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Chapter

Natural Fibers: Applications

Jatinder Singh Dhaliwal

Abstract

Fibers derived from bio-based sources such as vegetables and animal origin are termed as natural fibers. This definition includes all natural cellulosic fibers (cotton, jute, sisal, coir, flax, hemp, abaca, ramie, etc.) and protein-based fibers such as wool and silk. There are also man-made cellulose fibers (e.g., viscose rayon and cellulose acetate) that are produced with chemical procedures from pulped wood or other sources (cotton, bamboo). Natural fibers being cost effective and abundantly available yields high potential in various industrial and commercial applications such as in the interior applications of the passenger cars, panels for partition and false ceiling, partition boards, roof tiles, coir fibers in packaging, furniture applications, as insulating materials in low energy houses, geo-textiles for soil protection and erosion control, enhancing barrier properties, composites etc. Due to research and developmental work in modification and treatment methods of natural fibers, utilization of natural fibers has observed a significant growth in various applications. The chapter addresses the potential applications of natural fibers in various commercial sectors for the development of environment-friendly products with an aim to replace synthetic fibers or inorganic fillers with cost-effective and efficient products.

Keywords: natural fibers, polymers, composites, applications, modification

1. Introduction

The transition toward a bio-based economy and sustainable developments as a consequence of the Kyoto protocols on greenhouse gas reduction and CO_2 neutral production offers high perspectives for natural fiber markets. Changing to a bio-based economy requires substitution of common raw materials that are currently largely produced from fossil (petrochemical) or mineral resources, by-products produced from renewable (plant and animal based) resources [1]. The development of a sustainable global economy, which permits improving purchasing power and living standards without exhaustion of resources for future generations, requires a fundamental change in attitude. On ecological grounds products should then be preferred that are based on photosynthetic CO2 fixation [1]. The benefit of those sustainable resources is that they can be regrown within the foreseeable future, without negative side effects on global biodiversity. Therefore, competitive products based on renewable resources need to be developed to have high quality, show excellent technical performance, and harm the environment less than current products based on petrochemical materials [2, 3]. **Table 1** below shows the major natural fiber producers in the world, their potential applications and associated by products.

Natural fiber	Main producers	Fiber market	By-product
Cotton	China, USA, India, Pakistan	Textile fabric: apparel, home furnishing, upholstery, non-wovens, specialty paper, cellulose, medical and hygienic supplies (hydrophilic absorbents)	Linter, cottonseed, stalks
Kapok	Indonesia	Pillow, mattress	Seeds, wood
Jute	India, Bangladesh	Hessian, sacking, carpet backing	Stalks (sticks)
Kenaf	China, India, Thailand		
Flax	China, France, Belgium, Belarus, Ukraine	Textile fabric, composites non-woven, insulation mats, specialist paper	Seeds, shives
Hemp	China		
Ramie	China	Textile fabric	Leaves, stem
Abaca	Philippines, Ecuador	Specialty paper, tea bags	Leaves, juice
Sisal	Brazil, China, Tanzania, Kenya	Twine and ropes	Short fiber, juice, poles, stem
Henequen	Mexico		
Coir	India, Sri Lanka	Twine, ropes, carpets, brushes, mattress, geotextiles, horticultural products	Copra, water, shell, pith, wood, leaves
Wool	Australia, China, New Zealand	Knitted wear	Lamb meat, cheese
Silk	China, India	Fine garments, veils, handkerchiefs	Worms, cocoons, fruits, wood

Table 1.
Natural fiber type, producers and markets [4].

In 2017, global fiber production exceeded 100 million mt resulting in the largest fiber production volume ever. Global fiber production saw a 10-fold increase from 1950 to 2017 from <10 million mt to over 100 million mt. Synthetic fibers have dominated the fiber market since the mid-1990s when they overtook cotton and became the dominant fiber. With around 65 million mt of synthetic fibers, this fiber category made up approximately 60% of the global fiber production in 2017. Polyester has a market share of around 51% of the total global fiber production. More than 53 million mt of polyester is produced annually. Cotton is the second most important fiber since synthetics took the lead in the mid-1990s [4]. With around 26 million mt, it has a market share of approximately 25% of global fiber production. An increasingly important fiber category is man-made cellulosics (MMCs) with a global production volume of around 6.5 million mt and a market share of around 6–7% in 2017. Wool has a market share of around 1% with a global production volume of a little over one million mt. Other plant-based fibers, including jute, linen, and hemp, together have a market share of about 5%. Silk and down have market shares of less than 1%. The need to decouple growth from resource consumption gets more urgent every year. The significant growth in fiber production results in a significant use of natural resources and a huge production of textile waste. There is a growing awareness of the urgent need for a more responsible use of resources, enabling growth without increased resource consumption.

An innovation toward a circular economy and dematerialization can be seen in almost all fiber categories. Accelerating such initiatives will help to reduce the overall fiber footprint on the planet [4].

Natural fibers have three main components lignin, cellulose and hemi-cellulose, percent of each vary with each type of natural fiber. Hemicellulose is strongly tied to cellulose fibrils presumably by hydrogen bonds. Hemicellulose polymers are branched and fully amorphous and have a significantly lower molecular weight than cellulose. Because of its open structure containing many hydroxyl and acetyl groups, hemicellulose is partly soluble in water and hygroscopic. Lignin is amorphous, highly complex, and mainly aromatic polymer of phenyl propane units but had the least water absorption of the natural fiber components. Amorphous lignin matrix helps in the combination of helically arranged cellulose microfibrils, which results in the formation of composite fiber. Lignin plays a very important role in the plant fiber such as water holding capacity, provide protection against biological attacks, and strengthened the stem against wind and gravity forces. Hemicellulose found in the plant fibers is believed to be a compatibilizer between cellulose and lignin [5].

However, the quality of natural fibers is greatly influenced by various factors like 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 [6].

