Natural Fibre Composites from Agricultural Crops

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CHAPTER I

HYBRID NATURAL FIBER COMPOSITES IN CHEMICAL ENGINEERING APPLICATIONS

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Abstract

Incorporating natural fibers into composite materials offers a harmonious synergy between renewable resources and engineering innovation. Hybridization, involving the combination of various natural fibers, allows for tailoring properties to meet specific performance requirements. This abstract delves into the pivotal role of hybridization, highlighting the enhanced mechanical, thermal, and sustainability attributes it imparts to composite materials. These materials work well in a wide range of applications, from structural reinforcement to filtration and separation. We look at case studies that demonstrate the effectiveness of hybrid natural fiber composites in improving equipment durability, process efficiency, and environmental impact reduction in chemical engineering applications. The interfacial compatibility of different natural fibers and polymer matrices is also highlighted in this abstract. Strategies to optimize interfacial adhesion, such as surface modification techniques, are discussed in the context of chemical engineering applications. This exploration highlights the importance of achieving effective bonding between the diverse components within hybrid composites.

1. Introduction

One of the most notable applications of natural fiber composites in chemical engineering lies in enhancing the sustainability and durability of infrastructure within chemical plants. Utilizing natural fibers such as jute, flax, and sisal as reinforcements in polymer matrices has shown remarkable

promise in fabricating corrosion-resistant pipes, tanks, and vessels. Fiber-reinforced composites have been strengthened for many years by the research community. Several researchers proposed various methods for strengthening and minimizing the brittleness of these materials [1]. Fiber-reinforced composite matrix toughness, which significantly affects matrix-dominated composite properties, can be increased through various methods. However, the correlation between structural properties and failure resilience has grown to uncover a new toughness mechanism for biological composites [2-3]. The two kinds of fibers are synthetic and natural. In the past twenty years, synthetic fibers like glass and carbon have become more and more popular [4]. Composites made of synthetic fibers have a high strength-to-weight ratio and are frequently used in automotive and aerospace applications. When it comes to waterproofing, stretching, and stain resistance, synthetic fibers are more convenient. On the other hand, natural fibers are becoming more and more well-liked in research because of their resource sustainability, biodegradability, affordability, and light weight [5–6].

In many industrial sectors, natural fibers, particularly plant fibers, are replacing synthetic glass fibers as reinforcement or composite materials, in order to reduce environmental effects and thereby support long-term growth and a circular economy [7-9]. The production of these eco-friendly materials, however, faces technical and technological difficulties.

Natural fibers are gradually taking the place of synthetic fibrers in engineering applications. By reducing the use of synthetic fibers in terms of weight reduction, affordable material costs, and renewability, this replacement helps to preserve the environment. Despite their poor mechanical properties, natural fibers perform well in impact tests. As a result, high strength with higher mechanical properties is required for advanced applications. Hybridization may be a viable option for improving mechanical properties in such cases [10-12]. There are some restrictions in nonstructural applications, though, like a high moisture content and weaker strength and stiffness. As a solution, fiber hybridization with chemical modifications has been recommended. Another type of hydrophobic fiber can be added to hydrophilic fiber composites as an effective method for improving moisture resistance and reducing the deterioration of natural fiber polymer composite properties [13–14].

Figure 1. Natural fibers are widely used as fillers









Figure 2. The use of natural fiber in the production of daily needs

The most important parameter influencing the machinability of synthetic composites was discovered to be the direction of fiber alignment in the composite [15]. The cutting force is usually affected by the fiber's orientation in relation to the cutting direction. The chip is formed in front of the cutting tool edge by cutting the matrix along the fiber/matrix interface, depending on the fiber orientation [16]. Fiber alignment, referring to the orientation of reinforcing fibers within a composite material, has been found to exert a profound influence on the mechanical and thermal properties of the material. This alignment, typically categorized as unidirectional, woven, or randomly oriented, significantly affects the anisotropic behavior of composites, resulting in varied responses to external forces. Importantly, the same fiber alignment that impacts mechanical properties also extends its influence to machinability, dictating the ease with which the composite can be machined without causing undue damage to the cutting tool, surface quality, and overall structural integrity [17]. The machinability of a material is governed by a complex interplay of factors, including cutting forces, heat generation, chip formation, and tool wear. In synthetic composites, the direction of fiber alignment dictates the interactions between the cutting tool and the reinforcing fibers. When machining along the direction of fiber alignment (parallel to fibers), the cutting tool encounters a continuous sequence of fibers, leading to higher cutting forces and increased tool wear. Conversely, machining across the direction of fiber alignment (perpendicular to fibers) involves intermittent fiber cutting, resulting in reduced cutting forces and enhanced machinability [18].

