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Review Article

A Review on Natural Fibers' for Biopolymer Composites

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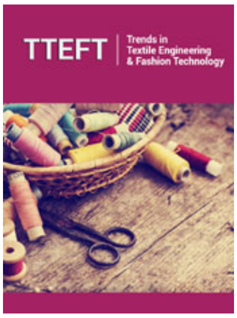

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Abstract

There has been much effort to provide eco-friendly and biodegradable materials for the next generation of composite products owing to global environmental concerns and increased awareness of renewable green resources. Increased use of natural materials in composites has led to a reduction in greenhouse gas emissions and the carbon footprint of composites. In addition to the benefits obtained from green materials, there are some challenges in working with them, such as poor compatibility between the reinforcing natural fiber and matrix and the relatively high moisture absorption of natural fibers. Green composites can be a suitable alternative for petroleum-based materials. However, before this can be accomplished, a number of issues need to be addressed, including poor interfacial adhesion between the matrix and natural fibers, moisture absorption, poor fire resistance, low impact strength, and less durability. Several researchers have studied the properties of natural fiber composites. These investigations have resulted in developing several procedures for modifying natural fibers and resins. To address the increasing demand to use eco-friendly materials in different applications, an up-to-date review of natural fiber and resin types and sources, modification, and processing techniques, physical and mechanical behaviors, applications, life-cycle assessment, and other properties of green composites are required to provide a better understanding of the behavior of green composites.

Keywords: Eco-friendly; Fiber; Composite; Reinforced matrix

Introduction

Composite materials are defined as inherently different materials that, when combined, produce a material with properties that exceed the individual constituent materials. The typical composite consists of a matrix holding the reinforcing materials. Fibers are the most important reinforcing materials, supplying the fundamental strength of the composite. However, reinforcing materials can contribute much more than strength. They can conduct heat or resist chemical corrosion. They can resist or conduct electricity. They may be chosen for their stiffness (modulus of elasticity) or many other properties [1-4].

The mechanical properties of fiber-reinforced polymer composites are critical in deciding their end applications. Mechanical properties of composites depend on the properties of the constituent fibers, the matrix, and the fiber/matrix interfacial shear strength. Fibers are the main load-bearing components of composite material, and the fiber strength directly depends on many factors such as fiber length, shape, bonding, voids, and moisture. In addition, surface treatment is essential. At the same time, the matrix is responsible for arresting cracks from propagation between fibers and holding fibers in the proper orientation, protecting fibers from the environment, and more importantly, transferring the load from the broken fibers to their neighboring intact fibers through the interface [5-13].

Natural fibers have increased interest in the last decade as a substitute for glass fibers in composite components, especially in the housing sector. Fibers like jute, sisal, coconut fiber (coir), ramie, banana, flax, hemp, etc., are cheap, have better stiffness per unit weight, and have a lower environmental impact. Structural applications are rare since existing production techniques are not applicable for such NFC products and the non-availability of semi-finished materials with adequate quality. The moderate mechanical properties of natural fibers prevent them from being used in high-performance applications, e.g., where carbon reinforced composites would be utilized. However, they can compete with glass fibers [14-17].

Advantages and disadvantages determine the choice of their consideration. The lower specific weight of NFCs resulted in higher specific strength and stiffness compared to glass fiber and is preferred, especially where parts are designed for bending stiffness. Many components are now produced as composites, mainly based on polyester or polypropylene can be replaced by fibers like flax, jute, sisal, banana, or ramie. It can be molded into sheets, boards, and gratings [18]. Natural fibers can be classified according to their origin or source, whether from plants, animals, or minerals, as in Figure 1. Table 1 indicates the applications of natural fibers where wide applications are now covered, varying from construction, automotive, piping, and furniture. The type of composite that could be produced from any natural fiber with the relevant testing method is indicated in Table 2. The classification of non-wood and wood fibers is represented in Figure 2. The new field of bio-based materials promises to deliver environmentally friendly, high-performance bio-fiber materials that can replace some synthetic materials [19-25].

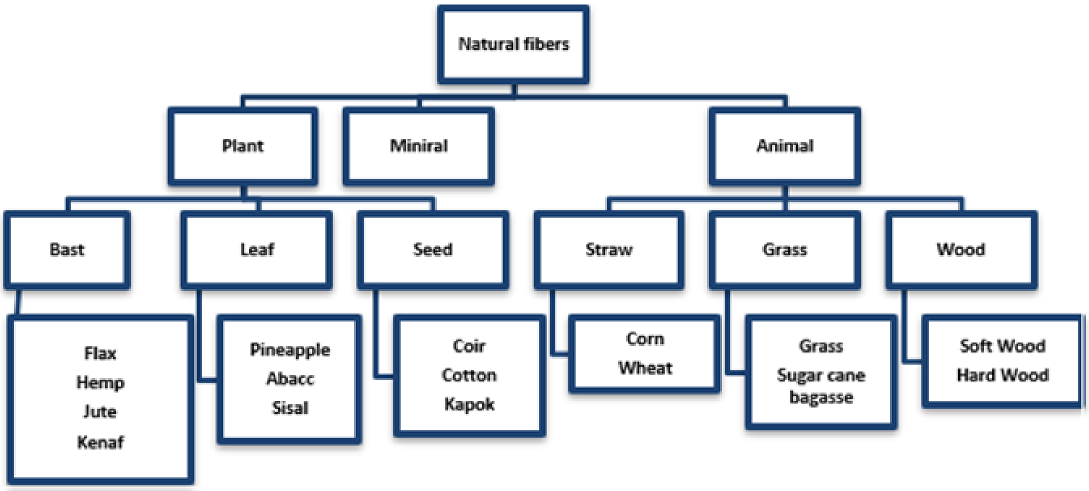

Figure 1: General classification of natural fibers [19-22].

Table1: Comparison of mechanical properties of natural fibers and human organs [21].

