

# Modification by Surface Treatment of Natural Fibers for Enhanced Performance in Fiber-reinforced Composites: A Comprehensive Review

Suchismita Swain<sup>1</sup>, Saroj Kumar Patra<sup>2\*</sup>, Shakti Prasanna Jena<sup>3</sup> and Vijay Prakash Sharma<sup>4</sup>

<sup>1</sup>ICFAI Business School, IFHE University, Hyderabad, Telangana, India

<sup>2</sup>School of Engineering and Technology, BML Munjal University, Gurugram, Haryana, India

<sup>3</sup>Department of Mechanical Engineering, Nalanda Institute of Technology, Bhubaneswar, Odisha, India

<sup>4</sup>University School of Business, Chandigarh University, Mohali, Punjab, India

## \*Correspondence to:

Saroj Kumar Patra  
School of Engineering and Technology,  
BML Munjal University,  
Gurugram, Haryana, India.  
E-mail: [sarajkumarpatra@gmail.com](mailto:sarajkumarpatra@gmail.com)

**Received:** September 15, 2023

**Accepted:** November 22, 2023

**Published:** November 27, 2023

**Citation:** Swain S, Patra SK, Jena SP, Sharma VP. 2023. Modification by Surface Treatment of Natural Fibers for Enhanced Performance in Fiber-reinforced Composites: A Comprehensive Review. *NanoWorld J* 9(S4): S203-S213.

**Copyright:** © 2023 Swain et al. This is an Open Access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CCBY) (<http://creativecommons.org/licenses/by/4.0/>) which permits commercial use, including reproduction, adaptation, and distribution of the article provided the original author and source are credited.

Published by United Scientific Group

## Abstract

Natural fibers are environmentally sustainable, reusable, and biodegradable compared to synthetic materials in industrial applications. As a result of their favourable specific strength-to-weight ratio, they are perfect for industries like automobile production that need lightweight yet robust components. Economically, natural fibers are preferable to synthetic since they are typically less expensive. However, there are difficulties in composite applications because of the incompatibility of natural fibers with polymeric matrices. Surface treatments are used to improve adherence and compatibility. Chemical, physical, or biological processes change the surface of fibers which improves the required characteristics of good natural fibers. The expense of chemical agents must be considered, however the increased mechanical properties that arise from treatments may allow for less fiber to be used. Enzymatic procedures or fungi are used in biological treatments to get rid of hydrophilic materials from fiber surfaces. The paper presents an exhaustive examination of natural fiber surface treatments, including their benefits, drawbacks, and potential applications in polymer composites. The article discusses about different methods of physical, chemical, and biological treatments, followed by discussion and future direction of research. The researchers can get an advanced concept on different surface treatment methods which will help them in choosing the best surface treatment method or to discover best research topic. The future of this research direction will be on integrating treated fillers, investigating biological methods and nano particle treatments, and improving the performance of composite materials. Researchers may advance the development of natural fiber composites by focusing on these opportunities, which will increase their uses, boost performance, and encourage sustainability.

## Keywords

Natural fibers, Composites, Surface treatment, Chemical treatment, Chemical modifications, Fiber-reinforced composites

## Introduction

Large volumes of greenhouse gases are released during the manufacture of glass fibers and materials made of petroleum. There has recently been an emphasis on utilising environmentally conscious green materials which are biodegradable, recyclable, and renewable to reduce the environmental effect of these materials. Fully green composites, a form of such materials created by mixing bio-composites manufactured from bio-fibers and resins obtained from renewable agro and forestry sources, are one example of such materials [1, 2]. When a composite of this sort reaches the scrap condition, it can be decomposed without any environ-