One of the primary concerns when machining composite materials is the potential for delamination – the separation of layers within the material. The direction of fiber alignment plays a pivotal role in mitigating or exacerbating delamination. Machining parallel to fiber alignment often leads to higher delamination propensity due to the continuous cutting of fibers, potentially compromising the structural integrity of the component. In contrast, machining perpendicular to fiber alignment minimizes delamination risks by promoting fiber deflection and minimizing fiber pullout [19-20].

Researchers have directed their attention towards examining the influence and resilience of composite structures in the past few decades, uncovering numerous design imperfections. These complexities arise due to the fact that outcomes are influenced not solely by material parameters, but also by the configuration of tests and samples. Moreover, damage manifests in diverse manners, encompassing phenomena like the separation of fibers from the matrix, surface micro buckling, matrix fissuring, and fiber rupture. Grasping

the response to impact, the energy absorbed upon impact, and the strength exhibited during impact prior to material failure holds paramount importance in formulating a pragmatic design for structures. The impact test serves as a technique for deciphering the notch sensitivity and fracture toughness of a composite material. An essential determinant influencing the behavior of an impact within a composite resides in the fracture toughness of the resin system. Understanding the impact of fiber alignment direction on machinability is of paramount importance for industries relying on composite materials. Manufacturers can leverage this knowledge to optimize machining strategies by selecting the most suitable cutting direction based on the intended application and performance requirements. For instance, components subjected to predominantly axial loading may benefit from machining perpendicular to fiber alignment to enhance machinability while preserving structural integrity.

2. Overview of Natural Fiber-reinforced Hybrid Polymer Composite

Hybrid composites are developed through the integration of multiple reinforcing materials in the same polymer matrix in order to enhance the composite's properties. When several strengthening agents are combined, they can have a synergistic or antagonistic effect. Furthermore, properties can be adjusted by balancing the advantages of one material against the disadvantages of another. The incorporation of multiple reinforcements in a matrix provides a broader range of properties that single fiber-reinforced composites cannot accomplish. As a result, scientists and researchers have given close attention to the hybridization of reinforcement materials of natural and synthetic origin.

Since synthetic fiber composites have been demonstrated to be of a higher quality than natural fibers, their use in the manufacturing and production sectors is unavoidable. Synthetic fibres are used to create high-performance polymer matrix composite products like building panels, fiber-reinforced plastic tanks, and aircraft and vehicle parts. Some of the most popular synthetic fiberres in the composites industry include glass, carbon, and aramid.

Due to their outstanding mechanical performance, synthetic fiber-reinforced polymer composites with glass, carbon, aramid, and boron fibers have been used extensively and frequently in engineering applications [21]. Due to their poor non-biodegradable and recyclable qualities, synthetic

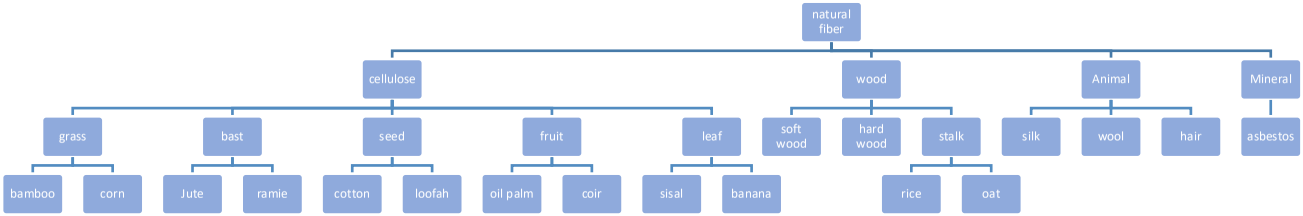


Figure 3. Natural fiber classification

fiber-reinforced composites have raised environmental concerns. Because of their advantages for the environment, such as their use of natural resources, low pollutant emissions, improved energy recovery, biodegradability, and high specific stiffness and strength, natural fibers are increasingly being used as an alternative to synthetic fibers in composites. Natural fiber composites' recyclability is an additional benefit that raises the sustainability aspects of these materials.

Cellulose is the primary constituent of natural fibers and is composed of long chains of glucose molecules. These chains are organized into microfibrils, which form the fundamental structural framework of the fiber. The arrangement and orientation of cellulose microfibrils significantly influence the fiber's strength, stiffness, and overall mechanical properties [22]. Alongside cellulose, hemicellulose is another polysaccharide present in natural fibers. Hemicellulose molecules surround the cellulose microfibrils, acting as a matrix that holds the microfibrils together. This matrix contributes to the fiber's flexibility, water absorption characteristics, and interactions with other materials.