		Tensile Strength	Elongation at Break (%)	Young's Modulus (GPa)
Natural Fibers	Flax	300-1500	1.3-10	24-80
	Jute	200-800	1.16-8	10-55
	Sisal	80-840	2-2.6	9-38
	Kenaf	295-1191	3.6	4.3
	Pineapple	170-1627	2.4	2-8.6
	Banana	529-914	3	60-82
	Coir	106-176	14.21-4.9	27-32
	Oil Palm empty fruit	130-248	9.7-14	4-6
	Oil Palm fruit	80	17	1-9
	Ramie	348-938	1.2-8	44-128
	hemp	310-900	1.6-6	30-70
	Wool	120-174	25-35	2.3-3-40
	Spider silk	875-972	17-18	13-15
	Cotton	264-800	3-8	6-12.6
Human tissues		130-160	3-6	17-20
Hard tissue tooth bone	Human compact bone longitudinal direction	130-160		
	Skin	76	78	

	Tendon	53-150	9.4-12	15
	Elastic cartridge	3	30	
	Heart valves	0.45 -2.6	0.45-2.6	
	Aorta	0.7-1.1	77-81	

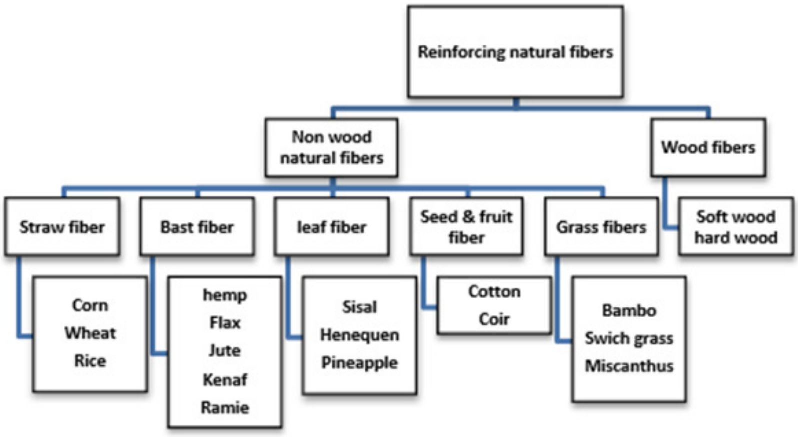

Figure 2: Classification of non-wood and wood fibers [19-22].

Table 2: Distribution of materials in global solid waste and their comparison to Plastic wastes [24,25].

Global Municipal Waste Categories	Percentage Waste (%)
Food scrap	14
Paper and paper board	30
Plastics	12
Yard trimmings	14
Rubber leather and textiles	8
Rubber leather and textile metals	9
Glass	5
Wood	6
Others	3

General classification of composites

There are two classification systems of composite materials: one is based on the matrix material (metal, ceramic, and polymer), and the second is based on the material structure.

General composite material classified based on matrix materials

A. Polymer matrix composite (PMC)

B. Metal matrix composite (MMC)

C. Ceramic matrix composite (CMC)

Composite material classified basis of reinforcing material structure

Particulate composites: Particulate composites consist of a matrix reinforced by a dispersed phase in the form of particles:

a) Composites with random orientation of particles.

b) Composites with preferred orientation of particles.

The dispersed phase of these materials consists of two-dimensional flat platelets (flakes) laid parallel to each other.

Fibrous composites:

A. Short-fiber reinforced composites. short-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in the form of discontinuous fibers (length <100mm).

B. Composites with random orientation of fibers.

C. Composites with preferred orientation of fibers.

D. Long-fiber reinforced composites. Long-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in the form of continuous fibers.

E. Unidirectional orientation of fibers. Bidirectional orientation of fibers (woven).

Laminate composites: A fiber-reinforced composite consists of several layers with different fiber orientations, called multilayer (angle-ply) composite.

Composite design: With all these factors in mind, one should design the composite he needs for any special application, bearing in mind the end user and requirements of the end product as well as sustainability and ecology. The design for sustainability methods can be established under the idea of sustainability in dimensions of ecology, economy, and social pillars. Design for sustainability concept is implemented in concurrent engineering, including concept, embodiment, and detail design processes. Integrating sustainability in engineering designs is crucial to producing greener products, system innovation, and services aligned with current market demand [23].

Green composites: Green composites are a specific part of bio-composites, in which natural fibers reinforce bio-based polymer matrix; they symbolize a developing area in composites. In a situation like an increment in oil price, using green composites helps improve the environment from an economic perspective. Table 3 shows the distribution of various materials present in the global solid waste. As shown in Table 3, plastic waste amounted to about 12% of the other solid waste generated by weight globally [24]. Natural fibers composites have gained application in the medical field in the human body due to their eco-friendly nature and acceptance inside the human tissues see Table 1 [21].

Table 3: Natural fibers Products and applications [19-21].

Natural Fiber	Product	Application
Coir	Coir fiber reinforced concrete	Building material in civil engineering
Banana stem	Banana stem reinforced PVC composite pipe	Petroleum industries
Almond shell, sugar cane leaves	Composite board	Automobile industries
Sugarcane bagasse	Recycling polymeric to produce building material boards and bricks	Building material
Coconut, oil palm, bagasse fibers	Reinforcement in Soil blocks	Construction purpose in building material
Coir	Coir polyester composite (light doom, engine guard, wall panels, light weight alternative building material, panels and insulators.	Automobile industries, building material, electrical industries.
Banana, pineapple leaf fiber	Banana, pineapple leaf fiber reinforced polyester composite	Automobile interior parts, electronic packages, building constructions.
Banana	Mat, yarn	Automobile, aerospace parts
Fenugreek and banana composite	Circular disc	Steam pipes, automobile interior parts, building construction materials.
Sugarcane fiber	Concrete block, increase strength of normal concrete	Building construction materials
Coconut coir, bagasse fiber	Composite panel	Wall ceiling, automobile interior.
Banana fiber	Composite panel using local plastic and agricultural waste	Construction material
Coir	Fiber boards	Furnituren and construction industries.
Hemp	Thermal insulating board	Building and public work sectors
Coir	Concrete	Buildings, road pavements, bridge decks

Municipal waste has become a threat to the environment in the last decades costing local governments considerable budgets to get rid of that, including materials used for various products, including home uses and industrial uses and the table below shows the distribution of such waste according to the category as indicated in Table 2.