2. Applications of natural fibers

2.1 Wind turbine blade

For centuries different sources like wood, oil, coal and currently materials like coke, natural gas, nuclear materials etc. are used for energy generation. With the significant increase in population, civilization, and industrialization, the consumption of energy has increased many folds. In today's scenario due to this imbalance of ecological system, more ecological awareness and stringent country law and policies have led to the increased interest on renewable and sustainable energy sources. There is a continuous search for sustainable development with minimum pollution and better efficiencies for reduction in energy consumption which have led to the development of wind energy. It is a prominent renewable energy source available to mankind which can be part of the solution of the global energy problem [7]. Currently the wind energy sector is growing, and highly efficient systems capable for converting the kinetic energy of the wind into mechanical or electrical energy are available. Generally the wind turbines consist of three rotor blades that rotate around a horizontal hub and convert the wind energy into mechanical energy and are the key component of the wind turbine. However the design aspect of these wind blades plays a major role in conversion process, the aerodynamic shape, the length of blades, and the material of construction used by the manufacturer.

Based upon the design of orientation of the shaft and rotational axis, wind turbines can be classified into two types (**Figure 1**). A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal-axis wind turbine (HAWT), and turbine with shaft normal to the ground is called vertical-axis wind turbine (VAWT). Today's leading large-scale turbine manufacturers favor HAWT-type turbines because of attributes like increased rotor control through pitch and yaw control [8–10].

Fiber-reinforced composite materials have been the choice for the commercial production of large-scale wind turbine rotor blades especially glass and carbon

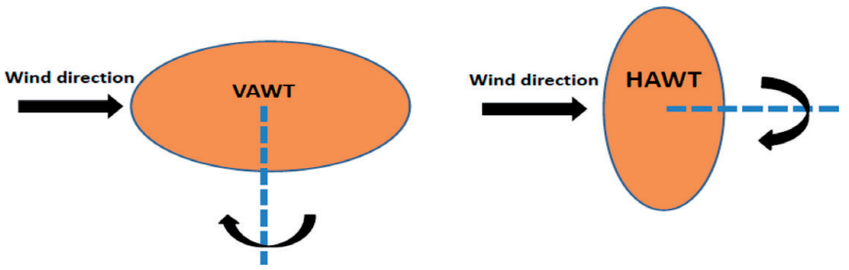


Figure 1.
Alternative configurations of shaft and rotor [8].

fibers. Carbon fibers are preferred over glass fibers because they provide superior mechanical strength due to their lower density and higher fatigue ratio which extends the life of the blades. The high cost of the carbon fibers which start with the expensive poly-acrylonitrile polymer (PAN) precursor and due to the environmental concerns and stringent laws, these are not considered as first choice since the commercial production of these types of fibers is highly dependent upon petroleum-based resources [11]. Because of these and similar reasons, researchers around the globe have shifted their focus on replacing these man-made fibers with natural fibers. Some of the main requirements for the wind turbine blade are (a) high strength, (b) high fatigue resistance and reliability, (c) low weight, and (d) high stiffness [12].

There is a huge potential to reduce the overall manufacturing cost of the wind turbine blades and replace the man-made fibers with natural fiber-reinforced composite materials. Balsa, flax, hemp, coir, abaca, alpaca, bamboo, and jute fibers have been marketed as potential and prospective substitutes to the traditional composite reinforcements. Lignin which is an aromatic biopolymer and abundantly available and can be sourced from plants and wood can be used as a precursor for production of carbon fibers. Low cost and easy availability can have a saving of 37–49% in the production cost of carbon fibers. However lignin has to be modified so as to be spun, stretched/aligned, and spooled into fibers, and these fibers can also be used in manufacturing of blades. Generally wind turbine blades are made up of array of sandwich panel strips and panels. Because of its light in weight and stiffness relative to density, balsa wood is being studied and used for making wind turbine interior panels and sandwich components [11, 12].

The performance of NFC-based wind turbine blades depend upon the following factors [10]:

1. Matrix selection—Matrix plays an important role in fiber-reinforced composites. It acts as a barrier against environment and protects the surface exposed from mechanical abrasion. Most commonly used matrices are polymeric in nature as they hold certain advantages being light in weight and easy to fabricate, can be designed to withstand harsh temperatures, etc. Thermoplastic (e.g., polypropylene, polyethylene, nylon, polycarbonate, etc.) and thermoset (e.g., polyurethanes, polyester, epoxy etc.) polymers are being used with natural fibers [13].

2. Fiber selection—All the plant-based fibers hold cellulose as the major structural component. Choice of the fiber depends upon the country or region and size of the wind turbine blade. It is important to know the availability of the fiber since it varies from country to country. The size of the blade governs the nature of mechanical performance requirements; therefore one particular fiber might not provide adequate strength for a particular size blade. Generally

better performance can be achieved with fibers having higher cellulose content and cellulose microfibrils aligned more in fiber direction. Typical examples are flax, hemp, kenaf, jute, and ramie fibers. The properties of the natural fibers do vary depending upon the chemical structure and composition, growing conditions, treatment procedures, harvesting time, extraction method, and storage procedures [14].

3. Fiber orientation—Orientation of fibers in polymer matrix ultimately governs the performance of the composite material which is best achieved when the fibers are aligned in parallel to the direction of applied load, however it's difficult to achieve in reality. Some alignment can be achieved during injection molding process and manual placement of long fibers [15–18].

4. Interference strength—Though the natural fibers are obtained from renewable resources and the composite materials will be environment-friendly, there are certain disadvantages also associated with unmodified or raw natural fibers. Some of the major problems can be high moisture uptake, low thermal stability, poor adhesion, poor mechanicals, etc. However, the majority of these can be overcome by employing suitable treatment/modification procedures [19–21].