Lignin is a complex and amorphous polymer that fills the spaces between cellulose microfibrils, providing rigidity and structural support to the fiber. However, it can also make fibers less accessible to chemical treatments. Lignin content can vary between different natural fibers, influencing their strength, stiffness, and resistance to degradation. Pectin, another complex carbohydrate, is found in the middle lamella that holds individual plant cells together. Proteins are present in minor quantities and contribute to the fiber's mechanical properties. These components can impact fiber-matrix interactions in composite materials.

Natural fibers possess a lumen, which is the central open space within the fiber, and a cell wall surrounding it. The cell wall consists of the primary cell wall and the secondary cell wall. The secondary cell wall, which is more rigid and dense, develops after the primary cell wall and significantly contributes to the fiber's mechanical properties. Within the macroscopic structure of natural fibers, microstructures such as pits, microfibril angles, and crystalline regions exist. These microstructures influence properties like fiber flexibility, mechanical strength, and the degree of water absorption.

Bark-derived fiber has one of the highest cellulose contents (30–76% by weight) and lowest microfibril angles (2–80) of the different natural fiber sources. Other natural fiber components like pectin and hemicellulose regulate additional characteristics like water absorption, wet strength,

swelling, and fiber bundle integration. To achieve the ideal reinforcement in natural fiber-reinforced composites, complete characterization of natural fibers thus becomes critical.

Within composites, the matrix assumes a pivotal role as the primary component safeguarding fibers or fillers against abrasion and challenging environmental conditions. Additionally, it serves to bind these fibers or fillers together, endowing the composite with heightened strength by absorbing energy amidst stress-induced deformation. The transmission of a load onto the composite material becomes facilitated through the matrix when subjected to external forces. To this end, factors such as type, attributes, and processing methodologies demand careful consideration. Consequently, the selection of a matrix capable of enduring greater fracture limits than the reinforced fibers becomes imperative. Two primary classifications of polymer resins function as matrices: thermosets and thermoplastics. Thermosets undergo curing at elevated temperatures, acquiring an irreversible solidified state. This transformation precludes their reversion to uncured forms. Thanks to intricate cross-linking catalyzed reactions, thermosets exhibit robustness and stability even under adverse circumstances. On the contrary, thermoplastics remain pliable, lacking intermolecular cross-linkages and exhibiting a propensity to melt at elevated temperatures. The viscosity of thermoplastics and their requirement for high processing temperatures restrict their practical applicability relative to thermosets. Commonly encountered thermosets encompass epoxy, vinyl ester, phenolic resin, polyester, and urethane.

Certain natural fibers like wood, jute, kenaf, rice husk, and hemp find application in bolstering the strength of thermosetting polymers such as epoxy, urethane, vinyl ester, phenolic, polyester, polymide, and polyurethane (PU), as well as thermoplastics including polyethylene (PE), polypropylene (PP), nylon, polycarbonate (PC), polyvinyl chloride (PVC), polyether-ether ketone (PEK), and acrylonitrile-butadiene-styrene (ABS) polymers and elastomers. In contrast to thermosets and elastomers with intricate cross-linked structures, thermoplastics offer enhanced design adaptability and simplified processing methodologies. Nevertheless, limited research has been conducted regarding the incorporation of agricultural residues as reinforcements in these polymer matrices, encompassing materials like soybean husks, pineapple fibers, and banana leaf fibers.

Table 1. The hybrid effect was investigated for a number of different reinforcing materials and matrices.

Matriks	Reinforcement	Tensile strength (Mpa)	Referencee
Epoxy	Flax/e-glass	164.23	24
Epoxy	Powder eggshell	73.83	25
HDPE	Palm oil shell	1.17	26
Epoxy	Jute/ carbon nano tube	36.00	27
Epoxy	Jute/tea leaf fiber	75.60	28
Corn starch	cornhusk fiber/sugar palm fiber	19.09	29
Epoxy	coir /woven-carbon fiber	354.51	30
polyester	Coconut coir/sugarcane leaf sheath	16.88	31
Cardanol resin	bagasse/coconut shell	37.28	32
Epoxy	banana bract/palm fiber	40000	33

Matrices necessitating high processing temperatures prove unsuitable for producing composites reinforced with natural fibers due to the inherent instability of most natural fibers at temperatures exceeding 200°C.

Numerous different matrixes and reinforcing materials were examined in order to determine the hybrid effect. The highest tensile strength values were produced by the mechanical properties of the E-glass/flax mixture. Glass fibers have an amorphous atomic structure connected by ionic bonds. The tensile strength of composite materials is greatly affected by the interfacial bond quality. Flax fiber's hydrophilic properties, which result in a weak interfacial area and reduce stress transfer between the fiber and the epoxy, have an impact on its tensile strength. This is because more fiber interactions result in ten times higher tensile strength for the flax/E-glass hybrid composite.