mental deterioration. Natural fibers were initially utilised in composite systems in ancient Egypt more than three thousand years ago, when walls were constructed by combining straw and clay [3]. Despite the fact that the first fiber reinforced composite was used in 1935, World War II saw a remarkable advancement in fiber composite technology. This was for the requirement of lightweight along with high strength materials. Following the World War II, several fibers were found in the 1970s, dramatically altering the way that conventional materials were used [4]. The academic community and several companies have paid growing attention to polymer composites reinforced with natural fibers during the past few decades [3]. This is most likely caused by the polymers' biodegradability. The value of natural fiber is seen in its inexpensive and lucidity of processing. Natural fiber polymer composites have been discovered to offer greater advantages than conventional materials when comparing the details of their individual qualities. These composites find applications in a wide range of aerospace and associated industries [5]. Natural fibers are economical, low density, and light weight, making them environment-friendly with minimal environmental pollution and non-hazardous. Their degradability supports recyclability, encouraging the demand of natural fibers reinforced composites [6]. Different plant components, including leaves, stems, fruits, bast, and seeds, were used to extract the natural fibers. The applicability of the fibers reinforced composites has increased steadily in recent years in a variety of areas. These composites have recently entered new application fields including biomedical devices and civil constructions [7]. Depending on their physical characteristics, natural fibers must be chosen. The efficacy of natural fiber is significantly affected by the plant's age [6]. More prevalent among the chemical components of fiber are cellulose, hemicellulose, and lignin, although additional additions such as wax, ash, and pectin were also present [8].

The main issue with natural fibers has been determined to be their incompatibility with hydrophilic thermoplastic matrices during inclusion, which results in unfavourable qualities of the composites produced. The bonding between the matric and fiber must consequently be improved by different fiber-polymer interface modifications, which enhances the performance of the final composite [9, 10]. Some other disadvantages of natural fiber composites include increased absorp-

tion of moisture, reduced fire resistance, low operating temperature restrictions, substandard mechanical qualities, and, mainly, the price fluctuations throughout the year harvesting [11]. Swapping out synthetic fibers for natural ones is an initial step in taking environmental considerations into account when choosing materials. However, the creation of materials fully produced from renewable resources is being driven by the need to decrease the emission of greenhouse gas, such as CO<sub>2</sub>, and the growing understanding of the limited nature of fossil energy supplies.

The article starts out by giving a quick overview of natural fibers and classifying them into mineral, plant, and animal fibers. After that, a thorough analysis of several surface treatment techniques for natural fibers is covered, with each approach being divided into physical, chemical, and biological treatments. For the purpose to ensure that the subject is completely comprehended, each treatment approach is discussed separately. The paper also contains a discussion part, which is followed by a conclusion that summarises the results and offers a preview of potential future study areas. With the help of this framework, readers may learn how to categorise natural fibers, comprehend various treatment philosophies, and discover possible research subjects.

## Natural Fibers

In substitute of synthetic fibers and petroleum-based materials, natural fibers are an emerging class of reinforcements that are renewable. In light of the increasing shortage of non-renewable resources, there has been a growing exploration and utilization of renewable plant resources in recent years. In simple definition, natural fibers are ones that aren't synthetic or artificial. They can come from the animals or plants [12]. The cellulose-producing plants may be divided into those that produce bast fibers, like jute, and flax, seed fibers, like cotton, and coir, leaf fibers, like sisal, and abaca, grass, and reed fibers, like maize, and rice, and core fibers, such as hemp, and jute [13]. Table 1 represents annual production of natural fiber of top ten fibers and the respective producer countries [3, 7, 14, 15].

The intricate nature of natural fibers lies in the complex constituents and cell structure [16]. Each fiber can be viewed

**Table 1:** Top ten natural fibers annual production and their producer countries.

Fiber	Type	Species	Largest producer countries	World production (10 <sup>3</sup> tons)
Bagasse	Stem	-	Brazil, China, India	75,000
Bamboo	Stem	(>1250 species)	India, Indonesia, China	30,000
Cotton	Seed	<i>Gossypium</i> sp.	India, China, USA	25,000
Jute	Stem	<i>Corchorus capsularis</i>	India, Bangladesh	2500
Wool	Animal	Sheep, alpaca, camel	China, New Zealand, Australia	2000
Kenaf	Stem	<i>Hibiscus cannabinus</i>	USA, India, Bangladesh	970
Flax	Stem	<i>Linum usitatissimum</i>	Belgium, Canada, France	830
Grass	Grass	-	-	700
Sisal	Leaf	<i>Agave sisalana</i>	Kenya, Tanzania	378
Kapok	Fruit	<i>Ceiba pentandra</i>	India, China	316