2.2 Hydrogel production

Hydrogels are polymers having a three-dimensional cross-linked hydrophilic structure produced by simple reaction of one or more monomers which renders them capability of absorbing, storing, and releasing water molecules. Hydrogels have been researched considerably over the past decades due to their promising application in various fields. Some of the application areas of hydrogels include the manufacture of personal hygiene products, medical devices, environmental, agricultural, drug delivery systems, pharmaceuticals, biomedical, tissue engineering and regenerative medicines, wound dressing, biosensor, separation of biomolecules or cells and barrier materials to regulate biological adhesions, etc. [22–26].

Hydrogels can be classified based upon the following [22]:

1. Source—Based upon the source, hydrogels can be categorized into two groups: natural and synthetic.

2. According to the polymeric composition—Preparation method leads to different class of hydrogels. (a) Homopolymeric hydrogels are formed using single monomer. Cross-linking will depend upon the nature of monomer and polymerization technique. (b) Copolymeric hydrogels are formed using two or more monomer species having at least one hydrophilic component. (c) Multipolymer interpenetrating polymeric network (IPN) is formed of two independent cross-linked natural or synthetic polymer components. In semi-IPN hydrogel, one is cross-linked, while the other component is non-cross-linked.

3. Type of cross linking—Based upon the chemical or nature of cross-linking junctions, hydrogels can be classified into two categories. Chemical cross-linked having permanent junctions and hydrogels with physical networks arising from physical entanglements or interactions [27].

4. Configuration—Based upon the chemical composition and physical structure, the hydrogels can be amorphous, semicrystalline, and crystalline.

5. Physical appearance—It is governed by the polymerization technique used for preparation. Hydrogels can be in form of matrix, films, microsphere, etc.

6. Network electrical charge—On the basis of the presence or absence of electrical charge located on the cross-linked chains, hydrogels are divided into four groups: nonionic, ionic, amphoteric, and zwitterionic (polybetaines) electrolytes.

2.2.1 Modification methods of natural fibers for hydrogel production

Lignin, hemicellulose, and cellulose are the major constituents of natural fibers. Lignin which coats or covers the cellulose part shows lower tendency to react with other molecules and poor adhesion with polymer matrix. Therefore the natural fibers most of the time have to undergo through treatment or modifications to improve the reactivity, interaction, and better adhesion with polymer matrix or other molecules [28].

For the hydrogel production, the natural fibers are modified in two stages:

- Pretreatment step—It is a very common step even used when NF are used in composite material production also. The main objective of this step is the removal of lignin which is nonreactive toward other molecules and is achieved by alkaline treatment [29].

- Chemical modification—The step involves insertion of molecules into active sites of natural fibers of cellulose [30].

Collectively these steps increase the water absorption and retention capacity throughout with the help of modifying agents and active site generation.

2.2.2 Hydrogel synthesis from plant fibers

Hydrogel synthesis methods are mass polymerization, solution, and reverse suspension (use of initiator and a crosslinking agent). Generally hydrogel synthesis based upon the plant fibers uses solution polymerization method [28]. **Figure 2** shows general hydrogel preparation process.

Table 2 shows the different polymerization techniques, method employed, and type of characterization required during hydrogel synthesis. Solution polymerization is typically the preferred method for synthesis.

As reported by [29], during hydrogel synthesis, increase in the fiber content increased the swelling and elastic modulus, whereas Liang et al. showed change in pH, temperature, and salts leads to change in swelling behavior. In acidic environment, hydronium ions interacts with hydroxyl groups of cellulose to form hydrogen

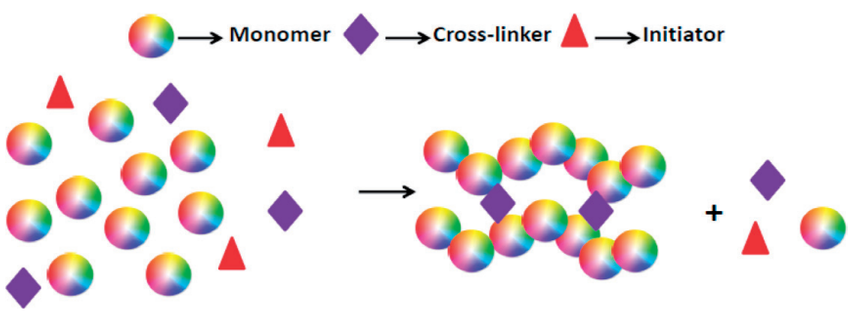


Figure 2.
Schematic for hydrogel preparation [22].

Raw material	Polymerization conditions	Method	Type of characterization	References
Modified sugar cane bagasse, sodium hydroxide, acrylic acid Cross-linker: N,N-methylenebisacrylamide Initiator: ammonium persulfate and sodium sulfite	Reactor: beaker of 250 ml Reaction temperature: 60°C Reaction time: 3 hours	Polymerization in solution	Swelling ability Swelling kinetics Swelling ability to pH change Swelling ability in saline solutions (NaCl, $CaCl_2$) Effect of temperature change on swelling ability	[31]
Flax fiber (shive) pretreated with NaOH sodium hydroxide, acrylic acid Cross-linker: N,N-methylenebisacrylamide Initiator: potassium persulfate	Reactor set to microwave with condensation System nitrogen as inert gas Reaction temperature: 22 min Power of irradiation: 160 W	Microwave assisted polymerization	Swelling ability Swelling kinetics Swelling ability to pH change Swelling ability in saline solutions (NaCl, $CaCl_2$, and $FelCl_3$) Biodegradability	[32]
Commercial nanocrystalline cellulose, acrylamide Cross-linker: N,N-methylenebisacrylamide Initiator: sodium persulfate and sodium bisulfite	Concentration of nanocrystals: 1, 3, 5, 6, 7, and 9.3% weight Reactor: 50 ml flask with stirring Nitrogen as inert gas Temperature: 25°C Reaction time: 20 hours	Polymerization by free radicals in solution	Rheology of the gelation process Swelling ability and kinetics Measurement of compression properties	[33]
Chitosan nanofibers, acrylamide Cross-linker: N, N-methylenebisacrylamide Initiator: potassium persulfate and sodium bisulfite	Concentration of 1.5% nanofibers with the monomer Reactor: 20 × 60 mm test tubes Nitrogen as inert gas Temperature: 40°C Reaction time: 20 hours	Polymerization by free radicals in solution	Measurement of rheological and compression properties Swelling ability and kinetics	[34]
Modified sugar cane bagasse Phosphoric rock acrylic acid partially neutralizing with NaOH and NH3 Initiator: potassium persulfate Cross-linker: N,N-methylenebisacrylamide	500 ml three-necked reactor equipped with reflux Reaction time: 3 hours Reaction temperature: 75°C	Polymerization in solution	Determination of NPK, release ratio (phosphorus), swelling ability	[35]