Studies by Alfatah et al. [26] demonstrated an undesirable connection at the interface between the filler and matrix when employing a solitary filler, leading to a reduction in tensile strength. This effect transpired due to the absence of a coupling agent that would have otherwise modified the surface particles of palm shells. Consequently, the lack of this agent resulted in diminished tensile strength, flexibility, and water absorption. Furthermore, natural fibers display a heightened sensitivity to elevated processing temperatures compared to glass fibers. Through meticulous process

optimization and parameter adjustment, it becomes feasible to compound polyamides at temperatures exceeding 200°C. Additionally, cellulose fibers are lighter and exhibit lower tensile values than glass fibers due to their lower density.

The inherent mechanical properties and other properties of natural fibers, which are listed in Table 1, determine the processing and properties of natural fiber hybrid composites. The tensile properties of fibers vary greatly. Many of these NFRC properties, such as the fiber-matrix bond, interaction, thermal stability, moisture sensitivity, and so on, are directly influenced by some of these traits. Natural fiber and matrix hydrophilicity and hydrophobicity, for example, threatens fiber-matrix compatibility and can reduce the mechanical performance of these composites. As a result, a plethora of techniques for chemically and physically altering fibers, as well as adding bridging materials during processing, have emerged.

3. Detailed explanation of each manufacturing technique's steps, requirements, and outcomes

3.1 Alkali Treatment

Alkali treatment involves the immersion of natural fibers, such as jute, flax, or hemp, in alkali solutions, typically sodium hydroxide (NaOH) or potassium hydroxide (KOH). This treatment induces a series of chemical reactions, including deacetylation, mercerization, and increased surface roughness. Deacetylation removes acetyl groups from the fiber surface, exposing hydroxyl groups that enhance fiber-polymer interactions. Mercerization, on the other hand, leads to fiber swelling and alignment of cellulose molecules, contributing to improved fiber crystallinity and mechanical properties.

The chemical modification brought about by alkali treatment imparts several improvements to natural fibers. Enhanced hydrophilicity, increased surface area, and improved fiber-matrix adhesion result from the removal of impurities and the exposure of active functional groups. These changes lead to enhanced wettability and interfacial adhesion, critical factors in optimizing composite properties such as tensile strength, modulus, and impact resistance. Additionally, the increased roughness and swelling influence moisture absorption behavior, influencing dimensional stability [34]. This treatment removes some of the lignin, wax, and oil from the fiber cell wall's outer surface, depolymerizes the cellulose, and exposes short-sized crystallites [35]. The addition of sodium hydroxide (NaOH) solution

to natural fibers increases hydroxyl group ionisation into alkoxides. The inclusion of sodium oxide (NaOH) in the fiber with surface modification facilitates the ionization of alcohol bodies by hydroxyl, which can be expressed chemically as follows:

$$\text{Fiber} - \text{OH} + \text{NaOH} \rightarrow \text{Fiber} - \text{O} - \text{Na} + \text{H}_2\text{O}$$

Successful alkali treatment necessitates careful control of treatment parameters such as concentration, treatment duration, and temperature. The extent of fiber modification depends on these parameters, with higher concentrations and longer durations generally leading to increased modifications. However, a balance must be struck, as excessive treatment can degrade fibers, resulting in reduced mechanical properties. Optimal conditions vary based on fiber type and intended application. The impact of alkali treatment on natural fibers extends to their applications in composite materials. Chemically-modified fibers offer improved compatibility with polymer matrices, resulting in composite materials with enhanced mechanical, thermal, and barrier properties. In sectors ranging from automotive to construction, the incorporation of alkali-treated natural fibers has led to lightweight, environmentally-friendly composites that find applications as structural components, packaging materials, and even reinforcement in concrete.

3.2 Silane treatment

Silane treatment involves the chemical bonding of organosilane compounds to the surface of natural fibers. The functional groups of silane molecules form covalent bonds with hydroxyl groups on the fiber surface, thereby creating a strong and durable interface. The resulting fiber-matrix adhesion significantly improves composite properties by reducing interfacial stress, enhancing load transfer, and mitigating moisture-induced degradation [36]. The primary advantage of silane treatment lies in its capability to enhance fiber-matrix adhesion. By effectively bridging the hydrophilic fiber surface with the hydrophobic polymer matrix, silane-treated natural fibers exhibit improved compatibility and wettability. This not only bolsters mechanical properties such as tensile strength and modulus but also leads to a reduction in moisture absorption and increased resistance to environmental degradation.

Silane treatment offers a versatile platform for tailoring composite properties based on the choice of organosilane compound. By selecting specific functional groups, researchers can tailor the surface chemistry of natural

fibers to match the characteristics of diverse polymer matrices. This tailoring allows for optimization of composite properties, making silane treatment a versatile tool for achieving desired outcomes in various applications [37-38]. It is well known that silk fibers have a central hollow region, the lumen, which allows for water to penetrate via capillarity, especially when the composite contains a high fiber content. However, the silan-hydroxyl group linkages are also susceptible to hydrolysis, and the breakdown under certain conditions must be investigated.