as a composite material, where resilient cellulose microfibrils are enveloped within a flexible matrix of lignin and hemicellulose. The structural makeup of a natural vegetable fiber cell consists of a secondary wall, which constitutes 80 percent of the thickness [17]. This secondary wall plays a crucial role as the primary component responsible for bearing loads. Moreover, these microfibrils are helically positioned along the axis of fiber, resulting in the formation of hollow cells at the ultimate level. The cell walls of the hollow tube are composed of four different distinct layers, namely three secondary cellular partition along with a primary cell wall, and a lumen, which is an open channel found at the centre. The prime constituents of these cell walls are cellulose, hemicelluloses, and lignin [18]. The characteristics of regular fiber strands may vary based on factors such as their source, age, and the method used for extraction [19]. Natural fibers are primarily classified as mineral, animal, and plant fibers as shown in figure 1.

### Animal fibers

Animal fibers are made of proteins, that come from animals. They come from wide sources, like angora, alpaca, mohair, silk, and wool. These animal-based fibers are usually utilised as reinforcement in green composites, such as silk and wool. Comparing to other forms of natural fibers, their special qualities, such as surface toughness, high aspect ratio, flexibility, and low hydrophilicity, make them beneficial for practical applications [18].

### Mineral fibers

Mineral fibers encompass fibers derived from minerals, which can be further categorized into classes like asbestos, serpentine, and anthophyllite amphiboles. Asbestos, specifically, refers to a collection of six naturally available mineral fibers. But the utilization of asbestos fibers is now extremely limited due to their association with severe health risks, including lung fibrosis, pleural disease, lung cancer, mesothelioma, and more [20]. As a result, the use of asbestos-based fibers has significantly declined over time. The adverse health effects associated with these mineral fibers have led to a shift towards safer alternatives in various industries.

### Plant fibers

Plant fibers are widely investigated as popular and frequently utilized natural reinforcements. The classification of natural fibers encompasses eight fundamental types. These include [3, 14, 18, 21-23]: Bast fibers, extracted from plant stems' outer cell layers. Such fibers possess exceptional tensile strength, surpassing that of any other natural fiber type. Flax, hemp, jute, ramie, sugar palm, rattan, and mesta are among the prevalent plants from which we get bast fibers. Leaf fibers, are collected from the foliage of various plants, including abaca, pineapple, sugar palm, Curaua, manilla, banana, Raphia, agave, henequen, and sisal. Seed fibers, obtained from the seeds of plants like kapok, milkweed, cotton, and loofah. Stalk fibers, derived from the stems or stalks of certain plants, including oat, bamboo, maize, rice, barley, wheat, and rye. Grass and reed fibers are obtained from specific types of grasses and reeds. Examples of grass fibers include bamboo, wheat, corn, sabal, canary, rape, esparto, bagasse, and rice straw. Reed fibers can be

sourced from plants such as papyrus and rattan. Wood fiber is derived from the fibrous material present in the wood of trees, including softwood and hardwood. Examples of wood fibers include those obtained from pine, spruce, oak, and eucalyptus trees. Fruit fibers are derived from the fibrous components found in various fruits, such as piña, coconut, coir, sugar palm, kapok, durian, and oil palm. Several significant natural fibers can be listed as follows. Root fibers could refer to the fibers derived from the roots of certain plants. These fibers are typically extracted from the roots of specific plants known for their fibrous characteristics. The examples are, luffa, swede, cassava, ramie, etc.

## Various Surface Treatment of Natural Fibers

The behavior of composites is greatly hampered by the interfacial adhesion between the constituents [13]. Natural fiber composites have great tendency to absorb moisture because of the hydrophilic and polar character of natural fibers, which is brought on by non-cellulosic components such as hemicelluloses [14]. This can lead to weak compatibility between the matrix-fibers, resulting in delamination and significantly reducing the composite's mechanical properties [13]. Furthermore, the hydrophilic character of natural fibers and the polymer matrices hydrophobic nature render them incompatible, further altering the fiber-matrix contact and producing materials with subpar mechanical properties [3]. Limitations of natural fiber composites also include poor interfacial bond, low wettability, and moisture absorption. To address these issues, chemical and surface treatments are required [24]. Optimizing the interfacial bonding and reducing water absorption are crucial steps in enhancing the mechanical properties [25, 26].

