Sustainable Natural Fiber Based Composites Materials: A Review

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Abstract

Natural fiber-based composite materials have emerged as sustainable alternatives to conventional composites, driven by the need for environmentally friendly solutions in various industries. This review provides a comprehensive overview of the natural fibers commonly used in composite manufacturing, including jute, flax, hemp, sisal, coir, and many more. The fiber characteristics such as tensile strength, elasticity, moisture absorption, and their mechanical and physical properties are presented and discussed, highlighting their influence on the overall performance of the composites. The interaction between these natural fibers and polymer matrices, including both thermoplastic and thermosetting polymers, is also focused on this review. Various manufacturing techniques employed to produce natural fiber composites are explored, including hand layup, compression molding, resin transfer molding, injection molding, extrusion molding, and automated fiber placement techniques. Lastly, the review explores the diverse applications of natural fiber-based composites across sectors such as automotive, construction, packaging, and sports equipment.

Keywords: *Composites, Natural fiber, Polymer matrices, Composites manufacturing techniques*

1. Introduction

In recent years, there has been a rising recognition of the limitations of nonrenewable resources, which has prompted a move towards reliance on renewable resources. The transition has generated considerable eagerness to develop composite materials that possess both biodegradability and ecological sustainability [1]. Composite materials began to emerge during the 1940s, initially employing fibers as reinforcing substances [2]. Composites may be designed to exhibit specific characteristics by altering the mix of the reinforcing and matrix phases [3], [4]. Composite materials are currently undergoing development and redesign efforts to enhance traditional products due to their favorable characteristics, like elevated specific strength, lightweight, robust damping capacity, and heightened specific modulus. Now, a rise in the development and use of bio-composite materials is seen in various engineering applications, particularly those incorporating natural fibers (NFs) as additives or reinforcements [5].

Manufacturers and researchers show significant interest in natural fibers, including flax, hemp, jute, banana, sisal, kenaf, etc., due to their biodegradable nature and similar mechanical qualities. In contrast to synthetic fibers, these fibers also have lower costs and densities, making them suitable for producing lightweight constructions [6]. Also, natural fibers provide several benefits owing to their abundant supply and widespread availability [7], [8]. However, there are significant drawbacks that limit the utilization of natural fibers and recyclable polymers in the development of new composites. These drawbacks include their vulnerability to moisture absorption, thermal degradation, and weathering effects on the fibers and the matrix. Additionally, these materials exhibit lower durability, inadequate interfacial adhesion resulting in debonding, and poor resin impregnation and wettability within the spaces between fibrils. Furthermore, the fibers are prone to breakage during the mixing stages of the manufacturing processes [9]. Researchers are endeavoring to overcome the limitations of natural fiber-based composites by carefully selecting various materials and designs. Despite the widespread use of natural fiber-based composites in industries such as automobiles, aerospace, packaging, construction, shipping pallets, and furniture, efforts are being made to achieve optimal outcomes [10]–[12]. Numerous research studies are underway to explore the untapped potential of these composites.

This article aims to provide an extensive overview of composite materials constructed from natural fibers. It explores the several categories of natural fibers that are frequently utilized according to their properties, the techniques employed in producing natural fiber-based composite, and their concrete uses.

2. Natural Fibers and Types of NFs

The term 'natural fibers' refers to a range of fibers derived from plants, minerals, and animals in their natural state [13]–[16]. These fibers are derived from leaves, stems, or seeds of multiple species of plants [17], [18]. Natural fibers have three major components: cellulose, hemicellulose, and lignin. In natural fibers, each individual filament is ten μm in diameter and consists of one primary cell wall and three secondary walls [19], [20]. Figure 1 provides a structural constitution of natural fiber cell wall [21], [22].