Green composites are widely investigated due to their potential properties. The biodegradable polymeric material is reinforced with natural fibers to form an eco-friendly and environmentally sustainable composite. The green composites eliminate the traditional materials such as steel and wood with biodegradable polymer composites [25]. While advanced green composites with high strength and stiffness developed recently could find their way into structural applications in the future, other special characteristics such as fire resistance and autonomous self-healing in green composites can improve their durability and safety [26].

Koronis G et al. [27] created so much database of biopolymers and natural reinforcements with the mechanical performance of several components for green composite. The matrix and reinforcement are screened accordingly to identify which holds both sufficient strength and stiffness performance along with the affordable cost to be a promising proposal for a green composite [27]. These composites can be further environment-friendly when the polymer matrix is biodegradable and comes from renewable sources [28,29]. Bajpai PK et al. [30] developed biodegradable composites from nettle and Grewia optiva natural fibers reinforced polylactic acid green composites [30]. Yong et al. [29] prepared green composites using jute fiber loading in natural rubber with different wt % [29]. Yusoff RB et al. [31] investigated hybrid green composites reinforced by kenaf, bamboo, and coir fibers with polylactic acid (PLA) polymer matrix [31]. Koyuncu M et al. [32] studied the effect of alkaline treatment on the mechanical properties of cotton fabric reinforced green epoxy composites [32]. Bamboo/PLA green composites also were fabricated by Surya Rao G et al. [33]. The 3D woven interlock fabrics were produced on a dobby loom using novel weaving patterns, with variation in binding point density. These fabric structures were then used to fabricate composites with green epoxy resin as a matrix development by Jabbar M [34].

Natural Fiber as Biodegradable Materials

Natural fiber reinforced scientists and engineers in different sectors have widely researched composites due to environmentally friendly characteristics such as biodegradability that can lead to a significant reduction in carbon footprint. Even advanced industrial sectors such as aerospace and automotive have tried using natural fiber reinforced composites in critical applications to promote sustainable technologies [35]. Many researchers have conducted research using natural fibers for fabricating green composites.

In Table 3, the physical and mechanical properties of jute fiber used in Composites are shown as low density, better elongation, and higher tensile strength of jute fiber. The tensile strength of jute fiber is higher than most natural fibers, as reported in the literature [36-39].

Natural fibers properties

Natural fibers are subdivided according to their origins: vegetable, animal, and mineral. Fibers from vegetables are found in the stem, leaves, seeds, fruit, wood, straw, or bagasse of cereals and fodder. The chemical composition and the structure of fibers are complex since their organization is similar to a composite material. It is designed by nature, forming a rigid matrix that contains crystalline microfibrils of cellulose merged with lignin and/or hemicellulose. Most fibers of vegetable origin, except for cotton, are composed mainly of cellulose, hemicellulose, lignin, waxes, and some water-soluble components [40].

Natural fibers primarily consist of cellulose, hemicelluloses, pectin, and lignin. The individual percentage of these components varies with the different types of fibers. This variation can also be affected by growing and harvesting conditions. Cellulose is a semicrystalline polysaccharide responsible for the hydrophilic nature of natural fibers. Hemicellulose is a fully amorphous polysaccharide with a lower molecular weight than cellulose. The amorphous nature of hemicelluloses results in them being partially soluble in water and alkaline solutions. Pectin, which functions to hold the fiber together, is a polysaccharide like cellulose and hemicellulose. Lignin is an amorphous polymer, but unlike hemicellulose, lignin is comprised mainly of aromatics and has little effect on water absorption [41-43] (Table 3).

The mechanical properties of natural fibers represent a cornerstone, especially in composite manufacturing and usage. A lot of attention has been given to the mechanical properties before deciding which fiber to use for any application (Table 4) [44]. It is mentioned earlier that the properties of natural fibers are of essential issue in the composite material, so it important to decide upon the tests needed for each fiber before assigning the fiber for any sage (Table 5) .

Table 4: Natural fiber products and testing methods [4,44].

Natural Fiber	Products	Various Testing Applied
Coir	Coir fiber reinforced concrete	Compressive test/Tensile test/Flexural test
Banana stem	Banana stem reinforced PVC composite pipe	Thermal test
Almond shell, sugar cane leaves	Composite board	Tensile test/Flexural test/Impact test
Sugarcane bagasse	Recycling polymeric to produce building material boards and bricks	Water absorption test
Coconut, oil bagasse fibers	Reinforcement in soil blocks	Water absorption test/Tensile test
Coir	Coir polyester composite (light doom, engine guard, wall panels, light weight alternative building material, Panels and insulators.	Impact test
Banana, pine leaf fiber pineapple	Banana, pineapple leaf fiber reinforced polyester composite	Thermal test/Conductivity
Banana	Mat, yarn	Tensile test/Flexural test
Fenugreek and banana composite	Circular disc	Thermal test/Cconductivity test
Sugarcane fiber	Concrete block, increase strength of normal concrete	Compressive test/Tensile test
Coconut coir, bagasse fiber	Composite panel	Thermogravimetric analysis/Water absorption test
Banana fiber	Composite panel using local plastic and agricultural waste	Tensile test
Coir	Fiber boards	Flammability test/Burning test
Hemp	Thermal insulating board	Thermal conductivity test/ensile test/Flexural test
Coir	Concrete	Quasi static strength test/Impact resistance test/ Microstructure test

Table 5: Mechanical Properties of natural fibers [41–43].