By enhancing the adhesion, natural fiber composites may be made stronger and more rigid. The fiber surface and matrix can both be changed to accomplish this. Low thermal stability characterises natural fibers [13], But physical, chemical, and biological treatments can get over this restriction. The natural fibers' surface is chemically modified or cleaned during pre-treatment, which enhances adherence and compatibility with the matrix [27]. Additionally, these processes improve the composite's durability, adhesion existing between the matrix-fibers, and strength [28]. Optimising the interfacial bonding is another crucial element. This entails shifting weight from the matrix to the fibers, cutting down on stress absorption, and generally enhancing mechanical characteristics [29, 30]. Physical, chemical, and biological modifications offer solutions to the challenges faced by natural fibers in composites.

### Physical modification

These methods aim to revamp the fiber-matrix interaction, improve bonding at the interface, and optimize the overall performance. These techniques involve altering the fiber surface's morphology, roughness, or topography to create an interface that promotes better adhesion with matrix. The goal is to increase the contact area to improve the interlocking mechanisms between the fibers-matrix [13, 31]. So, basically the goal is removing surface contaminants and establishing close molecule contact across the surfaces to cause a drop

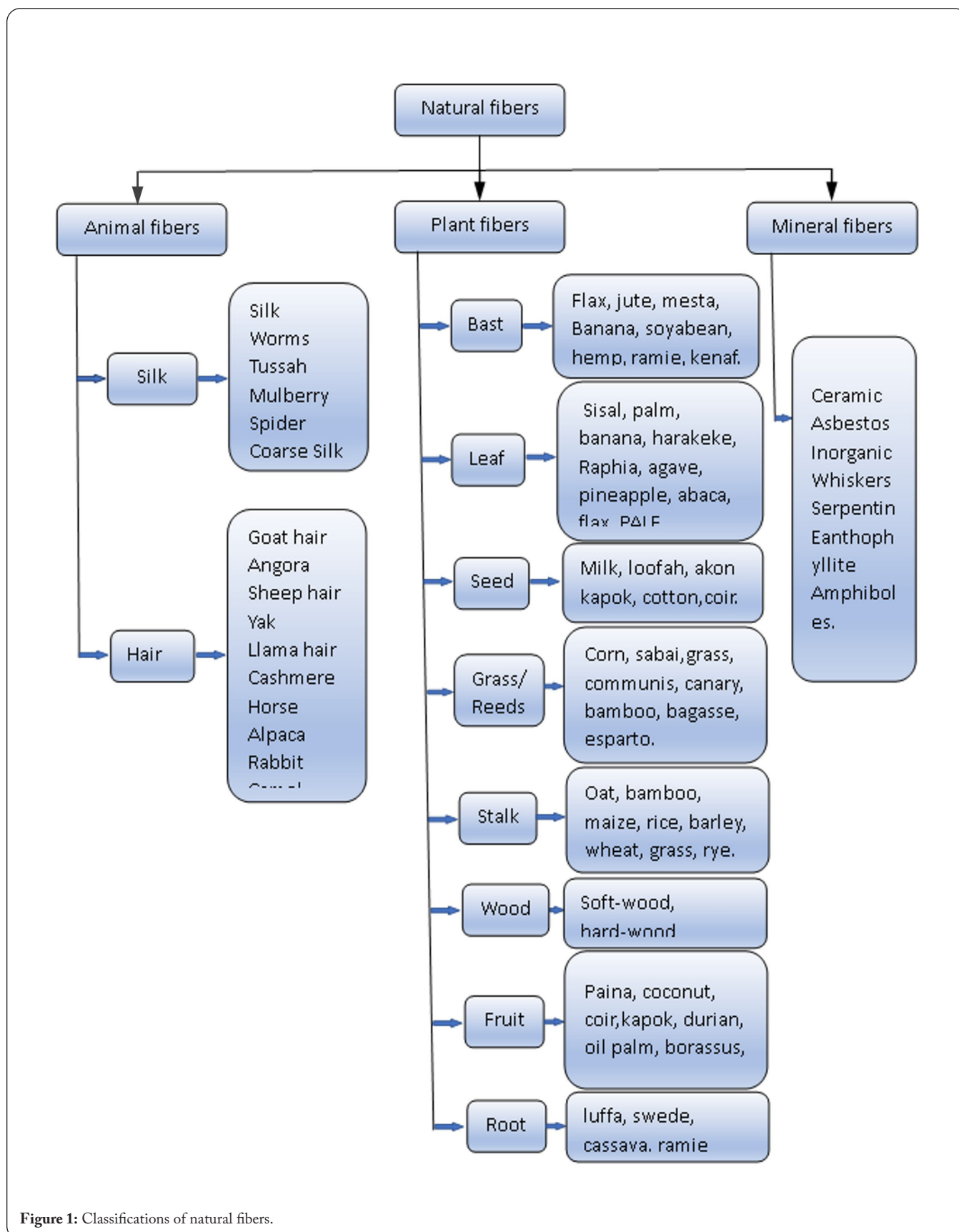


Figure 1: Classifications of natural fibers.

in molecular energy across the surface drastically. Physical treatment methods, such as steam explosion, ultraviolet (UV) treatment, plasma treatment, corona treatment, ultrasound treatment, fiber beating, and thermo-mechanical process,

dielectric barrier methods are specifically utilized to improve the surface properties [31]. These methods focus solely on changing the characteristics of the surface without altering the chemical characteristics of the fibers.

### Steam explosion process

This is a technique used to disintegrate lignocellulosic materials into their primary components, which include amorphous lignin, cellulose fibers, and hemicellulose. That is the process involves subjecting the natural fibers to high-pressure steam, which causes the fiber bundles to detach into discrete filaments. This separation allows for better dispersal of the fibers within the composite matrix, which results