Raw material	Polymerization conditions	Method	Type of characterization	References
Wheat straw pretreated with 1 M HNO_3 acrylic acid neutralized with KOH and dimethyldiallyl ammonium chloride acrylamide Initiator: potassium persulfate and ceramic ammonium nitrate Cross-linker: N,N-methylenebisacrylamide	Three-mouth reactor equipped with reflux Reaction time: 5 hours Reaction temperature: 50°C	Polymerization in solution	Swelling ability and water retention Swelling kinetics, re-swelling ability Swelling to pH change and in saline solutions	[36]
Cotton cellulose nanofibers Chitosan acrylic acid Initiator: potassium persulfate Cross-linker: N,N-methylenebisacrylamide	Three-mouth reactor with reflux Reaction time: 2 hours Reaction temperature: 70°C	Polymerization in solution	Swelling in saline solutions and to pH change	[37]
Cotton nanofibers, acrylamide and potassium acrylate Cross-linker: N,N-methylenebisacrylamide Initiator: potassium persulfate Catalyst: N, N, N, N-tetramethyldiamine	Concentration of nanofibers: 1, 5, 10, and 20% by relative weight to monomers Reactor: no report Nitrogen as inert gas Temperature: not reported Reaction time: 15 hours	Polymerization by free radicals in solution	Swelling ability and kinetics Swelling ability in saline solutions Water retention capacity Evaluation of the pH effect on the swelling ability	[37]
Cotton nanofibers, cassava starch, and sodium acrylate Cross-linker: N,N-methylenebisacrylamide Initiator: potassium persulfate	Crossl-inking concentration: 1–3% by weight Concentration of nanofibers: 5–20% by weight Reactor: Three-necked flask equipped with reflux with n stirring Reaction temperature: 70°C Reaction time: 3 hours	Polymerization by free radicals in solution	Kinetics and speed of swelling Swelling ability in saline solutions and pH change Mechanical properties (Young's modulus)	[38]
Pretreated flax fiber waste Acrylic acid, acrylamide Initiator: ammonium persulfate Cross-linker: N,N-methylenebisacrylamide	Flask with reflux Reaction time: 2 hours Reaction temperature: 70°C	Polymerization in solution	Swelling by pH change and saline solutions Water holding capacity in the soil Water retention by temperature change	[39]

Raw material	Polymerization conditions	Method	Type of characterization	References
Carboxylated cellulose nanofibers Carboxymethyl cellulose Acrylic acid acrylamide Initiator: ammonium persulfate Cross-linker: N,N-methylenebisacrylamide	Three-necked flask with reflux Reaction time: 2 hours Reaction temperature: 70°C	Polymerization in solution	Swelling ability Retention and release capacity Swelling to pH change and saline solutions Water retention capacity by temperature change	[40]
Kapok fiber sodium hydroxide, acrylic acid Cross-linker: N,N-methylenebisacrylamide Initiator: ammonium persulfate	Reactor: 250 ml equipped with mechanical agitation Nitrogen as inert gas Reaction temperature: 70°C Reaction time: 3 hours	Polymerization in solution	Elastic module Swelling ability Swelling ability to pH change Swelling kinetics Swelling ability in saline solutions (NaCl, $CaCl_2$, and $AlCl_3$)	[29]
Polyethylene glycol diacrylate Chitosan nanofibers Initiator: ammonium persulfate Cross-linker: NNNN-tetramethylethylenediamine	Reaction temperature: environment Reaction time: 30 minutes	Not reported	Swelling ability Retention and release capacity Resistance to compression and rupture	[41]
Commercial cellulose nanofibers, sodium acrylate poly (ethylene glycol) diacrylate Photoinitiator: 1-phenyl hydroxycyclohexyl ketone	Concentration of nanofibers: 0–2% by weight Reactor: Beaker Reaction time: 8 minutes	Photopolymerization by UV at 365 nm of wavelength to a power of 100 W	Swelling ability free and in saline solutions	[42]

Table 2.
Some of the reported hydrogel synthesis methods based upon natural fibers.

linking forces resulting in increasing chain cross-linking and decreasing absorption capacity, whereas in basic media due to the neutralization of active sites, the swelling ability decreased. A temperature between 0 and 50°C is reported to have positive effect on the swelling ability. Zhong et al. [35] found the inclusion of the phosphoric rock in polymer matrix results into better swelling ability and water release rate.

The effect of use of natural fibers at nanoscale level in the hydrogels also has been studied, and few of the advantages found are the following:

- Better mechanical strength of hydrogels
- Improvement in the swelling ability
- Increase the density of cross-linking points
- Promotes the formation of porous morphology

Hydrogels can be tailored and designed as per the requirements and needs for different applications. Natural fibers as part of hydrogels synthesis can provide an eco-friendly alternative and fulfill the potential.