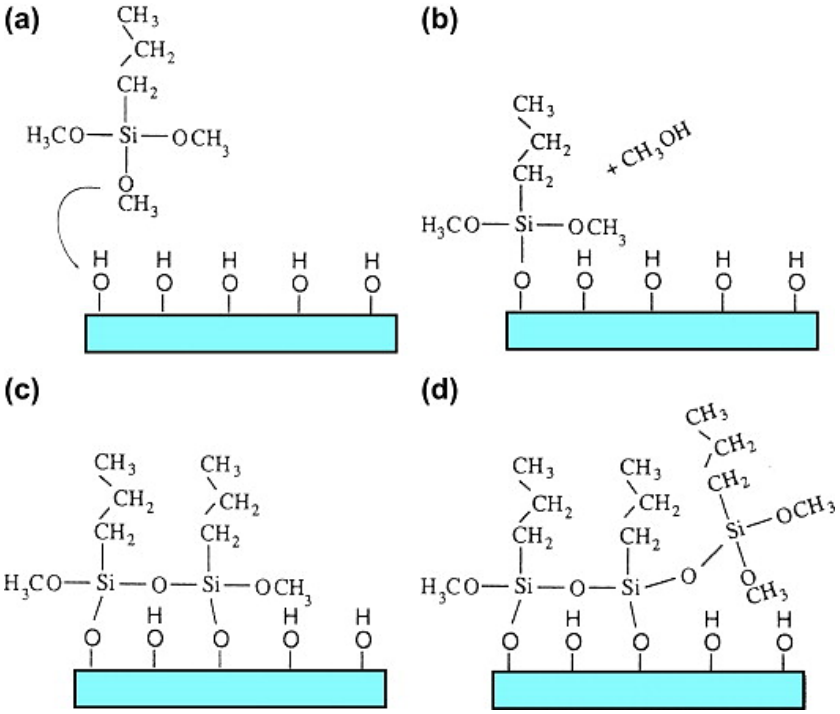


Figure 4. Silane surface modification process: (a) The hydroxylated surface is immersed within a solution containing n-propyl trimethoxysilane (nPTMS); (b) One of the methoxy groups within nPTMS forms a pair with a hydroxyl group, resulting in the release of methanol; (c) Two methoxy groups on a different nPTMS molecule undergo reaction, with one attaching to the hydroxyl group and the other binding to the methoxy group of the first nPTMS molecule; (d) The third nPTMS molecule solely reacts with methoxy groups. These molecules establish a connection not directly with the surface but rather with the silane film network.

Considering this knowledge, an optional strategy is activating the alkoxysilane by hydrolyzing the alkoxy groups and forming the more reactive silanol groups. To form a macromolecular interaction, silanol may interact with the hydroxyl groups of fibers or condense on the surfaces of fibers and/or in cell walls. Under heating conditions, the interfacial adhesion of treated fibers and polymer matrices becomes better, as are the properties of the resulting composites, by blocking the hydroxyl groups, which is reversible to hydrolysis, and by the formation of the macromolecular network, which is permanent. Water must be present during the hydrolysis of the alkoxy groups.

3.3 Acetylation

The reaction of organic compounds with the acetyl ion CH3COO- has been described by the surface modification of acetylation. The esterification method evolved from the plasticization of cellulose fibers. This process is additionally referred to as fiber acetylation. Ethanoic anhydride reacts in the hydroxyl groups of cellulose in the reaction of ethanoic anhydride and lingo-cellulosic materials [39].

Fiber – OH – CH3COOCOCH3 → Fiber – OCOCH3 – CH3COOH

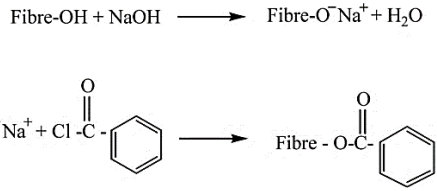
The polar hydroxyl groups in the fiber's cell wall are encouraged to be replaced by the less polar acetyl groups as a result of this chemical change [40]. As a result, the hydrophilic properties of the fibers are reduced, which enhances their compatibility with nonpolar matrices. With acetylation treatment, natural fiber moisture absorption can be reduced, and the composite's mechanical properties, such as interfacial compression and tensile and flexural strength, can be enhanced. Sometimes an alkaline pretreatment is followed by acetylation for better results [41–42].