in improved properties. However, one drawback of this process is that it tends to produce relatively short fibers. Consequently, the use of steam-exploded fibers can lead to inferior properties in certain aspects [32-34]. In their research, Vitrone et al. [35] discovered that in steam explosion pretreatment a pre-treatment temperature more than 195 °C produced large reed fiber boards under the best conditions. Main chemical and morphological changes were seen in the pre-treatment temperature range of 190 - 195 °C, according to scanning electron microscope and Fourier transform infrared spectroscopy analyses.

### Thermomechanical processes

Thermomechanical processes provide an alternative for separating lignocellulosic fibers into individual filaments. Lignin may be released from fiber bundles by thermal treatment approaching the glass transition temperature of lignin, yielding single fibers with increased strength and stiffness. That is subjecting the fibers to a combination of heat and mechanical forces. This process helps to break down the fiber bundles and align the individual filaments, results in enhanced fiber-matrix bonding and properties [31]. The glass transition temperature of lignin, such as kraft lignin, is around 142 °C. Heating fibers to about 200 °C softens lignin while depolymerizing it and hemicellulose, leaving behind cellulosic microfibrils. Heat-treated fibers offer advantages like steam explosion-treated fibers, such as clean, rough surfaces, and increased crystallinity. Heat treatment also enhances surface hydrophobicity by migrating lignin and extractives, improving compatibility with matrices like polypropylene. However, controlling moisture content is crucial during composite processing to avoid poor processability and porous products [36, 37]. Pires et al. [38] in their study using luffa cylindrical fibers, subjected to thermomechanical and thermo-hydrmechanical treatments in the study to improve their qualities. The procedures include hot pressing the fibers at various temperatures under dry and saturated circumstances. The fibers which were compressed at 160 °C in saturated circumstances had the best results, showing a much high value of modulus of elasticity and decreased absorption of moisture. These results demonstrate the potential of luffa cylindrical fibers in designing composite materials and demonstrate how thermomechanical and thermo-hydrmechanical treatments may be used to enhance their capabilities.