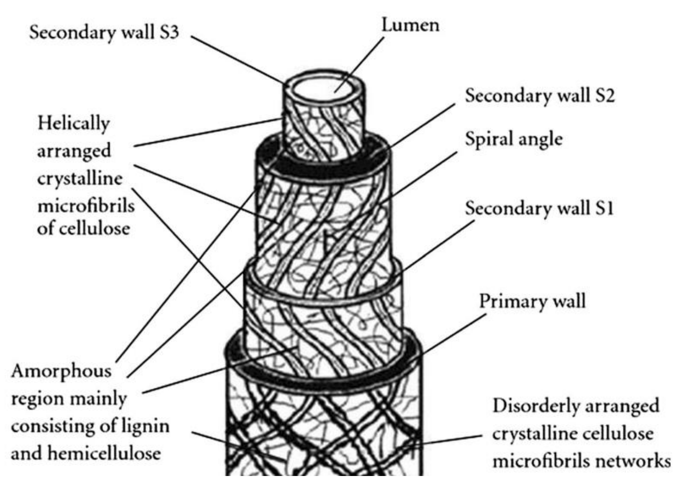

Figure 1. Structural constitutions of a natural fibers cell wall [21], [22]

Among the natural fibers, cellulose or plant-based fibers have gained attention from scientists, researchers, and engineers due to their convenient accessibility, degradability, renewability, and eco-friendliness [23]–[25]. Plant fiber comprises seeds, bast fibers, leaves, fruit, grasses/reeds, straws, and wood fibers [26]–[30]. The detailed classification of NFs is illustrated in Figure 2.

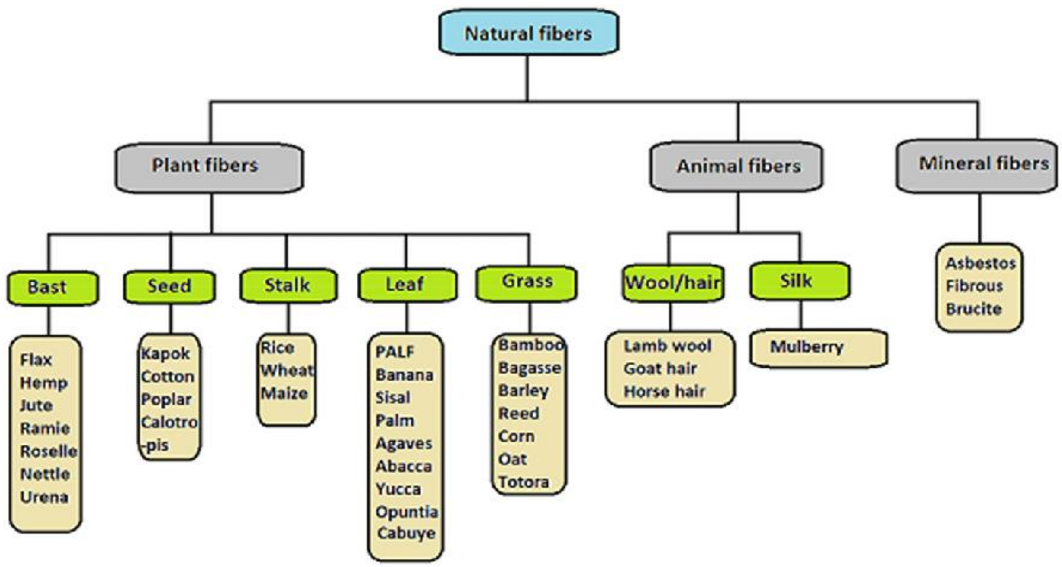

Figure 2. Classification of natural fibers [31]–[33]

3. Characteristics and Properties of Natural Fibers

Composite materials greatly value the distinctive characteristics and properties displayed by natural fibers. Materials such as cotton, jute, flax, hemp, wool, and silk are primarily well-known for their environmentally beneficial characteristics and properties and come from various sources, including plants and animals. In recent times, there has been a surge in researchers' interest in natural fibers on account of their renewability and sustainability attributes [27]. Natural fibers have greater strength and stiffness than synthetic fibers, depending on their chemical constitution and polymeric structure [34]. Here, Table 1 provides a concise overview of the characteristics of the NFs.

Table 1. Summary of natural fibers characteristics [27], [35]–[47].

Fiber	Description
Abaca	Manila hemp, or abaca, is a plant that is quite similar to banana plant. Although abaca plants resemble bananas, they are unsuitable for human consumption due to economic impracticability. In contrast to bananas, abaca plants are exclusively cultivated for their fibers [35].
Bamboo	Bamboo is popular because of its high strength-to-weight ratio [36], fast growth, low water usage, no pesticides or herbicides, and root-intact harvesting. Lighter, stiffer, and stronger than glass fiber [37]. An analysis by the U.S. Department of Energy shows that bamboo fiber mats require only 17% of the energy needed to create glass fiber mats [38].
Coir	Coir is highly desirable due to its superior durability compared to most natural fibers, is free from chemical treatment, and is widely available too [39], [40].
Cotton	Cotton fiber is exceptionally absorbent [41]. 46% of the world's natural and synthetic fibers production is cotton [42].
Eucalyptus	Although eucalyptus fiber is readily accessible, its resistance to fire and mold is inadequate. These bark fibers satisfy the requirements for insulating purposes [43].
Flax	Glass fiber possesses a lower specific tensile strength than flax fiber. Furthermore, it possesses low density, high strength, and rigidity [44].
Hemp	Young's modulus and mechanical strength of hemp fiber are both exceptional [44] excellent insulating properties [45].