2.3 Automotive application

Today more than 50% of the vehicles' interior constitutes different polymeric materials. Automotive manufacturers and associations are under tremendous pressure to improve on fuel efficiency and lower emissions. One of the best ways is to reduce the overall weight of the vehicle which can be possible in replacing metal with lightweight composite materials [43]. Automakers have taken initiatives to design and utilize natural renewable resources as part of composite materials, though the use of natural biomaterials like natural fibers in automotive dates back to 1940s when Henry Ford produced the first composite component using hemp fiber. Similarly many other automotive manufacturers started following the same path down the line. Natural fiber-based composites hold great potential especially in automotive industry where studies have reported NFRC can contribute to cost and weight reduction by 20 and 30%, respectively [44]. Natural fiber-reinforced composite materials are generally utilized in interior parts like door panels, dashboard parts, parcel shelves, seat cushions, backrests, cable linings, etc. Applications to exterior are limited due to the high demand of mechanical strength [45–48]. Finished automotive door produced from hemp fiber is shown in **Figure 3**.

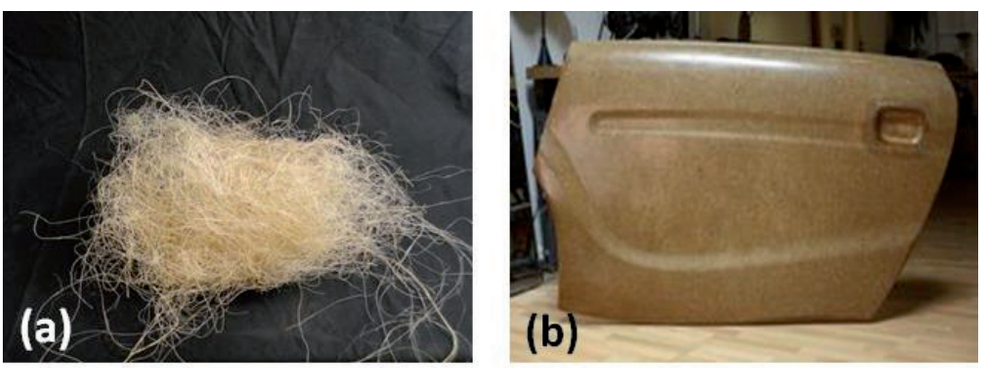


Figure 3.
Schematic of (a) hemp fiber and (b) automotive part produced using hemp fiber.

The properties of the natural fiber-reinforced composite materials depend upon the interfacial compatibility of the polymer matrix. The inherent characteristics and properties of natural fibers, generally issues like poor adhesion, moisture absorption, poor wet ability, etc., cause lower bonding with the polymer matrix. Therefore, modification or pretreatment of natural fibers is done prior to composite preparation. Several techniques and processes have been studied and reported. Few of them are stretching, calendaring, and production of hybrid yarns which result into change in physical attributes of natural fibers. Corona treatment (electrical discharge) method is another method used which makes surface rough resulting in better adhesion with polymer. The use of oxidizing agents such as sodium/calcium hypochlorite and hydrogen peroxide for removal of dust and oil from natural fibers has been reported. Alkali treatment of natural fibers also have been extensively studied and found to improve wet ability and improve adhesion significantly. Further improvement can be made by the use of grafted polymers like polypropylene/polyethylene-grafted maleic anhydride as compatibilizers and the use of coupling agents. These specialty products facilitate in the introduction and formation of covalent bonds and cross-linking effect [49–53].

In a report published by SABIC Innovative Plastics, wood flour and curaua fiber-based composites have been developed. Results are shown in the table below. The company claims that the composites developed are more resistant to fungi growth and have good dimensional stability, lower moisture absorption, and intended mechanical properties as required for the application. **Table 3** shows the comparison of unfilled PP and PA6 with filled natural fibers, glass fibers, and talc at similar loading level. Density advantage can be observed with NFRC as compared to other composite materials. Most of the mechanical properties of PP filled with NFs are almost similar to the talc-filled PP. Glass fiber-filled PP possess advantage in terms of tensile and flexural strength over NFRC and talc-filled PP materials. However, in automotive interior applications, composite materials with mild to high mechanical properties can serve the purpose. Mechanical properties of natural fiber-reinforced polymer composite are comparable to polypropylene talc and glass fiber composites (**Table 3**).

Property	PP	PP + 30% WP	PP + 30% GF	PP + 30% talc	PA6	PA6 + 20% curaua	PP + 20% GF	PP + 20% talc
Density (g/cm^3)	0.91	1.04	1.13	1.15	1.14	1.18	1.27	1.27
Tensile strength (Mpa)	19	28	65	25	63	83	101	73
Tensile modulus (Gpa)	1.4	2.3	4.5	2.2	1.4	5.5	6.5	6.5
Elongation at break (%)	50	2.5	3.0	5.0	>60	3.0	3.0	6.0
Izod impact strength (KJ/m^2)	5.0	9.0	9.5	8.0	10	9.0	9.0	9.0
Flexural strength (Mpa)	50	78	115	65	95	115	160	115

Table 3.
Mechanical properties of filled and unfilled PP and PA6 composites [43].

Natural fibers	Component description	Polymer matrix
Bast fibers (hemp, flax, jute, sisal, etc.)	Carrier for door panel, covered inserts, carrier for hard and soft arm insert, backseat panel, door bolsters, side and back walls, rear deck tray, center console, trunk trim, pillars, load floors, etc.	Polypropylene and polyester
Abaca	Under floor panel and body panel	—
Coconut	Seat bottom, back cushions, interior trim, seat cushioning, seat surfaces/backrests, etc.	Natural rubber
Coir	Seat covers, doormats, rugs	—
Cotton	Sound proofing, trunk panels, insulation	PP/PET
Fibrowood recycled	Plastic retainer for backseat panel	PP
Flax	Backseats, covers, rear parcel shelves, other interior trims, floor trays, pillar panels, central consoles, etc.	Mat with PP
Flax/hemp	Carrier for covered door panels	Epoxy resin
Flax/sisal	Door linings and panels	Thermoset resins
Kenaf	Door inner panel	PP
Kenaf/flax	Package trays and door panel inserts	—
Kenaf/hemp	Door panel, rear parcel shelves, interior trims, luxury package shelves, door panels	—
Wood	Carrier for door panels, covered door panels, instrument panels, covered inserts and components, covered backseat panels, etc.	Acrylic resin or synthetic fibers
Wood flour	Carrier for door panels, arm rest, and covered inserts	PP or polyolefin (POE)
Wool	Upholstery, seat cover	Leather

Table 4.
Applications of natural fibers in automotive industry [54–59].

