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Natural Fibers for Sustainable Bio-Composites

Tri-Dung Ngo

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Abstract

Over the past decade, the concept of utilizing green materials has become more mainstream. With considerable awareness of preserving the environment, sincere efforts across the globe can be cited in looking for bio-degradable and bio-based sources. Applications of bio-based materials from renewable and bio-degradable sources for preparation of higher valued green chemicals and bio-based products have forced many scientists to investigate the potential use of natural fibers as reinforcement materials for green bio-composites. Cellulosic fibers are becoming very interesting for bio-based material development as they possess advantages with their mechanical properties, low density, environmental benefits, renewability, and economic feasibility. Recently, natural-fiber polymer composites have received much attention for different industrial applications because of their low density and renewability. The bio-composites with natural fiber components are derivatives of depleting resources and can be considered to have substantial environmental and economic benefits. This chapter addresses the potential utilization of natural fiber for the development of green polymer composite materials, with the objective to elucidate the possibility of using these bio-based materials for various industrial applications.

Keywords: natural fiber composite, cellulosic fiber, green-product, bio-composite, thermoset, thermoplastic

1. Introduction

The advantages of composite materials over conventional materials stem largely from their higher specific strength, stiffness, and fatigue characteristics. Over the past few decades, one finds that polymer composites have replaced many of the conventional metals/materials in various applications. The composite materials are finding applications in diverse fields ranging

from household, office appliances, power tools, and business equipment to space crafts. A fiber-reinforced composite is a composite building material that consists of three components: (i) the matrix as the continuous phase, (ii) the fibers as the discontinuous or dispersed phase, and (iii) the fine interphase region, also known as the interface [1, 2]. Many different fibers have been utilized to reinforce polymer matrix composites. The most common are carbon fibers (AS4, IM7, etc.), glass fiber (E-glass, S-glass, etc.), aramid fibers (Kevlar® and Twaron®), and boron fibers. Recently, with advantages of reasonable mechanical properties, low density, environmental benefits, renewability, and economic feasibility, natural fibers have been paid more attention in composite applications. Natural fibers are one such proficient material which would be utilized to replace the synthetic materials and their related products for the applications requiring less weight and energy conservation.

Historical textiles are made from natural fibers and serve to create a special link between the natural environment and the social environment that underlies all our lives, from the everyday textile to patriotic to ceremonial [3]. Natural plant fiber composites as environmentally attractive materials have been proven and emerged as an alternative to the glass-reinforced composites used in many applications since the 1990s [4]. In recent years, there has been an increasing environmental consciousness and awareness of the need for sustainable development, which has raised interest in using natural fibers as reinforcements in polymer composites to replace synthetic fibers [5, 6]. In addition, weight saving opportunities could possibly be obtained by replacing traditional fiber composites with natural fiber composites. The use of low-density renewable natural contents in thermoset and thermoplastic composite materials is a viable means to reduce environmental impact and support sustainability development in the transport industry. The utilization of natural fiber composites has expanded considerably in the shopper merchandise for developing industry sectors throughout the last few years. High specific properties, renewability with lower prices, and natural fiber polymer composites have received much attention for development of different industrial applications. Different kinds of natural fibers mainly flax, hemp, and sisal with bio-resins systems have been actively developing for various interior components in automotive and aircraft industries [7, 8]. This chapter seeks to provide an overview of the science and technology in relation to the potential of natural fiber utilization for bio-composites.

2. Natural fiber

Natural fibers in simple definition are fibers that are not synthetic or manmade and are categorized based on their origin from animals, mineral, or plants sources as shown in **Figure 1** [9]. Some of the natural fibers are in readymade form such as vegetable, cellulose (cotton and linen), and mineral (asbestos) fibers. The fibers are produced and provided by nature from various parts of the plants, trees, and geographies.

The plants which produce cellulose fibers can be classified into bast fibers (flax, hemp, jute, kenaf, and ramie), leaf fibers (abaca, banana, pineapple, and sisal), seed fibers (coir, cotton, and kapok), as well as all other kinds (roots and wood). The photographs of some natural