3.4 Treatment with Benzoyl chloride

In the benzoylation process, benzoyl chloride is used to decrease the hydrophobicity of the fibers and increase the adhesion of the fibers to the matrix, increasing the strength of the composite. In the benzoylation procedure, the fibers' hydroxyl groups were first activated by an alkaline pre-treatment before being immersed in a benzoyl chloride solution for 15 minutes [43]. Benzoyl chloride that had adhered to the surface of the fiber was removed with an ethanol solution, then the material was washed with water and dried in the oven. Sisal fiber composites that had undergone alkali

pre-treatment demonstrated greater thermal stability after being treated with benzoyl chloride.

In the synthesis of organic compounds, benzoylation is a crucial transformation. The fiber treatments have been where benzoyl chloride is most frequently used. A good example of this is benzoyl (C6H5C=O), which is linked to a decrease in the hydrophilic nature of the treated fiber and an increase in interaction with the hydrophobic matrix [44]. The treated composite was found to have greater thermal stability than the untreated fiber composite [45].



The interfacial adhesion of the hemp fiber and the PE matrix was found to be improved by this treatment. The cellulose and lignin hydroxyl groups in the fiber are first activated by an alkaline treatment, and then the fiber is suspended in a 10% NaOH solution and benzoyl chloride for 15 minutes [46]. The isolated fibers were then washed with water and dried in an oven at 80 °C for 24 hours after being soaked in ethanol for an hour to remove the benzoyl chloride. The treatment was responsible for the treated fiber's reduced hydrophilicity.

4. Cotton fibers composite

The most significant natural fiber used in textile production is cotton, and this can be discovered in other products like fine paper [47]. Cotton has undergone extensive study due to its value. However, there is still a lot to learn about the intricate details of cotton fiber structure as of the time of writing. Understanding the relation between the structure and the performance characteristics of the fibers requires knowledge of these structural specifics. It's necessary for knowledge-based development.

Figure 5. Cotton plants that grow in Indonesia

The cotton plant is cultivated for fiber in more than 90 countries. The Republic of Indonesia's Ministry of Agriculture said national cotton production was 127 tons with a planting area of 703 ha in 2020. This number decreased by 54.6% from the previous year which was 280 tons with a planting area of 1,620 ha. East Nusa Tenggara is the largest cotton-producing province with production reaching 70 tons with a planting area of 147 ha in 2020. Then following that, Central Java province produces 21 tons of cotton with a planting area of 131 ha and East Java 15 tons.

Each cotton fiber is the result of the growth of epidermal cells on the surface of the cottonseed, inside the fruit of the cotton plant [48]. Cotton fiber processing includes unit operations from harvesting the boll in the field to separating the fiber from the seeds at the milking site and finally turning it into yarn or other engineered products. Throughout this processing stage, the different parts of the machine pull, drag, catch, and rub the fibers against

another surface or against each other until they are aligned into the desired shape.

Mature cotton fibers contain average (absolute dry matter percentage) cellulose, 94.0; waxy substance, 0.6; pectin (calculated as pectic acid), 0.9; organic acids, 0.8; nitrogenous substance (calculated as protein), 1.3; ash, 1.2; non-cellulosic polysaccharides, 0.3; and, unknown substance, 0.9 (total, 100%) [49]. Cotton fiber, a highly elongated and thickened single cell of the seed epidermis, is the most important natural textile fiber in the world [50]. Cotton fiber begins with swelling above the surface of the ovule near the day of the flower opening (or flower opening).

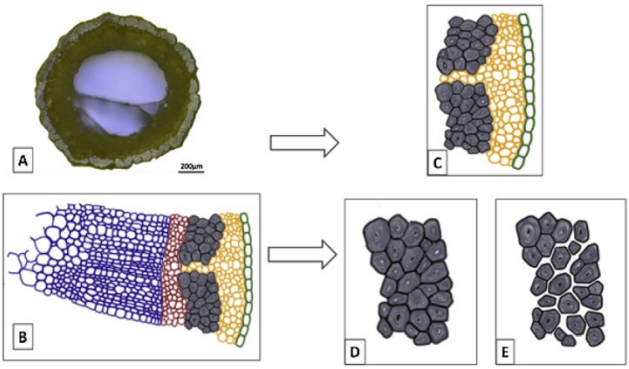


Figure 6. Fibers' location in stem

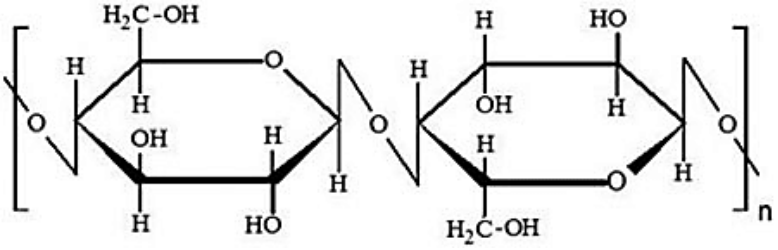


Figure 7. Chemical structure of cotton fiber

Since there is increased turgor pressure on some epidermal cells, the fibers' initial enlargement is diametrical, which likely involves loosening of the cell walls. The cotton fibers go through the following processes over the next 50 days: (a) extreme elongation (up to >2.5 cm) caused by primary wall

