Alternative Natural Fibers for Biocomposites

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Abstract The increasing cognizance of the ecological harm produced by synthetic materials has given rise to the rapid increase in the consumption of environmental-friendly materials. There has been a great upturn in demand for marketable consumption of ecological natural fiber-based composites in several manufacturing industrialized sectors, such as automotive, building construction, furniture, and aerospace in recent years. Natural environment-friendly fibers are renewable resources which are abundant in nature with benefits of low cost, lightweight, renewability, biodegradability, and higher specific characteristic as compared to synthetic materials. The enduring feasibility of natural fiber-based composite materials has increased their usage in several manufacturing sectors. In this chapter, different sources of natural fibers, their characteristics, and morphological structure are discussed in detail. Moreover, the primary use of ecological natural fibers, as well as their effective utilization as reinforcement in polymer composite materials were also summarized.

Keywords Seed fibers · Bast fibers · Leaf fibers · Grass fibers

1 Introduction

Natural fibers are the valuable, ecological, and renewable raw material source in the textile sector characterized as environment and human-friendly materials [1]. Currently, several world researchers, scientists, and practitioners are working on the development of high-quality, sustainable, biodegradable natural fibers-based products for the well-being of the people and society [2, 3]. Natural fibers have numerous advantages like less cost, lower density, lightweight, renewability, and biodegradable characteristics as compared to man-made fibers [4–6]. Moreover, natural fibers are abundantly available which as some promising properties such as high stiffness, high

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modulus, lower health risk during processing, and energy recovery with less carbon dioxide (CO_2) emission [7–10]. Owing to their specific characteristics, natural fibers are used as an excellent raw material in automotive, aerospace, building construction, furniture, packaging, military, railway coaches, and cosmetic industries [11].

Composites are specially designed multi-functional materials exhibiting special functional characteristics which are not found in other materials. Composite materials have interconnected structures formed by substantially combining a minimum of two or more compatible constituents that exhibit different compositions, properties, and, in some cases, forms [12, 13]. Among the different composites, fiber reinforced composites (FRC) have been used in multiple end products for many years, and their market share is constantly expanding. It is well recognized that adding fibers to polymers has numerous advantages, particularly in terms of composite mechanical properties. Synthetic Carbon and glass fibers are reinforced in polymers for use in high-performance end applications such as automobile and aircraft manufacturing industries [14, 15]. Different researchers worked continuously to enhance the performance-based characteristics of the FRC by using various combinations of matrix and reinforcement. However, all these high-performance materials are non-biodegradable and very difficult to recycle. The composites made from these high-performance materials are disposed of by landfills and incineration process which causes environmental impact [16–18]. In recent decades owing to concerns related to ecological issues, the research on the new alternative materials was increased to interchange the traditional FRCs with lesser environmental impact [19, 20]. This will draw attention to natural resources which can be used as reinforcements or fillers in composite materials. These natural fibers-based composites are termed Bio-composites/Green composites or Eco-composites [21]. Netravali et al. were the first to use the phrase "green composite." They developed and tested the mechanical characteristics of the coir fiber-based reinforced Polyhydroxybutyrate-co-volerate (PHBV) resin composites [22, 23]. European researchers referred these materials as biodegradable composites rather than green composites.

The furthermost significant characteristic of green composites is the complete 100% biodegradability. The NFR composites can be entirely resolved into water and carbon dioxide via microorganism degradation in the soil or burn up without the emission of toxic/hazardous gases. As a result, green composites are renewable, environmentally friendly, and biodegradable materials [24].

A view of some natural fibers is shown in Fig. 1. Cotton, jute, flax, sisal, ramie, and hemp are examples of vegetable fibers which are primarily composed of cellulose. These natural fibers can be further categorized as given below:

Seed fibers: These fibers are derived from seeds or seed cases for example Cotton and Kapok.

Bast/stem fibers: These fibers are extracted from the bast that surroundings the stem of the plant. Their tensile strength is higher than other fibers. As a result, these fibers are used to make strong yarn, fabric, packaging, and paper products. Flax, jute, kenaf, hemp, ramie, and banana fibers are an example of bast fibers.