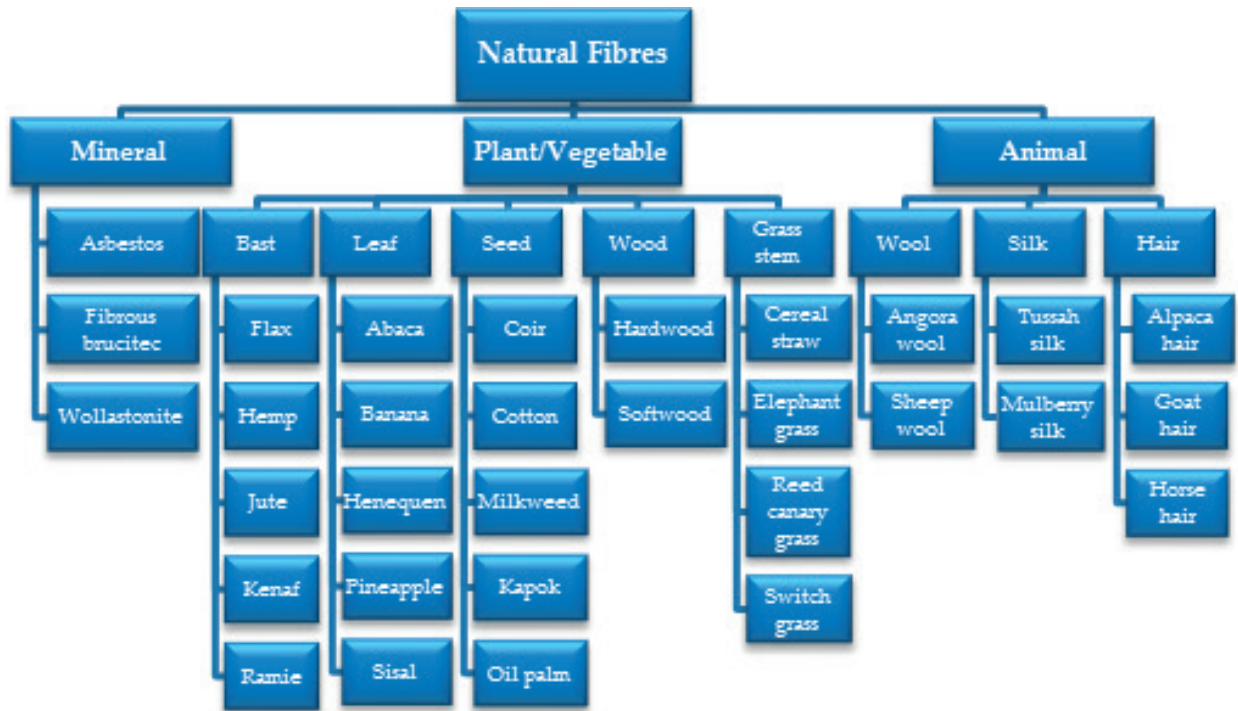


Figure 1. Natural fibers classifications.

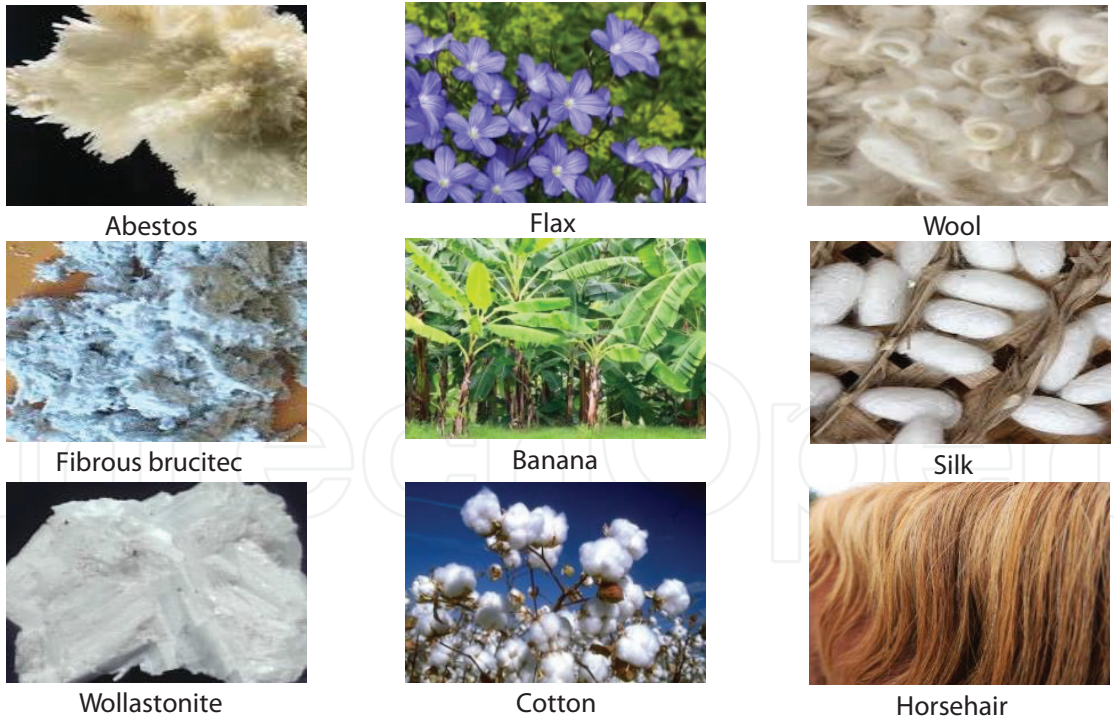


Figure 2. Photographs of sources of some natural fibers.