Fiber	Density g/cm^2	Diameter µm	Tensile MPa	Young's Modulus	Elongation at Break %
Cotton	1.5-1.6	-	287-800	5.5-12.6	7-8
Vakka	0.81	-	549	15.85	Mar-45
Date A	0.99	-	309	11.32	2.73
Date B	0.96	-	459	1.91	24
Bamboo M	0.91	-	503	35.91	1.4
Bamboo C	0.89	-	341	19.67	1.73

Palm	1.03	-	377	2.75	13.71
Coconut	1.15	-	500	2.5	20
Banana	1.35	-	600	17.85	3.36
Sisal	1.45	-	567	10.4	5.45
Jute	1.3-1.45	25-200	393-773	13-26.5	1.16-1.5
Flax	1.5	-	345-1100	27.6	2.7-3.2
Hemp	-	-	690	-	1.6
Ramie	1.5	-	400-938	61.4-128	1.2-3.8
PALF	-	20-80	413-1627	34.5-82.51	1.6
E-Glass	2.5	-	2000-3500	70	2.5
S-Glass	2.5	-	4570	86	2.8
Aramid	1.4	-	3000-3150	63-67	3.3-3.7
Carbon	1.7	-	4000	230-240	1.4-1.8
Pine Apple Leaf Fiber3000-3150					

The research on jute fiber reinforced composites is at the initial stage, and their practical applications require extensive study. However, some researchers investigated their feasibility for specific applications (Table 5). For example, Munikenche et al. [45] studied the mechanical properties, modulus, Poisson's ratio, and strength of woven jute fabric-reinforced composites using hand lay-up techniques [45].This is the first report by any single group of researchers in which tensile strength, compressive strength, flexural strength, impact strength, in-plane shear strength, interlaminar shear strength, and hardness are given. Ma Sheng et al. [46] discussed the effect of different jute fiber content and different jute fiber length on composite properties, such as tensile strength, flexural strength, and impact strength [46]. Hong CK et al. [47] enhanced the tensile and dynamic mechanical properties of the jute/polypropylene composites by the silane surfaces treatment to increase the interfacial adhesion between the jute fiber and the polymer matrix [47]. Abdul Jabbar et al. [48] evaluated the mechanical and dynamic mechanical properties of woven jute fabric-reinforced green epoxy composites [48]. The treated jute fibers were characterized by scanning electron microscopy and Fourier transform infrared spectroscopy. The treatments resulted in the enhancement of flexural and impact properties. In the other paper, Abdul Jabbar et al. [49] investigated the effect of chemical treatments and nano-cellulose spray coating over non-woven jute Composites on the tensile, flexural, drop weight impact, and compression after impact properties [49]. The results revealed the improvement in mechanical properties after chemical treatments and nanocellulose coating. Ameer studied the interdependence of moisture regain, hydrophobic treatment, and the mechanical properties of jute fiber-reinforced composite materials [50]. Compared to untreated fabric composites, the composites produced with hydrophobically treated reinforcement showed lesser moisture regain and improved tensile and flexural strengths. The mechanical properties of flax, jute, and jute/carbon woven fabrics were investigated and compared with each other and with 3K carbon woven fabric composites. Mechanical properties of the yarns and fabrics were characterized and compared for each scale. The fabric structure, yarn physical properties, fiber cross-section, and fiber molecular structure parameters of the fabric were investigated by Karahan M et al. [51-53].

Jute fibers

Figure 3: Jute fibers from jute plant.

Jute fibers are one of the largest sources of cellulosic bast fiber that occupies second place in world production after cotton [54]. This fiber is extracted from the ribbon of the stem, as shown in Figure 3, to extract fine fibers from the jute plant; the first parameter considered is if the fiber can be easily removed from the jute hard or core before the crop been harvested. Jute stalk, after harvesting, is submerged in soft running water in bundles for 20 days. Then, grabbed in bundles and hit with a long wooden hammer to make the fiber lose from the jute hard or core. Then, the extracted jute fiber is washed with water and left to dry [55,56]. In the recent study of the extraction method on crystallinity and chemical analysis of the extracted jute cellulose nanofibers via X-ray diffraction (XRD) and Fourier transform infrared (FTIR) analysis and its potential used as reinforcement material was studied and compared with those of raw jute fiber [53,57,58] (Table 6-8).

Table 6: Chemical and mechanical properties of jute fiber [58].

Properties	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Waxes (%)	Moisture Content (%)	Density (g/cm³)	Fiber Length (mm)	Diameter of Fiber (µm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Microfibrillar Angle (°)	Price (EUR/kg)
Jute fiber	64.4	12	11.8	0.2	0.5	1.1	1.46	0.8-6	5-25	393-73	13-6.5	1.16-1.5	8	0.3

Table 7: Mechanical properties of jute fiber reinforced thermoplastic and biodegradable polymer composites [58].

Reinforcement	Matrix	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (GPa)	Flexural Modulus (GPa)
Bidirectional jute fiber mat	Epoxy	110	4.45	55.8	3.02
Jute	Epoxy	69.66	6.19	94.08	5.91
Woven jute	Epoxy	15.23	0.2554	79.2	1.3555
Woven jute	Epoxy	12.79	0.1985	81.81	1.318
Jute laminate longitudinal (0-0)	Epoxy	112.69	14.59	-	-
Jute laminate longitudinal (0-90)	Epoxy	39.1	8.97	-	-
Jute	Epoxy	16.62	0.664	57.22	8.956
Jute	Epoxy	26.53	6.32	66.67	3.78
Jute	Polyester	60	7	92.5	5.1
Jute	Polyester	48.52	4.25	63.01	3.62
Jute	Polyester	77.1	5.07	176	19.26
Long jute longitudenal	Polyester	162	5.58	-	-
Long jute transverse	Polyester	0.43	0.98	-	-
Jute Mat	Polyester	23	4	-	-
Jute	Vinylester	-	-	199.1	11.89
Jute Mat	Vinylester	42	1.61	56.2	3.75

Table 8: Reinforced thermoset polymer composites [58].