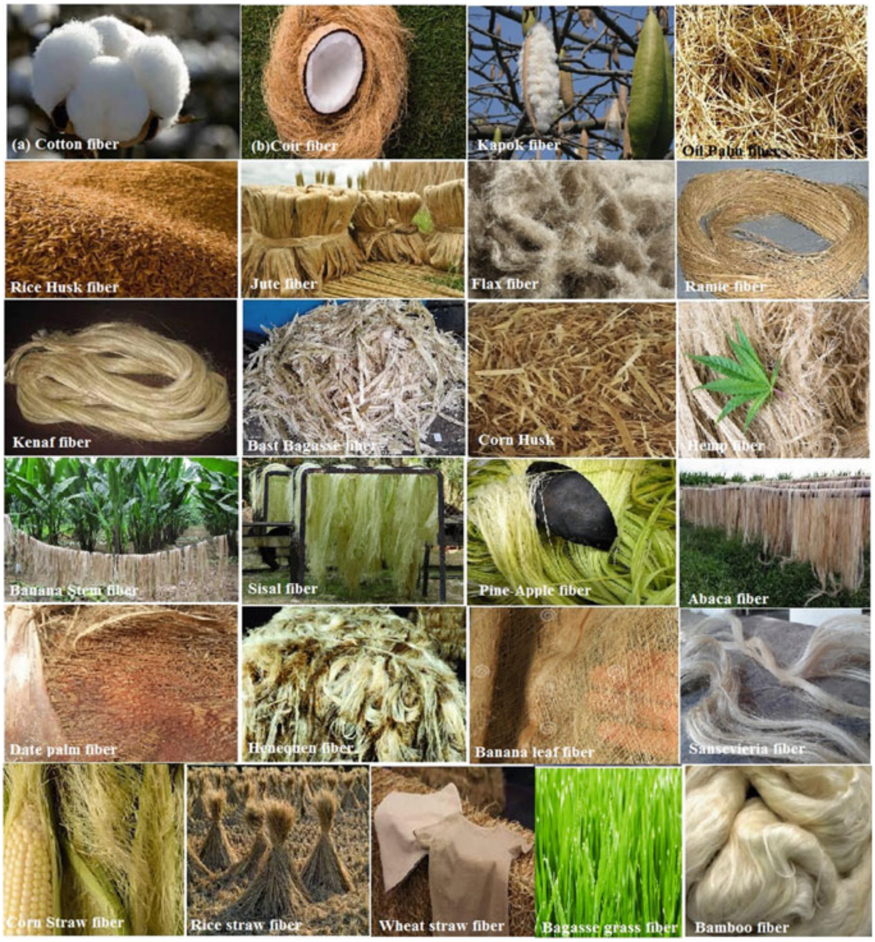

Fig. 1 View of some natural fibers

Leaf fibers: These fibers are obtained from the plant leaf, for example, sisal, pineapple, abaca, etc.

Straw fibers: These fibers are the straw or stalk of the plant, for example, corn straw, rice straw, wheat straw, etc.

Grass fibers: The bamboo and bagasse are examples of the grass fiber.

The comprehensive categorization of the plant/vegetable-based natural fibers is [25] shown in Fig. 2.