fiber sources are shown in **Figure 2**. Natural plant fibers are entirely derived from vegetative sources and are fully biodegradable in nature. The most common and commercially available natural plant fibers and their global production are shown in **Figure 3**.

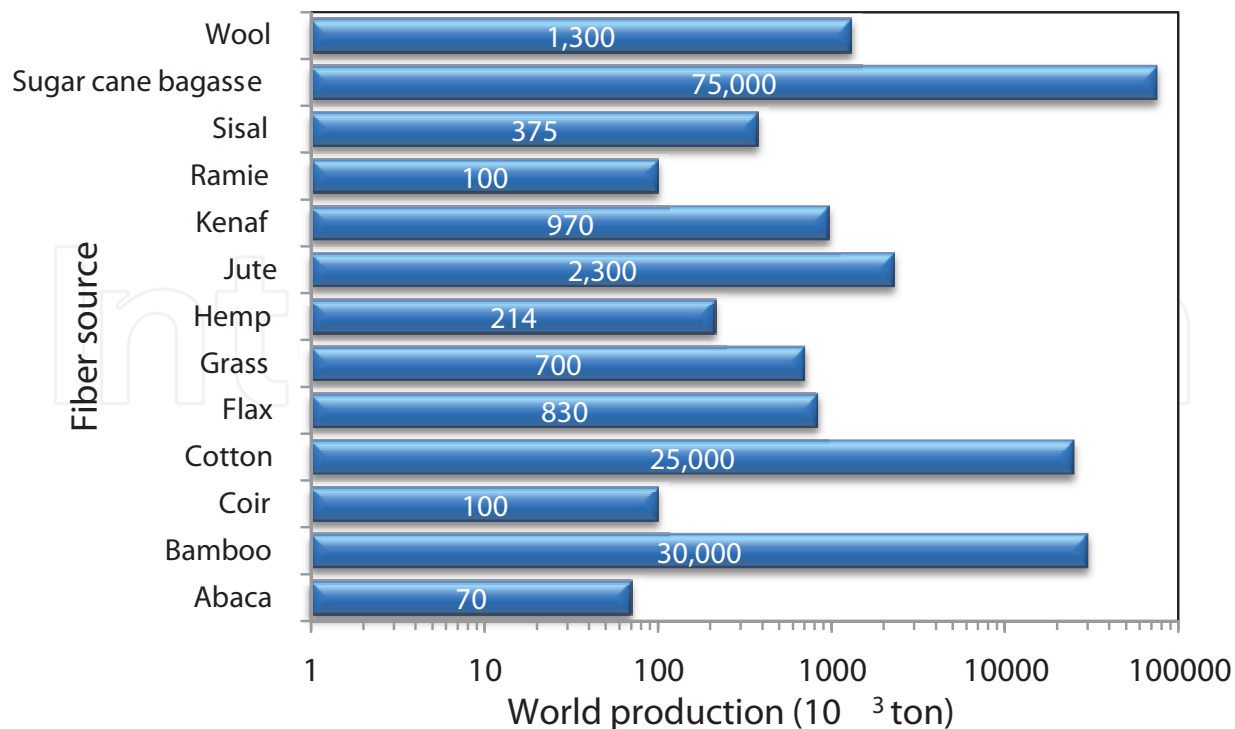


Figure 3. Natural plant fibers and their world production [18, 19].

Many of the plant fibers such as banana, coir, flax, hemp, jute, pineapple, and sisal find applications as resource for industrial materials. The main chemical components of natural plant fibers are cellulose, lignin, hemicelluloses, pectin, and wax. The components and their percentages vary depending on the type of natural plant fibers as shown in Table 1 [10–17].