synthesis; (b) transition wall expanding and primary wall remodeling; and (c) secondary wall expanding because of accumulation of nearly pure cellulose. Before the boll opens to reveal the fine fibers inside, a mysterious process of "ripening" and cell death takes place. The cell wall of cotton fiber determines parameters of industrial importance for fiber quality in addition to morphogenesis. For spinning yarn, the fiber length created by primary wall synthesis is crucial. Layers of thin "winding" cell walls and cellulose secondary walls, which also enable the fibers to dye deeply and absorb water, contribute to the fiber's strength. The grade of intermediary needed is determined by the ratio of cellulose secondary wall to fiber perimeter. However, cotton fiber has a number of shortcomings that require an effort to change its properties depending on the intended use. Certain limitations are associated with cotton fibers:

- Considerable water absorption, contingent on the fiber type, results in expansion, thereby influencing the product's performance and reliability.
- Inadequate bonding at the fiber-matrix interface and reduced mechanical properties often arise due to incongruous water absorption (where fibers are hydrophilic and matrices hydrophobic).
- Incompatibility exists between several polymer matrices and specific fibers.
- The substantial variability in cotton fiber characteristics and properties stems from the extensive diversity in fiber attributes.
- Susceptibility to fungal infestations and insect attacks.
- Flammability is a concern, and the degradation temperature remains relatively low. Natural fiber quality and attributes can substantially fluctuate based on factors such as weather conditions and agricultural practices (including harvest season, soil quality, climate, fertilization, location, etc.).
- Thermal conductivity in Natural Fiber-reinforced Composites (NFRCs) is comparatively lower in contrast to glass fiber-reinforced composites.
- The supply chain is intricate, marked by geographical constraints on availability.
- High water absorption (depending on the type of fiber) leads to swelling, which affects the performance and dependability of the product.

It represents a large proportion of natural fibrous materials based on cellulose (the chemical structure representing repeating units of cellulose fibers), and is highly flammable. A typical LOI value of cellulosic materials is centered around 20, the actual value is highly dependent on the morphology and other structural features of the constituent fibers as well as on the final shape and density of the fabric itself. Cotton is widely used to produce textiles suitable for domestic applications such as clothing, bedding, furniture, curtains, etc. However, cotton is also known as one of the most flammable textile materials with an LOI value of up to 18.4. It is very important for public safety to make this material non-flammable. Here are some treatments that can be done to modify the fiber properties, including:

Cotton fibers have been employed as reinforcement in diverse organic matrices like polyester, vinyl ester, and epoxy matrices. However, despite the benefits they offer, research exploring the utilization of natural fibers for enhancing inorganic matrices is currently limited. Although the authors of a prior study investigated the mechanical properties of geopolymer composites reinforced with short cotton fibers, the available literature is sparse in this domain. The findings from this study revealed that a further increase in short cotton fiber content beyond 0.5 wt% resulted in diminished mechanical properties. This decrease was attributed to challenges in workability, leading to the formation of voids and clumping of fibers. The impact of various parameters related to cotton fiber, such as length, weight, volume fraction, and other influencing factors, on the mechanical attributes of different thermosetting polymer composites, is a topic of significant concern. In general, sisal fiber assumes diverse configurations, including unidirectional short fibers, random orientations, varied weaves (plain, twill, and woven patterns), and distinct ply fiber orientations such as 0, 90, and 45 degrees.

Figure 8. Household needs product using cotton as a raw material

Due to increasing interest in environmental aspects, eco-friendly fibers with high specific strength and low cost are widely used to reinforce the matrix, which in turn is used to transfer loads to the reinforcement and to protect reinforcement from environmental degradation. The characterization technique of natural fiber-reinforced thermoset composites makes it possible to determine the mechanical performance of the resulting composites and it is primordial to assess their quality and select the appropriate application for using them. For example, the degree of vacancies in a composite can affect the quality of the biocomposite material and its mechanical properties.

5. Exploring Environmental Advantages of Natural Fiber Composites in Chemical Engineering Applications

The use of natural fiber composites can potentially lead to reduced energy consumption during manufacturing. These composites typically require less energy-intensive processing compared to their synthetic counterparts, translating to lowered greenhouse gas emissions. By examining empirical evidence, we unveil the correlation between energy-efficient production processes and the application of natural fiber composites in chemical engineering. Compared to many synthetic fibers, natural fibers have the advantage of lower melting or degradation temperatures. This property allows for processing at lower temperatures during composite fabrication. Traditional manufacturing methods for synthetic composites often require higher temperatures, which in turn demand more energy for heating and cooling. Natural fiber composites can be produced at temperatures that are not only energy-efficient but also mitigate the risk of thermal degradation.