Now different regions across globe opt for different natural fibers depending upon their availability and ease of use. European automotive industry prefers flax and hemp, whereas in Asian country India prefers jute and kenaf. Banana fibers are preferred in the Philippines, whereas sisal fibers are used majorly in the USA, Brazil, and South Africa. **Table 4** shows the use of natural fibers in various automotive components.

The use and development of natural fiber-based composite materials in automotive are going on good pace, and in time better composite materials with mechanical performance similar to synthetic fibers will be developed. Continuous development in fiber modification techniques, compounding machines, additives, polymers, etc. will yield a promising future ahead.

2.4 Barrier properties and applications

Cellulose is the primary component of green plants and is the most abundant organic compound derived from biomass. Due to its characteristic chemical and physical properties, it has been investigated and applied to variety of products and materials for many decades [60, 61]. Cellulose material exists in four different polymorphs [62, 63]:

- Type I—Native cellulose, the form in which cellulose occurs in nature.
- Type II—Regenerated cellulose, formed after recrystallization or mercerization with aqueous sodium hydroxide.
- Type III—This type of cellulose is produced by ammonia treatment of types I and II.
- Type IV—Heat treatment of type III yield type IV.

Type II is the most stable crystalline form of cellulose. The major difference between the type I and type II is the layout of their atoms. Chains in type I are layered in parallel fashion, whereas in type II they are in antiparallel.

About 36 individual cellulose molecules collectively form into a larger unit called elementary fibrils. **Figure 4** depicts the details of cellulose fibers and microfibrils. Depending upon the dimensions, functions, and preparation methods, nanocellulose can be subdivided into three main types: (a) microfibrillated cellulose (MFC), (b) nanocrystalline cellulose (NCC), and (c) bacterial nanocellulose (BNC) [64], as shown in **Figure 5**.

Various petroleum-based materials are widely used for packaging application to prevent food, drinks, cosmetic goods, consumer goods, etc. against physical

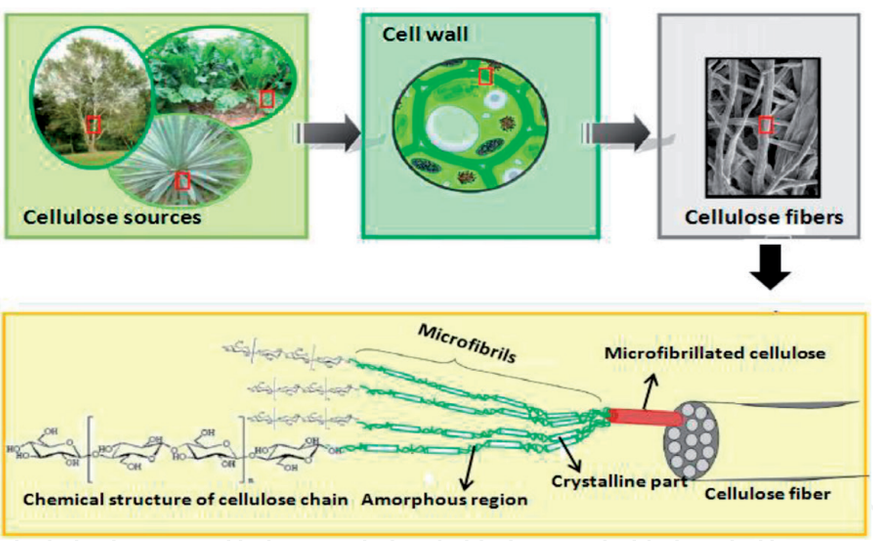


Figure 4.
From cellulose sources to cellulose molecules. Details of cellulose fiber structure with emphasis on cellulose fibrils [64, 65].

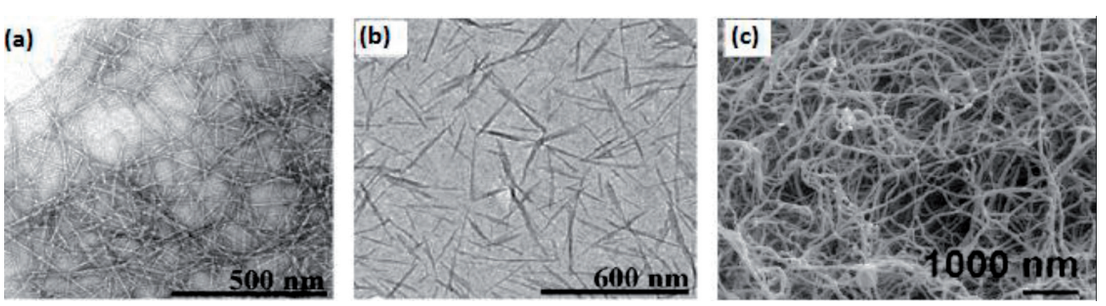


Figure 5.
TEM images of (a) microfibrillated cellulose, (b) nanocrystalline cellulose, and (c) bacterial cellulose.