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Waxes (wt%)
Abaca	56.0–63.0	20.0–25.0	7.0–9.0	3.0
Bagasse	55.2	16.8	25.3	—
Bamboo	26.0–43.0	30.0	21.0–31.0	—
Birch	41.0	32.0	22.0	—
Cedar	44.0	21.0	30.0	—
Coir	32.0–43.0	0.15–0.25	40.0–45.0	<2.0
Corn cobs	33.7–41.2	31.9–36.0	6.1–15.9	—
Corn stalks	35.0–39.6	16.8–35.0	7.0–18.4	—
Cotton	80.0–95.0	5.0–20.0	0	—
Curaua	73.6	9.9	7.5	—
Douglas fir	44.0	11.0	27.0	—
Eucalyptus	54.1	18.4	21.5	—
Flax	71.0	18.6–20.6	2.2	1.5
Grasses	25.0–40.0	25.0–50.0	10.0–30.0	—

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Waxes (wt%)
Hemp	68.0	15.0	10.0	0.8
Jute	61.0–71.0	14.0–20.0	12.0–13.0	0.5
Kenaf	72.0	20.3	9.0	<1.0
Oat straw	31.0–35.0	20.0–26.0	10.0–15.0	–
Oil palm	65.0	–	29.0	–
Pineapple	81.0	–	12.7	–
Ramie	68.6–76.2	13.0–16.0	0.6–0.7	0.3
Rice husk	35.0–45.0	19.0–25.0	20.0	–
Rice straw	41.0–57.0	33.0	8.0–19.0	8.0–38.0
Sisal	65.0	12.0	9.9	2.0
Sugarcane bagasse	25.0–45.0	28.0–32.0	15.0–25.0	–
Sorghum straw	32.0–35.0	24.0–27.0	15.0–21.0	–
Switchgrass	35.0–40.0	25.0–30.0	15.0–20.0	–
Wheat straw	38.0–45.0	15.0–31.0	12.0–20.0	–
Deciduous wood	38.0–50.0	23.0–33.0	23.0–34.0	–

Table 1. Natural plant fibers and their chemical composition.

Fiber-reinforced polymer matrix got considerable attention in numerous applications because of its good properties. Current indicators are that interest in natural fiber composites by industry will keep on growing quickly around the world. The application of natural fiber-reinforced polymer composites and natural-based resins for replacing existing synthetic polymer- or glass fiber-reinforced materials is huge. However, natural fiber quality is influenced significantly by the age of the plant, species, growing environment, harvesting, humidity, quality of soil, temperature, and processing steps, and there is a move to reduce the on-field processing to improve consistency and reduce costs. Properties of several natural fibers and commonly used synthetic fibers are shown in **Table 2** [20–23].

Fiber	Density (g/cm ³)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Abaca	1.5	–	980.0	–
Bagasse	1.2	1.1	20.0–290.0	19.7–27.1
Banana	1.3–1.4	2.0–7.0	54.0–789.0	3.4–32.0
Coconut	1.4–3.8	–	120.0–200.0	19.0–26.0
Coir	1.2	15.0–30.0	175.0–220.0	4.0–6.0
Cotton	1.5–1.6	3.0–10.0	287.0–597.0	5.5–12.6
Flax	1.4–1.5	1.2–3.2	345.0–1500.0	27.6–80.0
Hemp	1.4–1.5	1.6	550.0–900.0	70.0

Fiber	Density (g/cm ³)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Henequen	1.4	3.0–4.7	430.0–580.0	—
Jute	1.3–1.5	1.5–1.8	393.0–800.0	10.0–30.0
Kenaf	1.2	2.7–6.9	295.0	—
Palf	1.4	3.0	170.0–635.0	6.2–24.6
Pineapple	1.5	1.0–3.0	170.0–1672.0	82.0
Ramie	1.5	2.0–3.8	220.0–938.0	44.0–128.0
Sisal	1.3–1.5	2.0–14.0	400.0–700.0	9.0–38.0
Softwood kraft	1.5	—	1000.0	40.0
Carbon	1.4	1.4–1.8	1500.0–5500.0	230.0–240.0
E-glass	2.5	2.5–3.0	2000.0–3500.0	70.0
S-glass	2.5	2.8	4570.0	86.0
Kevlar	1.4	3.3–3.7	3000.0–3150.0	63.0–67.0

Table 2. Properties of several natural fibers and commonly used synthetic fibers.

3. Natural fibers bio-composites

Bio-composite materials are defined as composite materials in which at least one of the constituents is derived from natural resources. Generally, the term bio-composites cover composite materials made from the combination of:

- Bio-polymers-reinforced synthetic fibers such as carbon fibers, glass, Kevlar, etc.;
- Natural fibers–reinforced petroleum-derived polymers such as polyethylene (PE), polypropylene (PP), epoxy, unsaturated polyester (UPE), vinyl ester (VE); and;
- Bio-polymers reinforced by natural fibers.