Fibre	Description
Jute	Jute fiber is characterized by its favorable insulation properties and high strength-to-weight ratio [44].
Kenaf	It has low density and high specific mechanical properties [44].
Pineapple	Pineapple fiber possesses exceptional thermal, physical, and mechanical properties [47].
Ramie	Glass fiber may have a lower specific strength and modulus of ramie than ramie fiber. However, it is not as well-liked as other natural fibers due to the costly pre-treatments it demands [46].
Sisal	Sisal is a simple material to cultivate and regenerate rapidly. The fiber exhibits exceptional tenacity, tensile intensity, and resistance to abrasion, saline water, acids, and alkalis [44].

Raw materials' physical and chemical composition significantly influences natural fibers' ultimate mechanical properties [48]. Morphology, crystallinity, amorphous content, regular or irregular orderliness, processing method, the size of the natural fibers, and the stage of plant maturation are some additional factors to consider [49]–[51]. Moisture absorption, a significant concern about natural fibers, especially plant fibers, also depends on the chemical composition[50]–[53]. Specific properties influenced by chemical compositions and internal structures can be improved or modified through chemical treatments [54], [55]. Table 2 represents some physical and mechanical properties of natural fibers.

Table 2. Properties of certain natural fibers [52], [56]–[64].

Fibre	Density (g/cm3)	Diameter (µm)	Length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Moisture Content (%)
Abaca	1.5	10–30	4.6–5.2	430–813	31.1–33.6	2.9	14
Bamboo	0.6–1.1	25–88	1.5–4	270–862	17–89	1.3–8	11–17
Banana	1.35	12–30	0.4–0.9	529–914	27–32	5–6	10–11
Coir	1.2	7–30	0.3–3	175	6	15–25	10
Cotton	1.21	12–35	15–56	287–597	6–10	2–10	33–34
Flax	1.38	5–38	10–65	343–1035	50–70	1.2–3	7
Hemp	1.47	10–51	5–55	580–1110	30–60	1.6–4.5	8
Jute	1.23	5–25	0.8–6	187–773	20–55	1.5–3.1	12
Kenaf	1.2	12–36	1.4–11	295–930	22–60	2.7–6.9	6.2–12
Pineapple	1.5	8–41	3–8	170–1627	60–82	1–3	14
Ramie	1.44	18–80	40–250	400–938	61.4–128	2–4	12–17
Sisal	1.2	7–47	0.8–8	507–855	9–22	1.9–3	11

4. Manufacturing Composites

The fabrication method of composite materials utilizing natural fibers is crucial in determining their final characteristics and potential uses. When integrating natural fibers with polymers or other matrices, it is imperative to thoroughly assess several factors to achieve optimal performance. This section provides a summary of the leading manufacturing techniques employed in the fabrication of natural fiber composites.

4.1 Natural fiber preprocessing

Before integrating natural fibers into composites, it is crucial to carry out physical and chemical pretreatment procedures to improve their compatibility with the matrix material, as the presence of non-cellulose components such as hemicelluloses, pectin, and lignin in natural fibers leads to polar behavior. These components readily form hydrogen bonds with hydroxyl groups (-OH), causing the separation of fibers from the matrix [65]. This limits the mechanical properties of natural fiber-reinforced composites [65]. The chemical treatments are alkali treatment, silane coupling, acetylation treatment, benzoylation treatment, peroxide treatment, sodium chlorite treatment, acrylation and acrylonitrile grafting, permanganate treatment, isocyanate treatment, stearic acid treatment, fungal treatment [21], [26], [66]–[74]. Also, the process includes carrying out physical treatments such as corona treatment, plasma treatment, ultraviolet irradiation treatment, and ozone treatment as necessary [75]–[78]. The process may encompass the purification, desiccation, and surface modification of fibers to eliminate contaminants and moisture and enhance bonding between the fiber and matrix [79]–[83].