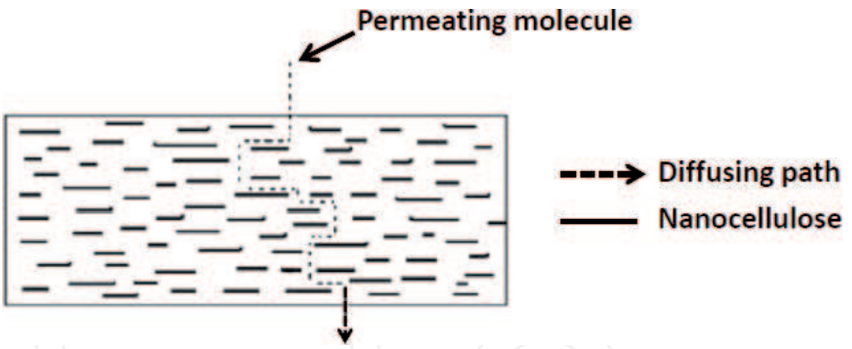


Figure 6.
Schematic representation of increased diffusion path within nanocellulose film [70].

and microbiological degradation and deterioration. These polymeric materials provide a layer of barrier against water vapor, oxygen, grease, and microorganisms. Packaging industry is one of the fastest-growing industries in the world. Now with the increased concerns due to the impact of these polymeric and other packaging materials like paper, glass, and metal on environment, materials derived from the renewable resources are strongly advocated. Recent research in more efficient and reliable preparation techniques for cellulose nanofibers and microfibrils synthesis, has attracted significant interest as potential barrier materials in packaging films. Cellulose nanomaterials have large surface area and diameter in range of 2–50 nm. Their ability to form hydrogen bonds results into strong network formation making it difficult for gas or water molecules to pass through it, thus providing excellent barrier properties [66–69].

Microfibrillated cellulose (MFC) films have better gas barrier property than cellulose nanocrystals (CNCs) because of the crystalline and amorphous regions in CNCs. Oxygen transmission rate (OTR) of 25 micron MFC film was found to be competitive with films of similar thickness made from ethylene vinyl alcohol (EVOH) and polyvinylidene fluoride (PVDF). OTR of MFC film was found to be lower than EVOH and PVDF films [71, 72]. **Figure 6** represents the kind of torturous path for permeating molecule because of nanocellulose. As reported, the barrier properties of MFC films can be tuned further. Rodionova et al. [73] in his work showed that oxygen permeability of MFC acetylated and carboxymethylated films can be further reduced. Carboxymethylated films had very low oxygen permeability of 0.009 and 0.0006 cm^3 m^{-2}/day kPa-1. Further the oxygen permeability can further be modified by using thermal treatment technique. **Table 5** shows the OTR and WVTR values of commercial polymer films and MFC film.

MFC film have poor water vapor barrier property as compared to PVDF film due to hydrophilic nature of cellulose molecules however it can be improved thereby using different pre and post treatments during production process.

Cellulose nanocrystals have been studied as potential fillers for natural polymers to enhance their barrier properties. Results reported as in Saxena et al. [74] showed that nanocomposite film made by casting aqueous solution containing xylan,

Barrier material	Thickness	OTR ($cm^3/m^2/d$)	WVTR ($g/m^2/d$)	Sources
EVOH	24 μm	0.16–1.86	NA	[69]
MFC	25 μm	0.5–2.347	47–55	[70]
PVDF	24 μm	8	0.3	[69]

Table 5.
Barrier properties of polymers and MFC.

sorbitol, and cellulose nanocrystals had low oxygen permeability of 0.1799 cm^3 μm/m^2 d kPa. As other reports [75, 76] also indicate that cellulose nanocrystals when used in other polymer matrix like PLA and PVOH improved in OTR and WVTR values. Studies based upon the use of microfibrillated and nanocrystals of cellulose in polymeric materials have opened possibilities in films, composites, and coatings to substantially reduce especially the oxygen permeation rate. Microfibrillated cellulose and its nanocrystals have oxygen-barrier efficiency better some of the commercially available polymers.

2.5 Other applications

2.5.1 Composites

There are considerable enhancement and suggestions for the natural fibers that can be implemented in order to enhance their mechanical properties resulting in high strength and structure so that it can be used as fillers and reinforcement agents instead of conventional materials like talc, calcium carbonate, mica, glass fibers, etc. After selecting the appropriate fiber and method of modification for the target application, the polymer matrix properties can be improved. Few of the parameters that effect the composite performance are the (a) orientation of fibers, (b) strength of fibers, (c) physical properties of fibers, (d) interfacial adhesion property of fibers, and many more [77–80]. Natural fiber-reinforced composite materials have shown better properties than pure polymer matrix in many cases. 75.8% of PLA's tensile strength was improved by the introduction of jute fibers. Properties of PP composites were improved by the incorporation of kenaf, cotton, and hemp fibers [77]. Ishagh et al. [81] investigated effects of azodicarbonamide (AZD) and nanoclay (NC) content on the physico-mechanical and foaming properties of HDPE/wheat straw flour (WSF) composites. With the increase of AZD, the average cell size and density increased, whereas with addition of nanoclay up to 5phr, the cell size and density increased. Idicula et al. [82] investigated thermophysical properties of banana sisal hybrid-reinforced composites. Increase in the thermal conductivity by 43% was observed in fibers which were subjected to mercerization and polystyrene maleic anhydride treatments. Chensong dong et al. [83] reported flexural properties of wheat straw polyester composites. Natural fiber-reinforced composites due to their certain advantages such as high stiffness to weight ratio, lightweight, and biodegradability gave them suitability in different applications in building industries. Sisal fiber reinforced composite have shown good tensile and compression strength making it suitable for wide area of applications, for instance, structural building members, permanent formwork, tanks, facades, long span roofing elements, and pipes strengthening of existing structures [84]. On the other hand, bamboo fiber can be used in structural concrete elements as reinforcement, while sisal fiber and coir fiber composites have been used in roofing components in order to replace asbestos. Natural fiber-reinforced concrete products in construction applications like sheets (both plain and corrugated) and boards are light in weight and are ideal for use in roofing, ceiling, and walling for the construction of low-cost houses.