The advantages of natural fiber over synthetic fiber in terms of its relatively renewable resources are its abundance, less damage to processing equipment, low weight, low cost, good relative mechanical properties such as tensile modulus and flexural modulus and improved surface finish of molded parts composite. The bio-composite materials made from the combination of natural fibers–reinforced petroleum-derived polymers and bio-polymers–reinforced synthetic fibers such as glass and carbon are nonbiodegradable and are not fully environmentally friendly.

Polymers can be categorized into thermoplastic and thermoset. Though thermoset and thermoplastic sound similar, they have very different properties and applications [24]. Thermosets are materials that undergo a chemical reaction (curing reaction) and normally transform from a liquid to a solid. In its uncured form, the material has small, unlinked molecules (known as

monomers). The addition of a second material (catalyst, cross-linker, and curing agent) and/or the presence of heat or some other activating influences will initiate the chemical reaction. During this reaction, the molecules cross-link and form significantly longer molecular chains and a cross-link network, causing the material to solidify. Subsequently, exposure to high heat will cause the material to degrade, not melt. On the other hand, thermoplastics are melt-processable plastics. When enough heat is added to bring the temperature of the thermoplastic above its melting point (softens enough to be processed), the thermoplastic liquefies. The thermoplastic solidifies back into glass-like solid state, when the heat source is removed and the processing temperature drops below its melting point. This behavior allows melting and re-shaping the thermoplastic as the temperature increases above and reduces below the melting temperature, respectively. Thermoset and thermoplastic materials each have their unique set of properties and position in the market. In general, the market for the thermosets has been well-established, and they tend to have been around for a long time. Frequently, the costs of raw materials for producing thermoset are lower as compared to thermoplastic. In addition, thermoset is often easy for wetting the reinforcing fibers and forming final composites products. Thermoplastics tend to be tougher than thermoset, can have better chemical resistance, do not need refrigeration as uncured thermosets frequently do, and can be more easily recycled and repaired. Elastomers are usually thermosets (requiring vulcanization) but may also be thermoplastics (thermoplastics elastomer). Elastomer is extreme flexible and possesses a huge rate of elasticity which means that when these types of polymers are submitted to a stress, even a small one, they deform significantly. Elastomers can reversibly extend from 5 to 700%. This deformation is reversible, and when the stress ends, the polymer returns to its original shape.

Bio-polymers are polymers obtained from natural resources and are consisting of monomeric units that are covalently bonded to form larger structures. Bio-polymers vary among their melt flow indices, impact properties, hardness, vapor transmission characteristics, coefficient of friction, and decomposition. Bio-polymers can be thermoset, thermoplastic, and elastomer. One can find vast range of applications of bio-polymers in different fields such as agricultural films, automotive, medical and pharmaceutical, food packaging, hygiene, and protective clothing. There are several types of polymers in the market. The most common thermoplastic, thermoset, and bio-polymers are summarized in **Table 3** [25–27].

Natural plant fiber polymer composites are a composite material consisting of a polymer matrix embedded with natural fibers [28]. Loose fiber, nonwoven mats, aligned yarns, and woven fabrics are possible forms of natural fiber for composites, with aligned variants offering the best mechanical properties. Natural plant fiber-derived bio-composites are renewable, lightweight, energy efficient, and environmentally friendly as compared to other binder fabric composites [29]. Utilizing natural plant fibers in particular would decrease waste disposal problems and reduce environmental pollution. The techniques utilized to fabricate bio-composites are based largely on existing techniques for processing plastics and conventional composite materials. Depending on the types and form of natural fiber-reinforced composites, the processing techniques would be chosen accordingly. For instance, compression molding, extrusion, hand lay-up, injection molding, resin transfer molding, and sheet molding compound can be utilized for short natural fibers, while compression molding, filament winding,