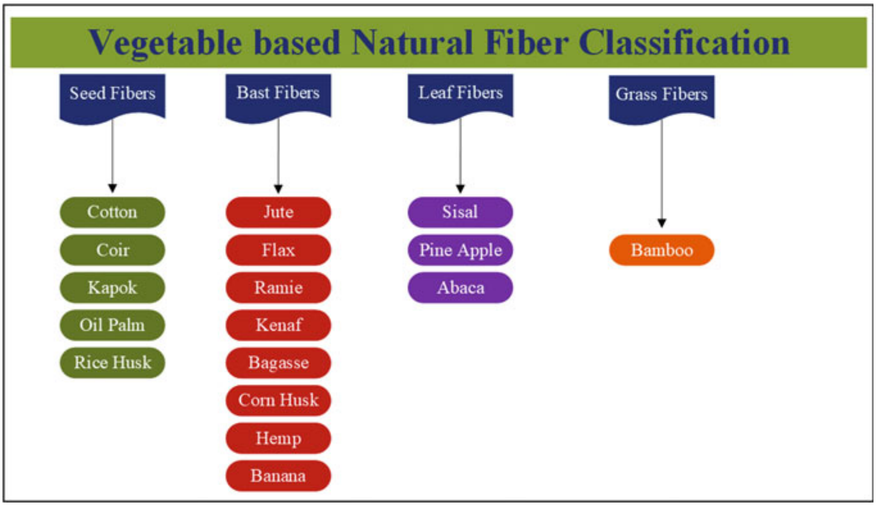

Fig. 2 Classification of vegetable-based natural fibers

2 Seed Based Fibers

2.1 Cotton (Gossypium *Genus) Fiber*

Cotton is a soft staple fiber which covers the seeds of the cotton plant (*Gossypium* genus), a tropical and subtropical plant native to the Americas, India, and Africa [26]. China, India, the United States, Pakistan, Brazil, Australia, Uzbekistan, Turkey, Greece, Turkmenistan, and Syria are the top ten cotton producers in the world in 2007 [27]. These countries account for roughly 85% of global cotton production. The diameter of the fiber is approximately 15–25 μm, while the length is approximately 10–50 mm [28]. The waxes and fats on the fiber surface makes it smooth, even and flexible.

Cotton fibers have a low elongation, which help the fabric in shape retention during use. A cotton fiber looks like twisted ribbon-like structure under a microscope. These twists in the cotton are termed as convolutions, and approximately 60 convolutions/cm are present in the fiber structure. The cross-section of cotton fiber is often described as kidney-shaped [29].

Cotton fiber also has several applications in field of interior design. A highly absorbent bath towels and robes, roller blinds, small pillows, and so on are the excellent examples of cotton products [30]. Cotton is normally blended with other natural and synthetic fibers to make high quality comfortable fabrics. Organic cotton is cultivated without the use of insecticides or any chemical fertilizers [31]; cotton from organic resource is used to make more expensive products ranging from tissues to kimonos [32].

*2.2 Coir (***Cocos nucifera***) Fiber*

Coir is the coconut fiber derived from the coconut shell/husk [33]. Coconut fiber is the coarser fiber among the various natural fibers. Coconut plants are mainly cultivated in tropical macroclimates [34]. In the world the coir fiber production is estimated to be 250,000 tones [28]. Coir fiber, in particular characteristics, is a light weight and strong/durable fiber that has gained scientific and commercial importance due to its exceptional characteristics [35]. Its high micro-fibrillar angle, imparts valuable characteristics such as resilience, resistance to weathering, strength, damping, and high breaking elongation [36]. The single fiber internal structure is slender and hollow, with thick walls of cellulose, and every cell is approximately 1 mm long and 10–20 μm in diameter [37].

Coir's properties are less affected by wet conditions than those of other hard fibers. The thickness of coir fiber limits the coarseness and weight of coir products [38]. Coir fiber is used to make Brushes, mattresses, bags, ropes, and upholstery in the automotive industry when combined with other materials [39, 40]. In recent developments, the coir fibers are used in roof greening, road embankments, bio-engineering, woven geotextiles, soil erosion control, capping landfills, mining, landscaping, ski slopes/ski lift tracks, re-vegetation, shoreline stabilization, stitched erosion control blankets, etc. [41].

*2.3 Kapok (***Ceiba pentandra***) Fiber*

Kapok is a member of the Bombacaceae family. It grows in tropical climates [42]. Kapok fiber is silk cotton that is yellowish or light brown. Kapok seeds are encased in the fibers. The fibers are composed of cellulose, light in weight, and exhibiting hydrophobic characteristics [43]. Kapok fiber is commonly used as oil-absorbing material, a buoyancy material, adsorption material, reinforcement material, biofuel, and so on [42, 44].

According to various sources, the kapok fiber varies in chemical composition. According to a study, kapok fiber is chemically composed of 64% cellulose, 13% lignin, and 23% pentosan by weight, while another study found that kapok fiber is composed of 35% cellulose, 21.5% lignin, and 22% xylan, with a high ratio of syringyl/guaiacyl units (4–6) and a high level of acetyl groups (14.0%) when compared to normal plant [45, 46]. These variations could be due to the different in kapok sources and different processing techniques.

Optical microscopy revealed a cylindrical shape, and smooth surface fiber of kapok [47]. The oval to round cross-section with a large lumen and thin cell-wall [48]. This hollow fiber structure distinguishes kapok fiber from other natural fibers and exhibiting the porosity of more than 80% [49].

2.4 *Oil Palm (*Elaeis guineensis*) Fiber*

Oil palm fiber (OPF) is considered as secondary material that is extracted from empty bunches which can be used as reinforcement in bio-composites. The fibers can also be gathered from some other parts of the plant, but the other part's fiber yield is lower than that of the fruit bunch [50]. Empty fruit bunches cause waste dumping issues [51]. Abdul Khalil et al. investigated the anatomy, chemical composition, cell wall structure, and lignin distribution, in depth [52]. These fibers are tough, with characteristics similar to coir fibers. The OPF is composed of approximately 29% hemicellulose and 65% cellulose [53].