Reinforcement	Matrix	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (GPa)	Flexural Modulus (GPa)
Jute	LDPE	17/5	1.1	20.7	0.6
Jute	HDPE	27.4	-	34,83	-
Jute	Polycarbonate PC	63.5	-	87	4.1
Jute fiber	Polypropylene PP	23.56-29.49	1.79-2/4	42.63-48.31	1/28-3.1
Jute fabric	PP	52	1.03	63	3.27
Jute fabric	PP	28.4	-	35.1	-
Jute	PP	32	0.85	38	1.685
Short jute	Polylactic Acid PLLA	55	0.867	67	2.83
Non-woven jute fabric	PLLA	81	1.12	82	4.3
Untreated woven jute (x-direction	PLLA	71	0.78	81	3.62
Untreated woven jute (Y-direction	Starch	22.3	2.47	36.4	-
Jute strand	Soy	37.1	1.04	38.4	1.12
Nonwoven jute	Soy	35.6	0.972	335	1.026
Woven jute	Biopol	81-42	1.92	-	-

Jute	Malated Castor oil MACO	-	-	14	1.7
Jute	Unsaturated polyester resin	-	-	34.1	1.8
Jute	Soy protein	64	6.1	24.1	4.074

Sisal fiber

Sisal fiber is derived from the leaves of the plant. Machine decortications usually obtain it. The strands are usually creamy white, average from 80-120cm in length and 0.2-0.4mm in diameter, and are lustrous in appearance. The global production is about 3000,000 tonnes. Brazil is the largest producer, followed by China, Mexico, Tanzania, Kenya, and Madagascar.

Sisal is a member of the agave family; Agave Sisalana is a commercially grown species. The plants grow for 7 to 12 years, producing a flower stalk 4 to 6 meters tall, and dying. Sisal is a xerophytic plant, and thus it can grow in dry climates, but it will not grow sufficiently in poorly drained soil. The life of the sisal plant is usually 15-18 years. Sisal is generally harvested once a year, but if the soil and the climate permit, it can be harvested three times in two years [59]. Uses of sisal fiber are sisal materials, including rope sisal core for steel wire rope, yarn and twine, sisal cloth polishing, buff carpet pulp, constructing materials, and doormats [59] (Table 9,10).

Table 9: Physical properties of sisal fibers [59].

Length (mm)	Width (µm)	Tenacity (cN/tex)	Elongation (%)	Moisture Regains (%)
2.88	22.6	57.2	3.02	13

Table 10: Chemical composition of sisal fiber [59].

Cellulose (%)	Hemicellulose (%)	Pectin (%)	Lignin (%)	Water Soluble Materials (%)	Fat and Wax (%)	Ash (%)
55-65	10-15	2-4	10-20	1-4	0.15-0.3	0.7-1.5

Sisal fiber is a potential reinforcement for polymer composites. Beyond its traditional applications (ropes, carpets, mats, etc.), sisal fiber has potential applications in the aircraft and automobile sectors. Sisal fiber's physical and mechanical behaviors depend on their source, age, location, fiber diameter, experimental temperature, gauge length, and strain rate. Fiber surface modification or treatment improves interfacial adhesion between the hydrophilic sisal fiber and the hydrophobic polymer matrix. This leads to a reduction in moisture absorption and an enhancement of mechanical properties. The surface modification includes

A. Peroxide (promotes grafting reactions),

B. Silane treatment (hydrophilic characteristics can be modified by introducing long chain structures onto the sisal fiber),

C. Alkali and permanganate treatment (forming a rough sisal fiber surface, which improves the contact area of the fiber with the matrix), and

D. Thermal treatment.

The mechanical and physical behaviors of sisal fiber-based polymer composites are sensitive to the manufacturing methodology, fiber length, fiber orientation, fiber volume fraction, and type of matrix used (either thermoset or thermoplastics). Sisal fiber-based hybrid composites take advantage of their individual constituents. Overall, sisal fiber-based composites' fracture mechanics and fracture toughness must be studied in detail. The relationship between the mechanical properties and the manufacturing method must be established to use sisal fiber effectively in different applications. Glass-sisal fiber hybrid composites were developed, and their mechanical properties were evaluated. Similarly, the effects of processing parameters, treatments, gauge length, and matrices on high-performance and high-cost Kevlar, carbon fiber-sisal fiber hybrid composites have yet to be studied. The recycling methodology and life-cycle assessment of sisal fiber and hybrid sisal fiber-based composites must be investigated thoroughly. Recycling of composites is an attractive subject of research in the future that will provide socioeconomic benefits (Figure 4) [60-62].

Figure 4: Sisal fiber after harvesting [59].

Banana fiber

The banana fibers are the waste product of banana cultivation due to the lack of suitable sustainable technology for its economic utilization. Therefore, these fibers can be obtained for industrial purposes without additional cost. The banana plant not only gives the fruit but it also provides textile fiber and is most commonly found in hot tropical climates [63,64]. All varieties of banana plants have fibers in abundance. The chemical composition of banana fiber is cellulose, hemicellulose, and lignin. Rani K et al. [65] have investigated the molecular structure of banana fiber and the grafted by butyl acrylate as below (Figure 5) [65].

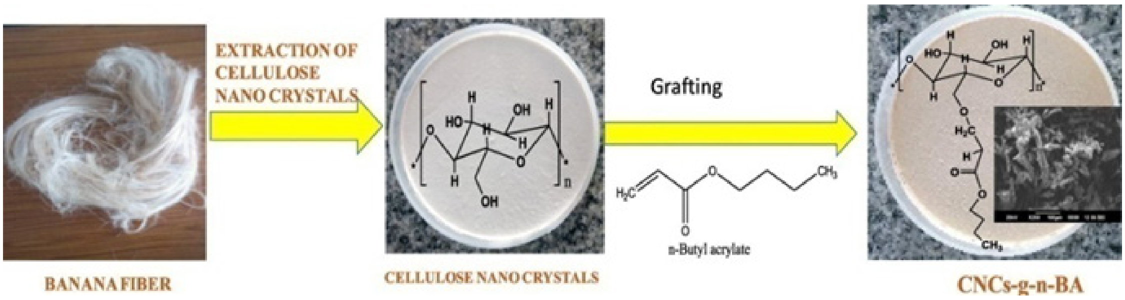

Figure 5: Molecular structure of banana fiber and the grafted by butyl acrylate as below [65].