4.2 Matrix Selection and Preparation

A matrix is employed in composites to bind the reinforcing components securely by surface adhesion. The primary duties of the matrix involve ensuring the composite's environmental resilience, surface aesthetics, and long-lasting nature [84]. Petrochemical-based thermosetting and thermoplastic polymers are commonly utilized as a matrix in natural fiber composites. Bio-based, fully degradable matrices are also used with natural fibers [22]. The matrix is formulated in a manner that is appropriate for the selected manufacturing technique, be it liquid for infusion or molten for injection. The characteristics of polymeric matrices utilized in composites are categorized in Table 3.

Table 3. Classification of polymer matrices used for natural fiber composites [84]–[86]

Polymer Matrix		
Petrochemical-based resins		Bio-based resins
Thermoplastics	*Thermosets*	
Polyethylene (PE)	Epoxy	Polylactic acid
Polystyrene (PS)	Polyester	Cellulose
Polypropylene (PP)	Vinylester	Polyhydroxy alkanoate
Polyvinyl chloride (PVC)	Polyamide	Starch
Cellulose acetate	Polyurethane	
Polycarbonate (PC)		

4.3 Manufacturing Techniques

Initially, composites were made directly using human hands [87], [88]. Due to technological advancements and growing demand, processes such as additive manufacturing have evolved from semi-automated to fully automated. The closed mold techniques have gained popularity in the present century due to their superior precision, accuracy, and productivity [89], [90]. Choosing an appropriate manufacturing technique is crucial to shape the structure and achieve the specified composite technical qualities without any flaws. The primary manufacturing techniques for natural fiber composites include hand layup, compression molding, extrusion molding, injection molding, resin transfer molding, and automated fiber placement. Figure 3 displays these primary production procedures.

4.3.1 Hand layup

The hand lay-up process is widely used, uncomplicated, and cost-effective for manufacturing composites [91]. This technology allows for the easy preparation of long and continuous composite materials made from natural fibers and a wide range of products [88]. It involves the initial application of a release agent, which acts as an anti-adhesive substance, to the open mold. Subsequently, the fibers are positioned within the mold. The application of resins to the fibers is accomplished through pouring and brushing using a roller or brush [92]–[94]. The lay-up process involves progressively adding layers until the appropriate thickness is achieved. Entrapped air in the laminate is manually removed by giving pressure using squeegees or rollers. In order to achieve a stronger interfacial bond among different materials, it is necessary to incorporate fiber, matrix, or both with elements that potentially assist that bonding [70]. The laminates are then allowed to cure under normal atmospheric conditions [92]. Another procedure called spray layup is almost similar to the hand layup technique. In spray layup, resin and shredded fibers are sprayed onto a mold using a handgun during that process [95], [96].