### Plasma treatment

Plasma is a highly reactive gas, can alter the surface characteristics of natural fibers. Plasma is a partly ionized, quasi-neutral gas carrying ions, electrons, and UV radiation. Plasma generation needs an energy source for ionization,

a vacuum system for low pressures, and a reaction chamber. Cold plasma treatment is used to alter the surfaces without altering the mechanical qualities of fibers. It is characterised by high electron temperature and low gas temperature. Vacuum and atmospheric procedures are also used to cure plasma, and each has its own benefits. Surfaces modified by plasma undergo surface cleaning, material ablation, cross-linking, and chemical structure alteration, all of which have an impact on adhesion. For in-place processing, atmospheric plasma treatment is appealing, whereas vacuum plasma treatment is carried out in a chamber [31]. The polarity of the fibers is increased during plasma treatments, which enhances their compatibility with hydrophobic polymer matrices. Better adhesion and increased composite performance are the results of this improved compatibility. Flow, gas type, pressure, and concentration are either controlled or adjusted during plasma therapy [39]. Leone et al. [40] studied to improve the quality of polypropylene matrix composite laminates for interior parts in the naval industry by pre-treating flax fiber fabric with nitrogen plasma. To revamp the bond between the fiber and matrix, the textiles were subjected to varied exposure times (5, 10, and 15 min). In comparison to untreated textiles, the results show that a pre-treatment duration of 15 min produces the greatest results, with increased water absorption, tensile and flexural characteristics, as well as greater ultimate strength (6.8% increase) and modulus (22.31% increase).

### Corona treatment

Corona treatment is an intriguing method that efficiently causes surface oxidation in a variety of materials, improving the compatibility between hydrophilic fiber and hydrophobic matrix significantly. Multiple modifications are brought about by this technique to improve these materials' interaction and bonding [13]. A visual and audible discharge characterises the phenomena known as a corona. It happens when an object encounters a strong electric field gradient in one spot, potentially ionising the air around it and causing an electrical breakdown [31]. Corona discharges arise from the presence of non-uniform electrode geometries, just like a combination of a point electrode and a plane electrode. These discharges occur in close proximity to sharp-edge points where the electric field strength is intensified [41]. Corona discharges takes place near atmospheric pressure and are characterized by relatively low power electrical discharges. These discharges are induced by intense electric fields surrounding small radius needles, wires, or sharp edges on an electrode [42].

Corona exhibits a colourful glow that is often discernible in a dark setting. The associated hearable discharge, typically a soft hissing sound, becomes more pronounced as the output voltage rises. The corona process often generates ozone, an unstable and odorous form of oxygen [43]. This treatment can effectively cleanse the material's surface, leading to improved roughness and adhesion properties. It enables the creation of enhanced surfaces without altering the mechanical characteristics [44]. Due to its relative ease of establishment, corona has found widespread application in various processes. The modification process does not necessitate specific conditions, unlike plasma treatment that requires vacuum chambers (low

temperature). It is a cost-effective method with consumption of energy very low. Moreover, the operation can be readily implemented on a broad scale and integrated into a high-volume material processing, making it highly advantageous for industrial production lines [45, 46]. One drawback of corona treatment pertains to its limited insight depth. In certain cases, corona systems may only exhibit an effect on loosely arranged fibers and may not deeply penetrate yarn or woven fabric. Consequently, the impact of corona treatment on textiles is constrained and tends to be transient in nature [47].

### Dielectric barrier treatment

There are some parallels between the corona treatment method and the plasma dielectric-barrier discharge (DBD) technology, but there is also a significant distinction. When using a corona treatment, there is no dielectric material present, and the discharges take place directly between exposed metal electrodes. The DBD plasma method, on the other hand, uses two plane metal electrodes which are parallel, at least one of these has a dielectric layer. The charge which are transferred are accumulated on the surface of this dielectric layer, which then disperses it equally throughout the whole electrode surface [48, 49]. The recommended materials for dielectric barriers in this application include glass, silica glass, and, in certain situations, ceramics, polymer layers, or thin enamel. Breakdown processes inside the gas gap are triggered when an alternating voltage is given to the electrodes, in the range of low-frequency AC to 100 kHz. Transient micro-discharges are created as a result, which are dispersed throughout the dielectric surface and last just nanoseconds. These kinds of discharges are frequently utilised in surface treatment procedures that produce ozone [50, 51]. The DBD technique's short duration and partial homogeneity in treatment or discharge are two important drawbacks. This method is widely used for sterilising surfaces, depositing films, extracting components from flue gases, converting greenhouse gases, and treating fabrics, polymers, plastic foils, and metal surfaces [52].