These fibers are obtained after the fruit is harvested and fall in the group of bast fibers. This plant has long been a good source of high-quality textiles fiber in many parts of the world, especially in Japan and Nepal. Banana fiber is similar to that bamboo fiber, but its fineness and spin ability are better. It can be spun through almost all the methods of spinning, including ring spinning, open-end spinning, bast fiber spinning, and semi-worsted spinning, among others. Interestingly banana stem particles have been used in composites with PVC for piping to reduce the cost of material [66-68]. Monzon et al. [69] after comparing banana and flax composite, have concluded that flax composite has higher modulus strength than banana composite. This can be attributed to high flax fiber modules [69-71] (Table 11).

Table 11: Physical and mechanical properties of banana fibers used in composites tensile strength (N).

Tensile Strength (N)	Density (g/mm^2)	Diameter (mm)	Strain (%)	Average Fiber Length (mm)	Young's Modulus (N)
17.2	1.3	0.6	37	1500	4.7

The banana fiber has many advantages such as highly strong fiber, smaller elongation, shiny appearance depending upon the extraction & spinning process, lightweight, absorbs as well as releases moisture very fast and bio-degradable and has no negative effect on the environment and thus can be categorized as eco-friendly fiber. This good environmentally friendly feature makes the materials very popular in engineering markets such as the automotive and construction industry [72].

Manual extraction of banana fiber produces good quality fiber, but it is much more time-consuming. The labor expense is relatively high, and output is quite low. Hence efficient extraction of banana fiber can only be possible through mechanization. Banana fibers are extracted by using a decorticator machine or defibering machine. By using the decorticator crushing action, the pulpy material was removed. After the extraction, the fibers were washed and allowed to dry. Gentle combing was done to remove excess pith from the fibers. Washing was done by immersing the fibers in the large centrifugal washing machine and allowed to dry. The banana was reported to have been washed with alkali, which improves its water absorbency, luster, and strength [73-77]. The extracted fibers were observed to be in long strands and slightly dull yellowish, as shown in Figure 6 [21,64,78]. The new banana fiber extraction machine can be designed with higher efficiency, as shown in Figure 7. This machine will reduce manual work and is suitable for mass production. Compact structure and easy disassembling will be another advantage (Figure 8) [79,80].

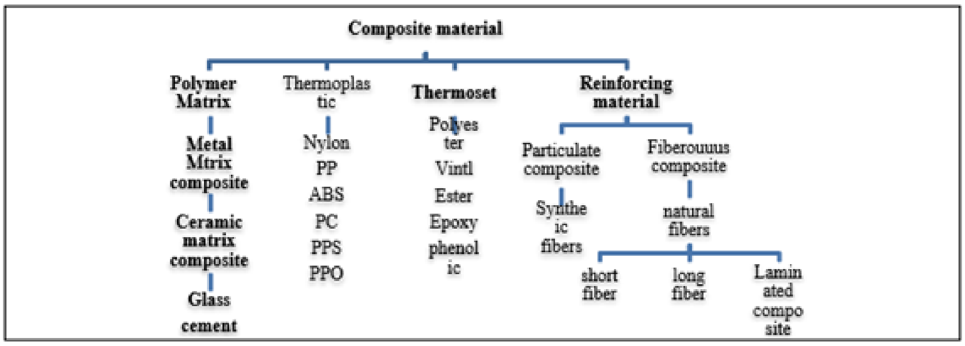

Figure 6: Composite materials matrix and reinforcements [21].

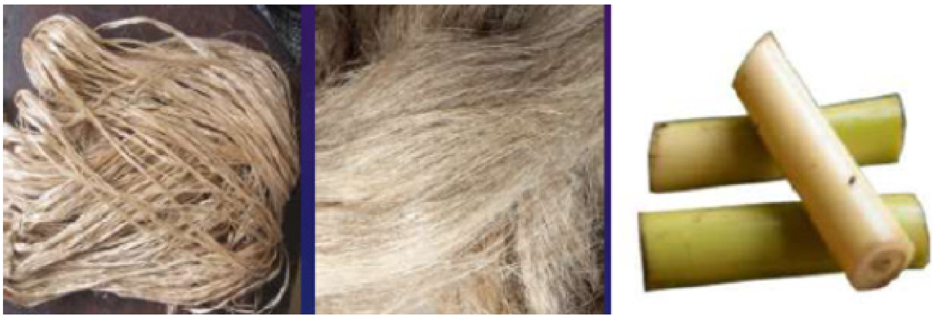

Figure 7: Banana fibers from banana plant.

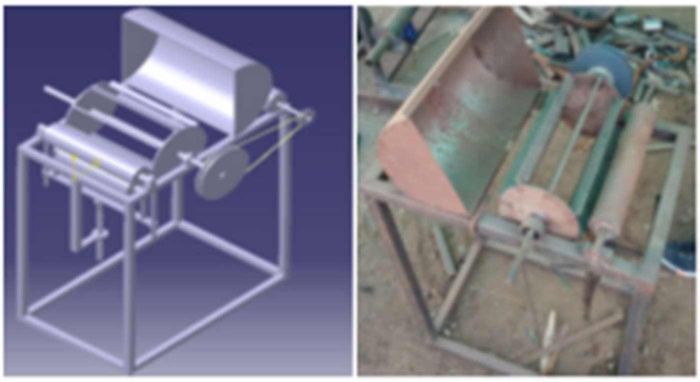

Figure 8: Banana fiber extraction machine [79,80].