	Polymers	Density (g/cm ³)	Elongation (%)	Tensile strength (MPa)	Young's modulus (GPa)
Thermoplastic	Acrylonitrile butadiene styrene (ABS)	1.0–1.1	270.0	47.0	2.1
	Cross-linked polyethylene (PE)	0.9	350.0	18.0	0.5
	Ethylene vinyl acetate (EVA)	0.9–1.0	750.0	17.0	0.02
	High-density polyethylene (HDPE)	0.9–1.0	150.0	32.0–38.2	1.3
	High-impact polystyrene (HIPS)	1.0	2.5	42.0	2.1
	Low-density polyethylene (LDPE)	0.9	400.0	10.0–11.6	0.2–0.3
	Nylon 6 (PA 6)	1.1	60.0	81.4	2.8
	Nylon 6,6 (PA 6,6)	1.1	60.0	82.7	2.8
	Polycarbonate (PC)	1.2	200.0	69.0	2.3
	Polyethylene terephthalate (PET)	1.5–1.6	300.0	55.0–159.0	2.3–9.0
	Polyether ether ketone (PEEK)	1.3–1.5	1.6–50.0	92.0–95.0	3.7–24.0
	Poly ether ketone (PEK)	1.2–1.4	20.0	100.0–110.0	3.5
	Poly methyl methacrylate (PMMA)	1.1–1.2	2.5	72.4	3.0
	Polypropylene (PP)	0.9–1.3	80.0	35.8	1.6
	Polystyrene (PS)	1.04	1.6	34.0	3.0
	Polyvinyl chloride (PVC)	1.3–1.5	50.0–80.0	52.0–90.0	3.0–4.0
Rigid thermoplastic polyurethane (RTPU, PUR-RT)	1.1	5.0	75.0	4.0	
Thermoset	Epoxy (EP)	1.2–1.3	1.3	600.0	80.0
	Melamine formaldehyde (MF)	1.5–1.6	0.6	65.0	12.0
	Phenol formaldehyde (PF)	1.2	1.2	45.0	6.5
	Rigid thermoset polyurethane (RPU)	1.2	90.0	60.0	2.2
	Unsaturated polyester (UPE)	1.1	2.0	60.0	3.4
	Urea formaldehyde (UF)	1.5–1.6	0.8	65.0	9.0
	Polyurethane rubber	1.2–1.3	300.0–580.0	39.0	2.0–10.0
Biopolymers	Poly-lactic acid (PLA)	1.2–1.3	2.1–30.7	5.9–72.0	1.1–3.6
	Polyhydroxyalkanoates (PHA)	1.2–1.3	2.0–1200.0	10.0–39.0	0.3–3.8
	Polyhydroxybutyrate (PHB)	1.2	1.56–6.0	24.0–40.0	3.5–7.7
	Poly-3-hydroxybutyrate (P-3-HB)	1.3	0.4–6.0	40.0	3.5
	Poly-3-hydroxybutyrate-co-3-hydroxyvalerate (P-3-HB-3 HV)	0.2–0.3	1.6–20.0	23.0–40.0	3.5
	Poly-3-hydroxybutyrate (P-3-HB)	1.2	1000.0	104.0	—
	Polycaprolactone (PCL)	1.1	700.0	16.0–23.0	0.4

Table 3. Properties of polymers and bio-polymers.

hand lay-up, pultrusion, and resin transfer molding can be applied for long fibers. The properties and performance of products made from natural fiber composites depend upon processing techniques, the properties of their individual components, as well as their compatibility and interfacial bonding between polymer and fiber. A number of drawbacks of natural fiber composites like higher water absorption, inferior fire resistance, and lower mechanical properties as compared to synthetic fibers may limit their applications. The physical, mechanical properties, and fire resistance of the natural fibers can be further enhanced through the treatment, while their moisture absorption can be reduced through surface modification and addition of coupling agents. The bonding strength between fiber and polymer matrix in the composite is considered a major factor in order to get superior fiber reinforcement composite properties. An essential requirement for good fiber matrix adhesion is optimized impregnation of the reinforcing system. Because of pendant hydroxyl and polar groups in natural plant fibers, this leads to extremely high moisture absorption of natural plant fiber resulting in weak interfacial bonding between the fiber and the hydrophobic matrix polymers. In addition, the coupling between natural plant fiber and polymer is considered a challenge because of the various chemical structures of both fibers and matrix. This results in ineffectual stress transfer at the interface of the produced composites. To develop composites with good mechanical properties, chemical modification of fiber is carried out to reduce the hydrophilic behavior of fibers and their moisture absorption [30, 31]. Many attempts have been made to modify the natural fiber surface in order to enhance their adhesion with the matrix through acetylation, acrylation, alkaline treatment, benzylation, corona treatment, graft copolymerization, heat treatment, plasma treatment, silane treatment, stearic acid treatment, and other chemical modifications [32–41]. The surface chemical modifications of natural fibers have achieved various levels of success in improving adhesion with polymer. Coupling agents have also been utilized in the composite formulations. A coupling is defined as a compound which provides a chemical bond between two dissimilar materials. Coupling agents act as the bridge between polymer and natural fibers and improve their bonding. Mechanical properties of several bio-composites are presented in **Table 4**.