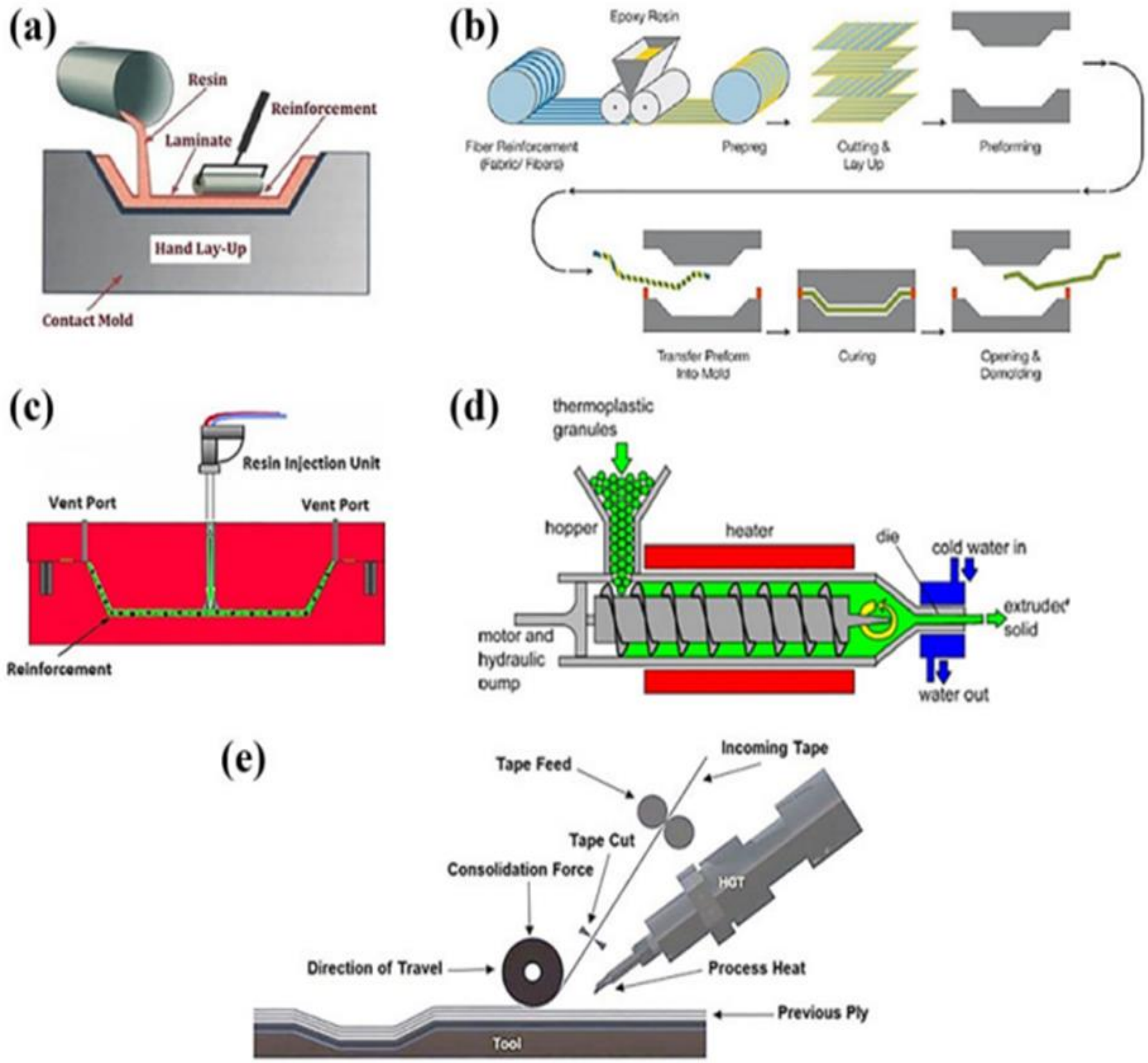

Figure 3. The following manufacturing processes are commonly used in the industry: (a) Hand layup process, (b) compression molding, (c) resin transfer molding, (d) extrusion process, and (e) automated fiber placement [97].

4.3.2 Compression molding

The compression molding technique produces bulk composite components specifically for automotive, aerospace, and maritime applications. Two distinct types of compression molding process exist: hot compression molds and cold compression molds [26], [98]. Only pressure is exerted during cold compression, and curing occurs at ambient temperature. In contrast, the hot compression method involves the simultaneous application of pressure and temperature, with curing achieved by heating the mold [99]. The cavity is initially filled with materials that have been heated using this technique. The mold's core exerts significant pressure on the chamber, resulting in the compression and deformation of the pieces. The compression force must be maintained until the composite solidifies. The mold can be opened at this point, and the composite can be extracted [100]. The crucial variables to be considered in relation to this technique include the material quantity, heating duration, pressure exerted on the mold, and duration of cooling [101].

4.3.3 Extrusion Molding

Extrusion molding is a commonly employed technique for fabricating composite materials, enabling the production of materials that possess exceptional rigidity and durability [102]. The process commences by storing the thermoplastic material in the shape of pellets or grains within a hopper. Subsequently, they are transported to a heated barrel, where they are melted. The liquefied plastics are then utilized to get the desired form of the composite [84], [102]. A rectangular die was employed at the extruder's end, and the resulting extrudates were then cooled to the ambient temperature. Sometimes, silane was used in the extrusion process to enhance the characteristics of the particular product [103], [104]

4.3.4 Injection Molding

The injection molding method enables the cost-effective and efficient manufacturing of intricate components with precise dimensions [105]. This procedure commences by introducing the polymers in the shape of pellets or granules into the hopper and subjecting them to heat until they reach a molten state. The liquefied components are subsequently introduced into a chamber created by a divided die mold and retained within the mold. The molten substance is cooled to a solid before the mold opening [106].