Banana fiber possesses good specific strength properties comparable to conventional materials, like glass fiber [81]. Some of the mechanical and physical properties of the banana fiber are presented in Table 3 [19-21,81]. In the last few years, there has been intense research on banana fiber composites. These researches show that banana fiber composite exhibits superior properties to conventional composites. Numerous studies have shown that adding banana fiber reinforcement can significantly enhance many properties, such as stiffness and strength [82]. All these properties make the materials suitable for various applications such as construction, automotive, electronics, and packaging (Table 12).

Table 12: Physical and mechanical properties of banana fibers used in composites.

Water absorption after 24h (%)	Density (g/mm^2)	Diameter (mm)	Elongation (%)	Fiber Length (mm)	Tensile Strength (MPa)
12-25	1.3	0.1-0.2	1.5-3	20-50	400-900

A number of investigations have been conducted on banana fiber composites. Laly et al. have investigated banana fiber reinforced polyester composites and found that the optimum content of banana fiber is 40% [83]. The mechanical properties of banana-fiber-cement composites were investigated physically and mechanically by Corbiere-Nicollier [84]. It was reported that kraft pulped banana fiber composite has good flexural strength. In addition, short banana fiber reinforced polyester composite was studied by Pothan et al. [83] the study concentrated on the effect of fiber length and fiber content [85]. Paul AS et al. [86] investigated the thermo physical properties of the banana composites as a function of the banana fiber loading and for different chemical treatments given to the banana fiber [86]. However, Komal et al. [87] study the effect of chemical treatment on the mechanical properties of banana fiber reinforced polypropylene composites [87]. El Meligy et al. [88] used raw and treated banana fiber composites; treated banana fiber composites reduced swelling and improved strength and dielectric properties [88]. Treated banana fiber composites reduce swelling and improve strength and dielectric properties. Jamil M et al. [89] treated banana fiber to increase the adhesion between banana fiber and polymer matrix [89]. Venkatesh N et al. [90] Waranet carried out the tensile, flexural, impact, and water absorption banana/epoxy composite. This study showed that increasing the mechanical property and decreasing the moisture absorption by adding sisal fiber in banana/epoxy composites of up to 50% by weight [90]. Hassan MZ et al. [91] showed that fiber length, fiber content, and chemical treatment variables significantly influence the mechanical behavior of banana composites [91]. Arthanarieswram VP et al. [92] have combined banana fibers with sisal and reinforced them with epoxy to form a composite. He added layers of glass fibers, which consolidated and improved the strength of the panel's flexural rigidity [92].

The mechanical and tribological properties of a developed banana fiber-reinforced composite with various orientations have been investigated by Chavali PJ [93]. The results show that both volume fraction and fiber orientation significantly affect the mechanical properties of the banana/glass fiber reinforced hybrid composite materials [94]. Another structure of banana woven fabric reinforced epoxy composite was prepared by the hand lay-up method, as shown in Figure 9 [95].

Figure 9: Pseudo-stem banana fibers in the woven fabric configuration [95].

During the last few years, the interest in using natural fibers hydrated with other natural or synthetic fibers as reinforcement has increased significantly. Prasad V et al. [96] study the new set of jute and banana fiber hybrid polymer matrix composite [96]. Thanushan et al. [97] focused on the post-peak behavior and durability of banana fiber and coconut coir-strengthened cement-stabilized soil blocks [97]. Batu et al. [94] Lemu designed the mechanical properties of banana/glass fiber reinforced hybrid composite materials at different fiber volume fractions and orientations [94].

Banana fibers must be spun and woven to produce a textile grade of banana fibers; banana fibers can be spun to get yarn, although the machinery should be adapted to the high stiffness of these fibers. Better results are obtained when blending banana fibers with other softer fibers and then twisted to obtain the yarns (Figure 10) [76]. Many investigations have been carried out on the various form of banana structure in the composite, whether unidirectional strands, random fibers, or else it si deduced that banana fiber yarn is the best fiber configuration for obtaining the best mechanical properties in composites [81].

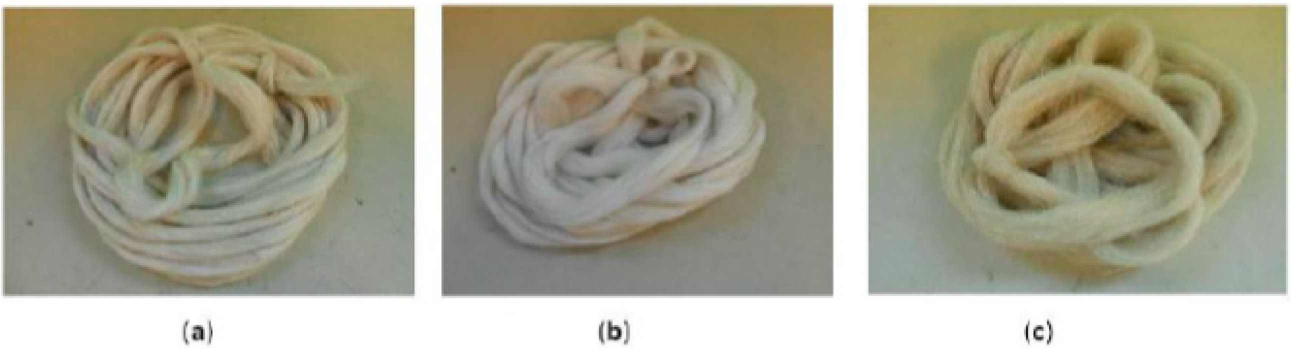

Figure 10: Drawing silver of banana fiber blended with (a) cotton (b) polyester (c) wool [76].

Chemical Treatment of Natural Fiber

Alkali treatment

Therefore, chemical treatment of natural fiber is an alternative solution often applied to overcome this problem [98]. One of the common and widely used techniques to clean and modify a natural fiber surface is an alkali treatment process [99,100]. Hot-alkali treatment was used to pretreat jute fabrics to improve their interfacial compatibility leading to better cohesion and interfrictional forces between fibers leading to high modulus and high flexural strength [101].