The longitudinal structure shows the slender shape with the tapering and sealing end. The fiber cross-section is filled with the lumen [53].

2.5 *Rice Husk Fiber*

Rice husk is the rice grain's rigid shielding cover. After the rice harvesting, the grain and husk are further processed to obtain the rice husk. Until late 1800s, husk was a manually separated. Burning of rice husk (ash) produces amorphous reactive silica and it has potential applications in material science [54]. Panthapulakkal et al. investigated the improvement of processing of rice husk/PE composites, as well as swelling, density, water absorption, and extrusion rate [55]. Because of its mechanical properties, rice husk is unsuitable as a filler in a variety of applications [56, 57].

The longitudinal view shows the tip-like structure on the top with micro-bumps. The cross-sectional view indicates the inclined *epidermis* fibers, which resulted in a bulge on the external surface. The region between the bulges and contiguous inclined areas containing the amorphous silica concentrations [58].

3 Bast Based Fibers

3.1 *Jute (*Corchorus capsularis*) Fiber*

Jute fibers (*Corchorus capsularis* and *C. olitorius*) varies in color from off-white to brown. This fiber is obtained from the plant's bast and skin. Jute bushes can reach heights of 1.5–4.8 m and have stem diameters ranging from 1.25 to 2.0 cm [59]. Furthermore, the retting technique can be used to draw those fibers [60]. Jute fibers with an excessive tensile elasticity and occasional extensibility might be grown in 4–6 months.

Jute fibers are attractive owing to their biodegradability, recyclability, and environmental friendliness [61]. These fibers are brittle and have very low creep value. The coarse nature of the jute fiber limits the fineness of the yarn. Jute fiber applications include packaging, sack material, tapestry coatings, and electrical insulation. This fiber is not appropriate for food packaging applications due to broken hair problem, which may add impurities to the food [62].

On the longitudinal view, the crosswise marks are clear on the fiber surface which are called nodes or joints. A cross-sectional view indicates that the fibers have a small central canal similar to the lumen present in cotton. The sides have a polygonal shape with round edges [63].

*3.2 Flax (*Linum usitatissimum*) Fiber*

Flax fiber is extracted from the stems of the *Linum usitatissimum* plant. Fibers are approximately 1 m tall and 2–3 mm in diameter [64]. Flax fiber, like cotton fiber, is a cellulose based fiber, with more crystalline structure. This results in stronger fiber which are stiffer to handle, and more easily wrinkled. The molecular fine structure of flax fiber determines its properties, which are influenced by cultivation conditions and the type of retting procedure [65].

Their diameter is about 20 μm. Flax fibers are much less twisted than cotton fibers with a lumen in the centre [66]. On longitudinal images of fibers, several dislocations are seen, that are regions of the cellular wall in fibers where the path of the microfibrils differs from the microfibril angle of the encompassing secondary wall. These distortions appear during the extraction process. Fibers may be polygonal, oval, or irregular in form. The shape of fibers is decided via fiber length, plant growth situations, and adulthood [67].

*3.3 Ramie (*Boehmeria nivea*) Fiber*

Ramie (*Boehmeria nivea*) is an Asian bast fiber that is ordinarily produced in China and Brazil. It has been grown for hundreds of years in China and is commonly called "China Grass" [68]. It's far a perennial herbaceous plant in the Nettle family that can be harvested three to six times consistent with year. The plant lives for about 7–20 years and grows to a top of 1–2.5 m [69]. Due to the presence of gum, pectin, and different substances in the bark, chemical remedy is required before using the fibers [70]. Nam et al. investigated the physical characteristics of ramie fibers, and the composites were created through the identical authors [71]. To create bio-composites, ramie fibers are used as a reinforcement in variety of thermoset and thermoplastic resins [72–74]. Ramie fibers are less explored than the alternative noted bast fibers due to the aforementioned problems (availability and impure). Summerscales et al. and other researchers reviewed bast fibers and their use as composite reinforcements [66, 75].

Fibers are oval to cylindrical in form and white with a high luster. The surface of the fibers is rough, with small ridges, striations, and deep fissures. Ramie fiber is outstanding by way of its coarse, thick cell wall, loss of twist, and surface properties.