4.3.5 Resin transfer molding

In the resin transfer molding (RTM) process, the resin is heated beforehand and then placed into a holding chamber rather than directly fed into an open mold [107]. Here, in the RTM technique, the textile layers are assembled in a solid mold, and the resin with low viscosity is then subsequently injected to saturate the preforms. The relationship between resin viscosity and infiltration quality is clear: the lower the resin viscosity, the higher the infiltration quality [108], [109]. Finally, the vacuum is frequently employed to prevent the formation of air bubbles and facilitate the infusion of the resin into the cavity [110].

4.3.6 Automated Fiber Placement

Automated fiber placement (AFP) is a sophisticated technique for manufacturing extensive and intricate composite structures. Manual hand layup can be mechanized by employing a programmable robotic device. This technique uses an automated machine to precisely position the continuous fiber-reinforced composite tape and construct a structure incrementally, layer by layer. During the AFP process, the entering tape is heated using either hot nitrogen or a laser. Subsequently, each tape is compressed against the mold using a roller to achieve appropriate compaction, as depicted in Figure 2(e). The AFP technology allows for the fabrication of highly customized parts by enabling the placement of each ply with variable orientations and angles, optimizing their ability to bear the necessary stresses [5], [111].

5. Applications

Natural fiber-based composites are very emerging materials. They have been employed in several industries such as automotive, aerospace, civil, building, aircraft components, packaging, sporting equipment, electrical parts, and biomedical sectors, most notably due to their environmentally friendly nature, lightweight properties, resistance against friction, excellent mechanical performance, sound attenuation capabilities, and vibration dampening characteristics [112]–[115]. Natural fibers are utilized to create insulation materials for various applications, including blowing insulation, pouring insulation, impact sound insulation materials, thermal insulation for ceiling panels, and acoustic soundproofing [116]. Automobile businesses use natural fiber composites composed of polyester, polypropylene, flax, hemp, and sisal for their light weight and other properties [117]. Giants like Mercedes-Benz, Volkswagen, Audi, and others use natural fibers such as flax, hemp, sisal, and wool-incorporated composites to make side and back door panels, headliner panels, boot lining, seat backs, noise insulation panels, molded foot, seat back, boot lining, hat rack, engine cover, interior insulation, bumper, wheel box, and roof cover [118], [119]. Natural fiber composites have been developed for load-bearing parts in structural applications, including beams, roofs, walls, and pedestrian bridges [120], [121]. The utilization of jute fiber/polypropylene composite has been observed in essential structural applications, including indoor components in housing [84], [122], temporary low-cost outdoor housing for defense and rehabilitation [123], [124], as well as transportation [122]. Rice husk fiber, cotton, ramie, jute fiber, and kenaf are utilized in many applications, such as construction materials, the furniture sector, clothes, ropes, sewing thread, fishing nets, packaging materials, and paper production [123]. In the medical sector, the present research focuses on natural fiber-based polymer composites to assess their suitability in orthopedics [124]. Other than that, for bone tissue engineering, drug delivery, antibiotic applications, vascular grafts, biosensors, and artificial hearts, natural fiber (e.g., ramie, flax, kenaf, banana, coconut, sisal, oil palm, etc.) incorporated composites are used [125]–[127]. Even in musical instruments (i.e., guitar and violin), composites are used to replace wood [128].

6. Conclusion

Natural fibers are mostly known for their environment-friendly properties and characteristics. As a result, this natural fiber has garnered significant interest in major industries such as automotive, aerospace, military, medical, packaging, civil, and technology. Natural fiber composites possess desirable mechanical properties, eco-friendly characteristics, good thermal properties, lightweight, lower production costs, and renewable nature [129]. These attributes make them a superior choice of composite material compared to synthetic fiber composites made from glass and carbon [129]. However, some limitations have hindered their acceptance as a dependable substitute for traditional composites, such as inadequate bonding between the natural fibers and the matrix, moisture absorption, limited fire resistance, reduced impact strength, and diminished durability [26]. This article has concisely explained natural fibers' inherent features and distinctive characteristics. It briefly discusses the manufacturing process of composites using natural fibers, including the techniques employed and the various applications of composites based on natural fibers. Meanwhile, further study is required to address the constraints of composites and explore alternatives to synthetic fibers for commercial uses.

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