Zin M et al. [102] showed that alkaline treatment improved surface topography, heat resistivity, interfacial bonding with epoxy matrix, removal of impurities, and increased surface roughness [102]. Also, the alkaline treatment improved the thermal stability and heat resistivity [103].

Raharjo was showed the diameter measurement showed that the alkaline treatment reduces the average fiber diameters due to the decline of the hemicellulose and lignin content as fiber matrix. This caused an increase of the tensile strength and elastic modulus due to the reduction of diameters as the divider mean. At the same time, the cellulose content as a structural supporter of the fibers was relatively constant [104].

Acetylation of natural fibers

Acetylation describes a reaction introducing an acetyl functional group (CH3COO-) into an organic compound. Acetylation of natural fibers is a well-known esterification method causing the plasticization of cellulosic fibers [98]. Acetylation can reduce the hygroscopic nature of natural fibers and increase composites' dimensional stability [105-108]. Acetylation was used in surface treatments of fiber for use in fiber-reinforced composites [109]. Also, improve the fiber-matrix adhesion [110]. Petr L et al. [111] claim that chemical methods of acetylation on the final properties of biopolymer composites proved to enhance the properties of composites [111].

Benzoylation of natural fibers

Benzoylation of fiber improves fiber-matrix adhesion, thereby considerably increasing the strength of the composite, decreasing its water absorption, and improving its thermal stability [108,112]. Nair et al. was observed that the thermal stability of treated composites was higher than that of untreated fiber composites. Benzoylation Improve hydrophobicity [109].

Acrylation and acrylonitrile grafting

The Acrylation reaction is started by free radicals of the cellulose molecule. High-energy radiation generate radicals' cellulose [113]. Treated natural fibers with silane and acrylation led to the strong covalent bond formation, thereby improving the tensile strength and Young's modulus marginally [98]. Composites' tensile strength was improved, and water absorption of composites was decreased [114]. Improve UV-protective properties, hydrophobicity, and mechanical properties [102]. Mishra et al. [115] also found that grafting of chemically modified fibers with AN increased tensile strength and Young's modulus of fibers [115].

Silane treatment

Silane is a chemical compound with the chemical formula SiH4. Silanes are used as coupling agents to let glass fibers adhere to a polymer matrix, stabilizing the composite material [116,117]. Silane coupling agents may reduce the number of cellulose hydroxyl groups in the fiber matrix interface [98]. Silane coupling agents were shown to effectively modify the natural fiber-polymer matrix interface and increase the interfacial strength [118]. Natural fiber treated with silane Improves hydrophobic and mechanical properties [102,109].

Enzyme treatment

Currently, the use of enzymes in the field of textile and natural fiber modification is also rapidly increasing. A significant reason for embracing this technology is that the application of enzymes is environmentally friendly. The reactions catalyzed are very specific and have a focused performance. It reduces the lignin content [102,119-121].

Mercerization or alkali treatment is one of the common techniques widely used to modify fiber surfaces. Furthermore, this treatment was considered the most straightforward and cheapest treatment method compared to other chemical treatment methods [122]. It reduces moisture regain and improves mechanical properties [102].

Methacrylate improves tensile and flexural strength [102,123], while ozone affects surface energy and contact angle [102,124]. Peroxide reduces moisture regain [102,125,126]. Sodium chlorite improves tensile strength, young's modulus, and elongation at break [98,102,127].

Applications of natural fiber reinforcement composites

Within the last 20-25 years, natural fiber research has experienced an explosion of interest, particularly in replacing glass fibers in composite material applications [128]. The mechanical properties of many natural fiber reinforcement composites are negatively impacted at the fiber/resin interface and the laminar level if moisture is present at the interface. Automotive, civil engineering and aerospace are the three main natural fiber reinforced composites applications. Where it's been used for secondary or even primary structural components. Examples for secondary structural applications include window, door, frame, and roof panels in automotive and spring or trim tabs in an aircraft. In contrast, examples of primary structural applications include front and rear bumper reinforcements in an automotive [129-131]. Natural fibers were used in the construction industry to improve their tensile strength, ductility, impact resistance, toughness, and to reduce drying shrinkage [62,132]. Based on extensive experimental studies, we concluded that banana fiber reinforced hybrid composites could be an alternative to pure glass fiber reinforced composites, with comparable and even higher load withstanding capabilities. Using banana fiber reinforced hybrid composites to fabricate hockey products would cut costs and lower the environmental impact stemming from using biodegradable organic materials. It will also lead to the development a domestic economy based on domestic resources [75].

The application of green composites in automobile body panels seems feasible as green composites have comparable mechanical performance with synthetic ones. Mercedes-Benz used an epoxy matrix with the addition of jute in the door panels in its E-class vehicles back in 1996 [133]. Another paradigm of green composites' application appeared commercially in 2000 when Audi launched the A2 midrange car: the door trim panels were made of polyurethane reinforced with a mixed flax/sisal material [134]. Flax fiber has been the most relevant natural fiber for the German automotive industry [135]. Hariprasad K et al. [136] investigated composites reinforced by milkweed, kusha grass, sisal, banana, and hay mixed with polypropylene 10:90 (wt. %) for automotive applications [136]. Automotive brake friction composites containing 5wt.%, 10wt.%, 15wt.%, and 20wt.% of natural fibers (hemp, ramie, and pineapple) were developed by Tej Singh [137].

Conclusion

During the last few years, the interest in using natural fibers as reinforcement in polymers has increased significantly. Natural fibers are not only strong and lightweight but also relatively very cheap and bio-degradable.

a) Scientists and engineers have widely researched natural fiber-reinforced green composites for their applicability in different industrial sectors due to their sustainable nature. They also have a significant reduction in carbon footprint.

b) The main factors influencing natural composites' mechanical behavior are fiber length, fiber content, and chemical treatment.

c) Banana fibers used as a reinforcing material have offered various advantages as they are environmentally friendly, relatively low density, and abundantly available.

d) Even advanced industrial sectors such as aerospace and automotive have tried using natural fiber reinforced composites in critical applications.

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