### Ultrasound treatments

The term "ultrasound," which is used to describe sound waves with frequencies higher than 20 kHz, is most frequently used in medical and diagnostic settings. Ultrasound has, however, also been used in relation to cellulosic fibers in some cases [31]. Ultrasound treatments have shown successful in eliminating numerous chemicals and contaminants from surfaces, even without the requirement for surfactants in the washing process but being less popular than the plasma treatments previously addressed. This efficiency can be linked to a phenomenon known as acoustic cavitation, which is primary reason for the chemical and physical effects seen in liquid-liquid or solid-liquid systems. This phenomenon includes the production and collapse of bubbles [53].

The consequence of this method on natural fibers, notably cotton, have been the subject of much investigation. These investigations have shown that cotton's crystalline structure may change due to ultrasonic treatment, altering the material's mechanical and chemical characteristics in the process [42]. Many academics have looked at the use of ultrasound to heal

cellulosic fibers. The application of ultrasound in paper and pulp technology is covered in detail by Willems [54]. Rosales et al. [55] investigated how *Agave tequilana* fibers for biopolymer composites would react to alkali and ultrasonic treatment. The process led to morphological alterations, a higher in cellulose concentration, a lower in lignin content, an increase in crystallinity, and all of these modifications. The enhanced fibers had a high heat resistance, which made them appropriate for the production of automobile parts.

Lower frequency ultrasound produces more powerful cavitation, although its effects are often more localised. In contrast, because cavitation bubbles last for a shorter period of time at higher frequencies, cavitation is less vigorous. Nevertheless, despite these variations in cavitation features, there hasn't been much study on ultrasonic alterations [31].

### Ultraviolet treatments

The wavelength of UV light, ranges from 10 to 400 nm. With different organic compounds, it has the power to trigger chemical reactions that have consequences beyond simple heating. Natural fibers' molecular structures can undergo photochemical reactions that can change their mechanical characteristics. UV radiation is a possible energy source that might start these processes. Furthermore, UV radiation offers a safe and eco-friendly method for modification of surface in natural fibers [56, 57].

Gassan and Gutowski [58] explored tossa jute fiber treated with corona discharge and UV radiation. The fibers' surface energy treated with corona was higher, although the improvement in polarity for yarns was very marginal. Gains in polarity were much greater after UV therapy. It's important to balance fiber strength with surface polarity. The composite flexural strength increased by 30% under ideal treatment circumstances. Abdullah-Al-Kafi et al. in their study prepared unsaturated polyester resin with jute fiber and E-glass fiber by hand lay-up at room temperature. Improved mechanical qualities came from jute fiber optimisation and glass fiber integration. The qualities were further enhanced by UV pretreatment of the fibers, with a jute and glass ratio of 1:3 exhibiting the greatest performance and interfacial adhesion as seen by scanning electron microscope examination. Benedetto et al. [60] studied to assess the physical, chemical, and mechanical characteristics of prata banana fibers following UV exposure for 7 and 15 days. In contrast to natural fibers (69.99 MPa and 87.40 MPa), UV treatment led to superficial structural changes that improved the elastic modulus (238.94 MPa) and tensile strength (89.77 MPa). Thus, the mechanical characteristics of composites made with these fibers can be enhanced by the clean UV surface treatment.

### Chemical modification

Chemical modification, which includes chemical processes, can enhance the bondage between natural fibers and the matrix. Natural fiber-containing composites have poor bonding at the interfaces because of the difference between the hydrophilic character of natural fibers and the hydrophobic nature of matrix [13]. Natural fibers can be chemically treated

to lessen their natural hydrophilicity and improve their matrix adhesion abilities. Chemical treatments can be carried out using a variety of techniques, including benzylation, alkaline, silane, acetylation, peroxide, sodium chlorite, isocyanate, permanganate, oleoyl chloride, acrylation, and acrylonitrile grafting and triazine treatments [14, 61]. Some of them are discussed in the subsequent section.