Bio-composites	Fiber content (%)	Tensile strength (MPa)	Young's modulus (GPa)	References
PHB/kenaf	40.0	70.1	—	[44]
PLA/abaca	30.0	74.0	8.0	[45]
PLA/bamboo	20.0	90.0	1.8	[46]
PLA/flax	30.0	53.0, 100.0	8.0	[47, 48]
PLA/hemp	45.0	65.0	—	[49]
PLA/jute	35.0	50.0	—	[50]
PLA/kenaf	40.0	52.9	7.1	[51]
PP/cotton	30.0	58.5	4.1	[52, 53]
PP/coir-alkaline, silane	10.0–30.0	42.1–47.8	2.0	[54]
PP/curaua	5.0–20.0	29.5–31.2	1.4–3.5	[55]
PP/flax Flax-MAgPP, CaO	40.0	96.9–109.0	7.9–10.1	[56]
PP/flax	30.0	52.0	5.0	[57]

Bio-composites	Fiber content (%)	Tensile strength (MPa)	Young's modulus (GPa)	References
PP/flax-acetylation	30.0	39.0–40.0	4.9–5.0	[58]
PP/hemp	30.0	44.0	3.9	[52, 53]
PP/hemp-MAgPP	40.0	52.0	4.0	[59]
PP/jute-non woven mat	32.0	39.0	8.4	[60]
PP/jute	35.0–50.0	76.0–87.0	4.0–5.3	[61]
PP/jute	30.0–45.0	52.0–54.0	4.2–5.1	[62]
PP/kenaf	30.0	46.0	5.0	[63]
PP/kenaf	50.0	53.0	7.5	[64]
PP/rice husk	30.0	32.1	27.5	[52, 53]
PP/sisal	30.0	45.5	3.9	[52, 53]
PP/wood pulp	27.0	28.0	4.2	[58]
PP/wood BKP-MAgPP	40.0	50.0	3.0	[65]
PP/glass-chopped strand mat	20.0	77.0	5.4	[66]
Epoxy/bamboo	57.0	392.0	29.0	[67]
Epoxy/coconut coir-sisal	40.0	56.0	—	[68]
Epoxy/flax yarn-aligned	45.0	133.0	28.0	[69]
Epoxy/hemp	65.0	165.0	17.0	[70]
Epoxy/jute	52.0	216.0	31.0	[69]
Epoxy/rice husk	25.0	117.1	6.76	[71]
Epoxy/sisal	73.0	410.0	6.0	[72]
Epoxy/sisal	48.0	210.0	20.0	[73]
Epoxy/glass	40.0	335.0		[74]
PF/banana	45.0	7.0–23.0	175.0–398.0	[75]
PF/grewia optiva	30.0	37.9	0.8	[76]
PF/glass	25.0	7.0–17.0	175.0–316.0	[75]
UPE/flax	34.0	143.0	14.0	[77]
UPE/jute	35.0	50.0	8.0	[78]
UPE/rice husk	25.0	73.4	6.0	[71]
UPE/glass	47.0	201.0	13.0	[78]
VE/flax	24.0	248.0	24.0	[77]
VE/glass-woven	59.0	483.0	33.0	[77]

Table 4. Mechanical properties of bio-composites.

Eco-friendly bio-composites from crop-derived plastics and plant-derived fibers would be the materials for near future not only as a solution to the growing environmental threat but also as a solution to alleviating the uncertainty of the petroleum supply. The market size of natural fiber composites is projected to reach USD 6.50 Billion by 2021, at a compound annual growth

	Manufacturer	Model	Application
Automotive Industry	Audi	A2, A3,A4, A4 Avant, A6, A8, Coupe, Roadstar	Boot-liner, hat rack, seat back, side and back door panels, spare tire-lining
	BMW	3, 5, and 7 series	Boot lining, door panels, headliner panels, molded foot well linings, noise insulation panels, seat back
	Citroen	C5	Interior paneling
	Chrysler	Chrysler Sebring	Interior door panel
	Daimler Chrysler	A, C, E, and S class, EvoBus	Business table, dashboard, door panels, pillar cover panel, windshield
	Fiat	Alfa Romeo 146, 156, 159, Brava, Marea, Punto	Door panels
	Ford	Mondeo CD 162, Focus Ford fusion and Lincoln MKZ	Boot liner, B-pillar, door panels Seating headrests
	General Motors	Cadillac De Ville, Chevrolet Trail Blazer	Cargo area floor mat, seat backs
	Lotus	Eco Elise	Body panels, interior carpets, seats, spoiler
	Mercedes-Benz	C, S, E, and A classes Trucks	Door panels, glove box, instrument panel support, insulation, molding rod/apertures, seat backrest panel, seat surface/backrest, trunk panel Bumper, engine insulation, internal engine cover, interior insulation, roof cover, sun visor, wheel box
	Nissan	Nissan Leaf	Floor mats
	Peugeot	406	Front and rear door panels, parcel shelf, seat backs
	Renault	Clio, Twingo	Rear parcel shelf
	Rover	2000 and others	Insulation, rear storage shelf/panel
	Saab	9S	Door panels
	Saturn	L300	Door panel, package trays
	Toyota	Brevis, Camry, Celsior, Harrier, Raum	Door panels, floor mats, radiator end tank, seat backs, spare tire cover
Vauxhall	Astra, Corsa, Vectra, Zafira	Headliner panel, interior door panels, instrument panel, pillar cover panel	
Volkswagen	Bora, Golf, Passat	Boot lid finish panel, boot liner, door panel, seat back	
Volvo	C70, V70	Cargo floor tray, natural foams, seat padding	

