fibrous derivatives include bone formation by fiber-reinforced calcium phosphate cement [184], formation of high-strength hydrogels [185], tissues for repairing the injured nervous system [186], hard tissue engineering [187], etc. Mechanical properties and application analysis of spider silk bionic material were reviewed by Gu et al. [188].

The distinctive qualities of keratin and sericin-based electrospun nanofibers make them appropriate for a variety of applications in diverse disciplines. These nanofibers are mainly produced by electrospinning, and there are numerous tools commonly utilized to create nanofibers. Sericin and keratin biopolymers' chemistry as well as the processes used to extract them from their respective natural resources, such as wool and natural silk fibers, have come under fire in recent years. In the review by Mowafi et al. [189], it was explained how keratin or sericin might be combined with different natural and synthetic polymeric materials to enhance their rheological characteristics and create an electrospinnable composite that could be used to create a useful nanofibrous mat. Moreover, they examined the addition of bioactive compounds, nanosized metals, and metal oxides to keratin and sericin-based electrospun nanofibers that give them additional activities.

In particular, nanofibers have a lot of potential in the biomedical industry because of their large specific surface area. Due to their biocompatibility and biofunctionality, animal nanofibers have drawn a lot of attention in biomedical applications such as tissue engineering, scaffolds for cell growth, and more [190].

Scaffolds are implants or injectable materials that are used to introduce genes, medicines, and cells into living organisms. A standard three-dimensional porous matrix, a nanofibrous matrix, a thermosensitive sol-gel transition hydrogel, and a porous microsphere are a few examples of the various polymeric scaffolds for cell/drug transport. A scaffold offers an appropriate surface for cell adhesion, proliferation, differentiation of function, and migration. Drug delivery to specific areas can be accomplished with scaffold matrices using high loading and efficiency. A detailed review of scaffolds produced by animal fibers is given in [191–193].

Petre and Leeuwenburgh [194] reviewed the use of fibers in bone tissue engineering. Ressler [195] examined chitosan-based biomaterials for bone tissue engineering applications in detail. Qasim et al. [196] reviewed electrospinning of chitosan-based solutions for tissue engineering and regenerative.

Biomaterials from animal fibers are also used in the additive manufacturing process known as “bioprinting,” which creates a habitat for living cells. These substances, also known as bioinks, are derived from hydrogel precursors that gel in a way that is appropriate for various bioprinting techniques [197].

Flexible strain sensors with exceptional stretchability and sensitivity have numerous applications in the realms of medicine, smart robots, intelligent clothing, and human-machine interaction. Designing strain sensors in the face of escalating environmental contamination is made possible by the use of natural fibers in green manufacturing. Natural fibers that have been commercialized include cellulose fibers (cotton and fibrilla), protein fibers (wool and silk), and their regenerated components (viscose and silk fibroin). These materials are inexpensive, simple to obtain, and biodegradable [198].

The efforts in the literature using 3D woven fabrics in ballistic applications were reviewed by Junare et al. [199]. Hammouche et al. [200] conducted a comparative study of capacitive humidity sensors based on keratin film, keratin/graphene oxide, and keratin/carbon fibers.

Feather nanocomposites were also extensively reviewed in the literature as hybrid composites due to their unique biocompatible properties. Rangappa et al. [201] examined bioepoxy-based hybrid composites from nanofillers of chicken feathers in detail. Vilchez et al. [202] reported in detail on the upcycling of poultry feathers with (nano)cellulose. Alternatively, poultry feathers are used as a precursor for carbon fibers [203].

Table 25 presents a comprehensive overview of the diverse applications of nanofibers in the pharmaceutical and biomedical fields. The table is divided into two main sections: “Nanofibers in Medicine” and “Nanofibers in Pharmacology,” each containing a list of specific applications. In the realm of medicine, nanofibers have found utility in various areas, such as artificial tissue engineering, wound healing, and organ regeneration. They are used to create artificial blood vessels, corneas, and skin while also serving as platforms for controlled drug release in applications like drug-release capsules and artificial skin. Nanofiber-based materials are also contributing to innovative medical solutions, including surgical adhesives, nerve and organ patches, and even treatments for rhinosinusitis. These applications underscore the potential of nanofibers to advance medical practices through their versatile characteristics and controlled functionalities.