3.4 *Kenaf (***Hibiscus cannabinus***) Fiber*

Kenaf fiber is derived from the *Hibiscus cannabinus* plant stem, which has been grown as part of the ISKARA (intensification of community sack community) program since 1979/1980 [76]. Those plant life are adaptable and may develop on a huge variety of surfaces, such as peat and flooded soil [77, 78] Kenaf fiber production can range from 2.0 to 4.0 tons of dry fiber/ha, dependent on the plant variety and cultivation climate conditions [79]. They thrive in unfastened, nicely-draining soil and are planted inside the same manner as jute. They can be harvested 4–5 months after blooming [80].

There are various capacity unique packages for kenaf complete stalk and outer bast fibers, including paper products, textiles, composites, constructing substances, absorbents, and so on [81]. The lumens are predominantly huge and oval to spherical in shape, and the cross-sections are polygonal with rounded edges.

3.5 *Sugarcane Bagasse Fiber*

Bagasse is the fibrous residue that remains after crushing sugarcane stalks to extract juice. It changed into primarily a waste product that caused disposal charges for sugar turbines. Due to the low calorific value and sucrose content material of bagasse, strength and bioethanol production is a low-performance system. Bagasse manufacturing in the international is excessive (75×10^6 tones) and is frequently produced in Brazil, India, South Africa, and China.

When as compared to bast and leaf fibers, bagasse fiber has lower tensile characteristics. Extrusion, compression molding, and different composite approaches were used to create bagasse reinforced thermoset and thermoplastic composites. Luz et al. compared compression and injection molding in terms of mechanical behavior and microstructural analysis of bagasse composites. Bilba et al. prepared and analyzed bagasse reinforced cement composites. The potential of bagasse fiber and its composites was thoroughly investigated [82–91].

3.6 *Corn Husk Fiber*

Corn is a broadly planted crop in many Asian international locations. Corn plant consists of the stems, leaves, and skins which has excessive ability to be considered a natural fiber. Amendment of corn husk fiber with 0.5–8% sodium hydroxide (NaOH) solution is understood to reduce hydrophilic properties whilst growing crystallinity, tensile energy, and thermal resistance.

The addition of corn husk fiber to polymer composites can improve their tensile strength, bending strength, and toughness properties. Despite being immersed in water and exposed to ultraviolet (UV) light, the mechanical properties of the corn husk fiber composite were significantly higher than those of the "pandan wangi" fiber-reinforced composite. This corn husk fiber composite has previously been found to be suitable for use as a substitute for wood, soundproofing panels, and building materials in several studies [92–94].

*3.7 Hemp (***Cannabis sativa***) Fiber*

Hemp (*Cannabis sativa*), a species of annual green plant native to Europe and Asia. Hemp fibers are known for their high tenacity and low homogeneity. Hemp fiber has an average length of 17–24 mm and an elementary fiber diameter of 10–17 μm. Hemp is mostly used to make rope. Nonetheless, its fibers are increasingly being used in clothing and technical products such as composites. Hemp is also used in the food (hemp seed oil) and cosmetic industries.

The fibers have thick walls and a polygonal cross-section with rounded edges. The fiber is roughly cylindrical in longitudinal view, with surface irregularities and lengthwise deformations caused by dislocations. The fiber ends are slightly tapered and blunt. Hemp fibers are coarser than flax fibers and more difficult to bleach. The fibers are extremely moisture resistant and rot very slowly in water [28, 95, 96].

*3.8 Banana (***Musa acuminate***) Fiber*

Musa plants (*Musa acuminata*) are native to South East Asia and are members of the Musaceae family. This plant produces biomasses such as bunches, pseudo-stems, leaves, and stalks, which are classified as useful materials with high fiber content. In tropical countries such as Malaysia and South India, banana is widely available. Banana trees are cut down and dried before being processed to extract the fiber. Some of the benefits of banana fiber include its high low elongation at break, lightweight, good fire resistance, strong moisture absorption, low density, high tensile strength, and modulus [97–103].

Longitudinal sections reveal parallel-oriented unit cells with tube-like structures made of cellulose, hemicellulose, and lignin. This structure aids in the transportation of water and nutrients throughout the stem. The fracture section shows the fiber's broken parts and entangled microfibrils. It could be due to the fiber extraction process. Furthermore, the fiber has a rough surface due to the presence of hemicellulose, lignin, and waxy components [104].