	Manufacturer	Model	Application
Constructions and other Industries	Bcomp	AmpliTex®, bCores®, powerRibs. Natural fiber (flax, balsa wood) composite reinforcement material	Automotive, summer and winter sports
	Enkev	Cocoform. Coir (coconut) fiber and natural latex rubber	Containers, boxes, trays, packaging
	FlexForm Technologies	Blends of sustainable natural fibers (hemp, jute, and kenaf) and fiberized thermoplastic polymers	Containers for shipping and storage, interior panels, load floors and underbody shields for cars and trucks, workspace panels and furnishings for offices and homes, structural support for agricultural seedlings
	GAF materials corp	DuraLife™. PP hardwood	Composite decking
	GreenCore	GreenCore NCell™. PP or PE matrix reinforced with up to 40% natural cellulosic microfibers	Containers, home & office furniture, housewares, lawn & garden products, power tools, sporting goods, storage, transportation, and toys Automotive, consoles, door handles, instrument panel components, load floors
	Green line	Plastics (PLA and PP) and additives, natural fibers (hemp and flax)	Cases for musical instruments
	Innovation in green composites technology	50% recycled resin, reinforced with flax (25%) and E-glass (25%) roving	BRP green wall panel
	Lingrove	Lingrove pre-impregnated/ thermoplastic composites, linen fabric, cores + resins	Furniture, music, sport, transportation
	Tech-wood International	Wood plastic composites	Modular house construction
	Trex company	Trex Transcend™. Wood plastic composites and PVC	High-performance decking and railing line
UFP technologies	Mix of 50% natural and 50% PP	Bolsters, door panels, load floors and packaging trays using natural fiber composites, seat backs	
UPM-Kymmene	Wood plastic composites	ProFi decking products	

Table 5. The applications of natural fiber composites.

rate (CAGR) of 11.68%, between 2016 and 2021 [42]. This growth is attributed to the high demand for natural fiber composites in the construction and automotive industries and driven by regulatory requirements and superior product performance. Lightweight, high stiffness-to-weight ratio, consumer awareness regarding recyclable, and bio-degradable materials are the advantages of using natural fiber composites in the composites market [43]. The wide applications of natural fiber composites are growing rapidly in several engineering fields.

Natural fiber-reinforced polymer composite use is of great importance in numerous applications including automotive, building and construction industries, sports, aerospace, and others, such as, decking, panels, window frame, and bicycle frame [79, 80]. Several automotive

components and construction materials are already produced with natural fibers composites with various polymers. The most common polymers used for the applications are polyester or polypropylene, and the natural fibers are flax, hemp, and sisal. Natural fiber composites have received considerable attention by many automotive and construction companies. However, the price, weight reduction, and marketing rather than technical demands will drive the application of natural fiber composites in this industry [81]. A summary of the utilization of natural fiber composites in automotive applications, building and construction industries, as well as others is shown in **Table 5** [82–98].

4. Summary

Natural fiber bio-composites have many advantages; they are relatively cost effective, exhibit good thermal and dimensional stability, low coefficient of friction, and low density and are more environmentally friendly. For these reasons, the popularity of these bio-composites is increasing, and a significant amount of scientific knowledge is already generated. To facilitate the utilization and applications of the bio-composites, all aspects must be present in society: (a) concept development, one of the steps in new bio-composite materials development to better address the future needs of applications, (b) material design, select the bio-composites for applications and to model designs to ensure that a material has the necessary performance capabilities, (c) material fabrication, select the right fabrication methods for the designed bio-composite materials, (d) product manufacturing, improve the way bio-composites, components, and systems are manufactured, as well as the final appearance and functionality of the product, (e) market, understand the market's need and size, and (f) regulations act to promote the utilization of the bio-composites.

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