2.5.2 Silk fiber applications

Silk which is a natural fiber and produced in more than 20 countries finds application in various sectors. Silk proteins are used as special diet for cardiac and diabetic patients due to its low sugar content, easy digestibility, and low cholesterol [83, 84]. The Japan Aerospace Exploration Agency (JAXA) has released a recipe as astronauts' food. Silk biopolymer is used in tissue regeneration for treating burn victims and as

matrix for wound healing. Silk fibroin peptides are used in cosmetics due to their glossy, flexible, elastic powder coating; easy spreading; and good adhesion properties [89, 90]. Silk is reported to be used to fight various health-related diseases like edema, cystitis, impotence, adenosine augmentation therapy, epididymitis, and cancer [91]. Derivatives of silk fibers are reported to be used as nonsteroidal anti-inflammatory agents for treating rheumatoid arthritis [85, 86]. Silk fibers are used as surgical sutures and as biodegradable microtubes for repair of blood vessels and as molded inserts for bone, cartilage, and teeth reconstruction [90, 93]. Due to the phenomenal mechanical properties of silk as a biopolymer, it is suitable for biomedical applications.

2.5.3 Natural fiber-reinforced building material

Various natural fibers have been exploited to be used as reinforcements for building/construction industry. Bamboo due to its lightweight and strength is a very popular construction material. Bamboo-based material has been developed to make eco-friendly roofing product. Other such products such as bamboo mat board (BMB), bamboo mat veneer composites (BMVC), and bamboo mat corrugated sheets (BMCS) have been developed. Sisal fiber-based roofing sheets also have been under development as economical alternative. Rice husk and rice straw are nowadays used to manufacture medium density fiberboards, particle boards, straw bales, cement-bonded boards, etc. Ground nutshell is used for manufacturing building panels, building blocks, chip boards, roofing sheets, particle boards, etc. Cotton stalk fiber is used for making panel, door shutters, roofing sheets, autoclaved cement composite, paper, plastering of walls, etc. Coir fiber is a highly durable fiber used in all types of matrices like fly ash-lime, polymers, bitumen, cement, mud, gypsum, etc. Jute coir composites are seen as cheap and economical alternative to wood for construction industry. Jute coir boards are used for the production of boards which are more resistant than teakwood against rooting under wet and dry conditions with better tensile strength. Jute with rubber, wood, and coir is considered as good alternative to plywood [94].

2.5.4 Geotextiles for soil protection and erosion control

Soil protection using natural fibers and other bio-based materials includes leaves, straws, and plant residues for the mulching of unprotected soil. Nowadays woven and nonwoven textiles and blankets made from wheat straw, rice straw, long wood shavings, coir, and jute are used as soil protection products. These products are categorized under two subgroups of the rolled control product (RECP) category. These can be open-weave geotextiles made using coir and jute fibers termed as erosion control

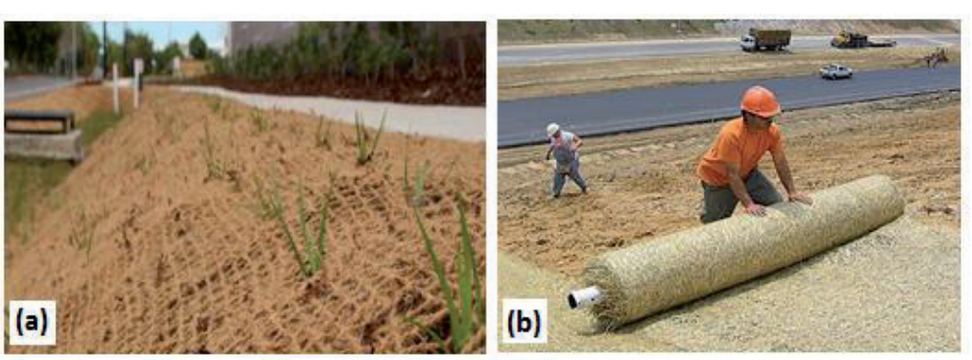


Figure 7.
Showing (a) coir fiber-made erosion control mesh and (b) coconut fiber-made erosion control blanket.

meshes (ECM) or nonwoven from natural fibers or synthetic fibers glued or bonded by nets or meshes called as erosion control blankets (ECB) as shown in **Figure 7**.

Natural fibers are also commonly used in rolls stuffed with straw or coir fiber bundles held together by nets which further can be used as slope interruption devices or sediment retention fiber rolls [95].

3. Summary

Natural fibers and the products designed around these materials possess many distinctive advantages: cost-effective, low coefficient of friction, ease of availability, exhibit good thermal and dimensional stability, environmental friendly, etc. Because of these and many more reasons, the popularity of natural fibers is on increase, and a lot of scientific data and research is being done around the globe. However for effective utilization of natural fibers in various potential applications, all the aspects associated with them has to be studied and presented: (a) target application, advantages, and disadvantages of using natural fibers; (b) product design, studies to be carried out on the development of prototype and other engineering software; (c) preparation and fabrication technique, particular technique, or process to be identified which should reduce possibility of failure, etc.; (d) commercial production, should be cost effective and eco-friendly; (e) marketing and sales, product should be marketed to show case its potential benefits toward society and environment with good after-sale service.

Despite of current prevailing aforementioned issues, several commercial products has been launched by various manufacturers, automotive industry the most active and leading the development of natural fibers based products. Gradually other sectors related to sports, furniture, medical, etc. are catching up.

Author details

Jatinder Singh Dhaliwal
Research and Development Center, Indian Oil Corporation Ltd., Faridabad, Haryana, India

*Address all correspondence to: singhj4@indianoil.in

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