4 Leaf Based Fibers

*4.1 Sisal (***Agave sisalana***) Fiber*

Sisal fiber is derived from the leaves of Sisalana, a Mexican perennial plant. Sisal plantations can be found in South and Central America, as well as Eastern Africa. In cross-section, the technical fiber appears as a crescent or a horseshoe. Polygonal elementary fibers with a round canal can be seen inside.

It is typically obtained through the decortication process, in which the leaf is crushed between rollers and mechanically scraped. The sisal fiber's length ranges from 0.6 to 1.5 m, and its diameters range from 100 to 300 μm. Because of its high cellulose and hemicellulose content, lower-grade fiber is processed by the paper industry. In the cordage industry, medium-grade fiber is used to make ropes, balers, and binders twine. After treatment, the higher-grade fiber is converted into yarns and used in the carpet industry [63, 105–107].

*4.2 Pineapple (***Ananas bracteatus***) Fiber*

Pineapple fiber (*Ananas bracteatus*) is a South American product. It has an intense luster and fineness. PALF extraction is limited due to low production, making it difficult to use in industrial applications.

The addition of fiber reduced the thermal conductivity and thermal diffusivity of the composite, which is actual for all plant fiber composites [108–111].

*4.3 Abaca (***Musa textilis*** Nee) Fiber*

Abaca fibre is derived from the fibrous banana, an evergreen, perennial tropical plant. The fiber is commonly called Manila. The plant is broadly grown inside the Philippines, in addition to on Java, Sumatra, Borneo, and in relevant and South American nations. The plant trunks are reduce as low as possible to obtain the fiber. Plaiting, thick fabrics, fishnets, sails, ship ropes, paper, and eventually creation boards are made from the fiber. The diameter of fundamental fiber is approximately 10–30 μm [112–115].

5 Grass-Based Fibers

5.1 Bamboo Fibers

Bamboo is a considerable resource that has been used in agriculture, handicraft, paper production, fixtures, and structure. Tries have lately been made to provide textile fiber from bamboo. Due to the fact a single bamboo fiber is most effective 2 mm long, it is utilized in textile manufacturing as a fiber package deal [116]. Bamboo is a grass that grows in no time. Environmentally friendly fibers derived from bamboo, which is renewable, speedy growing, degradable, and does no longer require cultivated land, are fee powerful and mainly beneficial for developing in hilly areas.

The fiber cell walls contained almost axially oriented cellulose fibrils. This fibrillar arrangement maximizes the fibers' longitudinal elastic modulus, while lignification increases their transverse rigidity [67, 117–120].

The surface of the single fiber is irregular and stripy with tree bark. The longitudinal direction of single fiber contains a small amount of lumen. Because the lumen is squeaky, degumming caused an intermittent disappearance of lumen length in the fiber structure. The cross-section of single bamboo contains a small round lumen. Moreover, the cell walls of most bamboo fibers were multi-lamellate with multiple layers [121].

Fiber has micro-cavities that make it softer than cotton and indulge the hygroscopic characteristics. The fibers are flexible, ecological, and decomposable. The fiber has the bacteriostatic, antifungal, antibacterial, hypoallergenic, hygroscopic, natural deodorizer, and UV light resistant characteristics. Moreover, the fiber is also exceptionally strong, durable, stable, and tough, with high tensile strength properties. The fibers are mainly used in the textile industry for clothing, towels, and bathrobes due to their versatile characteristics. It is also having applications in bandages, masks, nurse wear, and sanitary napkins due to its antibacterial characteristics. Fibers are also used UV-proof/antibiotic/ bacteriostatic curtains, television covers, and wallpapers, among other things, to decrease the special effects of microorganisms and the harm of ultraviolet radiation on human's skin. Bamboo fibers are furthermore used for decorative purpose [122].

6 Conclusion

Natural fibers are the effective reinforcement material in polymer matrix composites as a result of augmented environmental/ecological awareness. Natural fibers have excellent properties exhibiting materials that can be used in place of manmade fibers in numerous applications. The fibers that are naturally derived from plants and animals often exhibiting the excellent moisture absorption. The incompatibility of these fibers with polymers turns out to be the main disadvantage. To overcome this problem, natural material characteristics had been modified through chemical treatments of natural fibers. The chemical modification can improve the adhesion among the fibers and the resin with enhanced mechanical characteristics. Natural fibers can become the major reinforcement fibers for the composite and the capability of replacing synthetic fibers in various applications.

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