The manufacturing process for natural fiber composites is often simpler compared to their synthetic counterparts. This streamlined approach can result in fewer processing steps, reducing the overall energy input required. Additionally, some natural fibers possess inherent self-binding properties, eliminating the need for additional binding agents or energy-intensive chemical treatments. Natural fibers tend to have lower stiffness and strength compared to synthetic alternatives, which can be advantageous during processing. The reduced stiffness often necessitates less mechanical energy during cutting, shaping, and forming operations. This translates to decreased energy consumption when transforming raw fibers into composite components.

Chemical engineering principles are employed in the formulation and processing of the matrix material. This involves mixing, melting, or curing the polymer to achieve the desired properties such as viscosity, reactivity, and thermal stability. Incorporation of natural fibers into the polymer matrix marks a crucial step. Various techniques are employed, including hand lay-up, compression molding, injection molding, and even advanced methods like resin-transfer molding or pultrusion. These methods involve arranging the fibers in a desired orientation within the matrix and subsequently applying heat and pressure to consolidate the materials into a composite structure.

The trend towards green and sustainable manufacturing practices aligns well with the use of natural fiber composites. Many manufacturing techniques for natural fibers, such as pulping, carding, and weaving, are inherently less energy-intensive than those required for synthetic fibers. Integrating these processes with composite production further contributes to energy reduction. Natural fibers are often sourced locally, reducing the need for extensive transportation. In contrast, synthetic fibers may need to be transported from distant manufacturing facilities, increasing energy consumption due to transportation logistics. The localized sourcing of natural fibers minimizes transportation-related energy expenditure. The lightweight nature of natural fiber composites also has implications for energy consumption beyond manufacturing. The use of these composites in various applications, such as automotive and aerospace, leads to reduced energy consumption during the operational phase due to the lower weight of the end products. This effect contributes to overall energy efficiency throughout the product lifecycle.

The manufactured composite undergoes rigorous quality control and testing procedures. These tests may include mechanical testing (tensile, compression, flexural), thermal analysis, microscopy, and more. These evaluations ensure that the composite meets required performance standards and addresses any potential defects or inconsistencies. The manufacturing process for natural fiber composites in the chemical engineering sector embodies a synergy between materials science and engineering principles. It encompasses the selection of materials, surface modification, polymer processing, composite fabrication, curing, and quality assurance. The resultant natural fiber composites exhibit a unique balance of properties that make them suitable for a wide range of applications across various industries.

6. Future outlook of natural fiber composite

The cultivation of hemp, rice husks, bamboo, coconut, plantain, pineapple, sisal, and wheat husks is widespread across the globe. However, the by-products generated from these sources often go untapped, failing to be recycled into derivative products that possess greater value and utility. This could be attributed to the labor-intensive nature of natural fiber manufacturing processes, while the production of synthetic fibers demands substantial financial resources. As a result, entrepreneurs are actively evaluating the potential of engaging in such ventures. Conversely, when considering the forthcoming five years, the prospects for the natural fiber market appear promising. As per the compound annual growth rate (CAGR), the natural fiber market is projected to achieve a valuation of USD million by 2022 and further elevate to USD million by 2028. This study offers an extensive and comprehensive analysis of the global natural fiber market, achieving this by systematically delineating the current state and trends of the market, conducting a thorough examination of the competitive landscape involving key players, and providing an intricate breakdown of market segments categorized by type, application, and region.

Regenerate. This report's research period runs from 2016 to 2027 in several aspect such as: most popular fiber type (Figure 9), future product design (Figure 10), resin type (Figure 11), and profits earned as well as profits expected in the future (Figure 12).

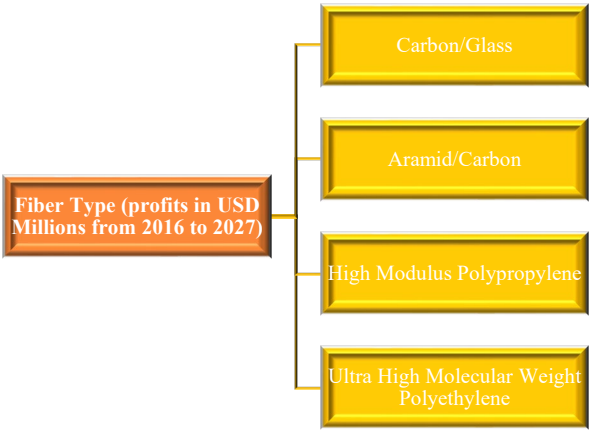


Figure 9. Most popular synthetic fiber and matriks