Table 25. Applications of nanofibers in pharmaceutical and biomedical fields [151].

Nanofibers in Medicine	Nanofibers in Pharmacology
Adhesion prevention materials	Anticancer drug delivery
Artificial bold vessels, cornea, and skin	Antimicrobial drug delivery
Dialysis membrane	Cell delivery and tissue engineering
Drug release artificial skin	Anti-inflammatory drugs
Drug release capsule	Antibiotic drug delivery
Facemask, skin, and vascular tissue engineering	Growth factor and protein delivery
Filling agent for artificial bone	Smart active drugs release systems
Nerve or organ patch	Neuroprotective drugs
Rhinosinusitis treatment	Nucleic acid delivery
Surgical adhesive sheet	Miscellaneous drugs delivery
Transdermal absorbent	Controlled release of gentamicin
Wound and therapeutic applications	Double-layered planar nanofibrous scaffold abdominal adhesion prevention
Wound covering and protective agent	Localized chemotherapy
Wound dressing and healing systems	Transdermal drugs delivery

In the context of pharmacology, nanofibers continue to revolutionize drug delivery systems. They offer targeted drug release mechanisms for applications such as anticancer and antimicrobial drug delivery, as well as the controlled delivery of growth factors, proteins, and nucleic acids. The table highlights the role of nanofibers in enhancing therapeutic outcomes through smart drug release systems, neuroprotective drugs, and more. Moreover, nanofibers are leveraged for transdermal drug delivery, contributing to the development of innovative therapies that improve patient comfort and treatment efficacy. Overall, Table 25 provides a succinct overview of the extensive capabilities of nanofibers in advancing both medical and pharmacological applications, showcasing their potential to transform the healthcare and pharmaceutical industries.

Important applications of mineral nanocomposites such as wollastonite include bioengineering [149]. A detailed review of mineral nanocomposites is given in [150].

6. Conclusions and Challenges

This work examined the main aspects of plant, animal and mineral natural fibers composites regarding end use applications in addition to structure and chemical composition. The main aspects of natural fiber composites, such as plant (cellulose base), animal (protein base), and mineral fiber composites, are discussed. In particular, composite materials with mineral or polymer as the matrix ingredient are examined. This paper has undertaken a comprehensive exploration of the diverse realms of natural fiber composites, specifically focusing on plant, animal, and mineral fibers, their structural compositions, and their end-use applications. The discussions have revolved around composite materials where mineral or polymer matrices interact with these natural fibers. A significant finding emerges from this review—the potential enhancement of natural fiber composite properties through the incorporation of nanofillers. By delving into the literature, it becomes evident that while natural fiber composites present an array of advantages, they also confront limitations and challenges.

The challenges that emerge from this study pave the way for a promising future in the field. Novel techniques aimed at bolstering the material properties of natural fiber composites are anticipated to take center stage [204]. These composites, found to be increasingly relevant across diverse sectors, indicate an ever-expanding scope for their application [205]. The synergistic application of nano-fillers alongside natural fibers within various matrix composites promises to be a transformative avenue [206]. Additionally, the incorporation of cellulose from plants, chitin from feathers, and silk into the production of green composites is expected to contribute to sustainable practices [207]. The utilization of waste materials for the manufacture of fiber composites not only addresses environmental concerns but also demonstrates a practical circular economy approach [208–213]. A pivotal aspect of the envisioned future involves embracing the principles of the circular economy, incorporating green raw materials, and ensuring the responsible disposal of high-performance composites [214]. Another important challenge is the application of naturally occurring polymers as polymer matrices, such as the polymers belonging to the group of polyhydroxyalkanoates (PHAs). A typical example is poly (3-hydroxybutyric-co-3-hydroxyvaleric acid) (PHBV). This polymer is of natural origin, and it is fully biodegradable. A detailed discussion about the application of PHBV in natural fiber composites is given in [215–217].

This review not only underscores the remarkable potential of natural fiber composites and their challenges but also offers a glimpse into the evolving landscape of their applications. It may serve as a foundation for future research endeavors, innovations, and advancements in material science and engineering.

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