#### Alkaline treatment or mercerization

Sodium hydroxide (NaOH) is primarily used in alkaline treatment to dissolve the cellulose in natural fibers [62]. Wax, lignin, and oils, present at the outside of the fiber cell wall are cleaned by chemical treatment of natural fibers. In particular, alkaline treatment causes a considerable change by breaking up the hydrogen bonds within the network structure. The (OH) groups that are active in the fibers are disassembled and ejected from the fiber during alkaline treatment. The rest molecules in reactive mode assist this process, whose effect is the creation of fiber cell-O-Na groups among molecular chains of cellulose. As a result, there are less hydrophilic OH groups, which increases the fibers' resistance to moisture. Additionally, during the treatment process, certain hemicelluloses, lignin, pectin, wax, and oil are eliminated [14]. An essential result of the treatment is surface roughness increases. Short fibers are often subjected to an alkaline treatment that involves heating them for three to four hours around at 80 °C in aqueous of about 10% NaOH solution. These are then cleaned and dried in an oven with ventilation. Smaller and higher-quality fibers are produced as a result of this procedure, which helps to break up fiber clusters. Furthermore, it is anticipated to improve fiber wetting, enabling greater interaction with the materials around it [3].

Nayak et al. [63] used 4% of NaOH solution treated for 1 h at 80 °C and dried for 24 h in oven, for the surface treatment of *Careya arborea* bast fibers. The outcome confirms that after the alkaline treatment, the percentage of cellulose increases and the non-cellulose materials is removed. In another study Nayak et al. [64] altered the surface of Eleusine Indica Grass Fiber in alkaline treatment by considering 5% concentration of NaOH at 80 °C for 1 h. After that it was treated in oven for 24 h at 60 °C. The results represent a decrease of 19.78% in cellulose percent and reduces the hemicellulose, lignin, wax, moisture content, ash, and density after chemical treatment. Sahu et al. [65] used the alkaline treatment for *Bauhinia vahlii* bast fibers and compared with other chemical treatment methods. They considered 5% NaOH solution at 80 °C for 1 h. The results indicate that the cellulose content increase by 9% and a simultaneous decrease in hemicellulose, lignin, and other contents.

#### Silane treatment

Silane is  $\text{SiH}_4$  [62] the hydrolyzable alkoxy group in the silane molecule goes through hydrolysis when it is in contact with moisture, creating silanols as a consequence. Following a reaction between these silanols and the hydroxyl groups in the fiber, solid covalent bonds are formed that chemisorb onto the fiber surface and securely adhere to the cell wall [66]. The result helps to keep the fiber from growing. This network's existence

contributes to the composite material's overall stability and integrity being improved [67]. Silane-treated fibers have been shown to have greater tensile strength [68]. Ravindran et al. [69] examined jute's mechanical characteristics and water absorption treated with 5% silane at 75 °C for 10 h. The results indicate that the surface treatment with silane treated jute shows an enhanced compatibility with vinyl ester matrix.

#### Acetylation treatment

The prime objective of acetylation is to wrap the molecules that give fibers their hydrophilic nature—the hydroxyl (OH) groups—with molecules that have a more hydrophobic feature. The goal of this coating technique is to change the fibers' surface qualities such that they are more hydrophobic and less likely to absorb moisture [3]. Acetic anhydride is applied to the fibers over a period of one to three hours at high temperatures after being initially submerged in acetic acid to achieve acetylation. Since the reactions of acetic acid and acetic anhydride with fibers are combined, this heating technique is used to speed up the reaction. These two chemicals can be used to efficiently cause the acetylation process, which results in the desired alteration of the fibers [13]. In general, acetyl groups and the OH groups in lignin and hemicellulose may interact to generate a hydrophobic change. Normally, alkali treatment is applied to natural fibers before they are treated with glacial acetic acid. The fibers are steeped in glacial acetic acid for an hour following the alkali treatment. They are then submerged for two to five minutes in acetic anhydride, which also contains two drops of concentrated sulphuric acid. After that, the fibers are cleaned and dried at 80 °C in an oven set for six hours. This sequence of actions speeds up the acetylation process and gets the fibers ready for other uses [24]. In this method, OH and the carboxylic/anhydride groups undergo an esterification process [67]. Gudayu et al. [70] in their analysis of sisal fiber using alkaline and acetylation treatment find that due to acetylation a reduction of moisture absorption reduces by 42% and in case of alkaline-acetylation treatment a reduction of 28%.

#### Benzylation treatment

Sometimes to enhance the surface property, benzoyl chloride is used, by lessening their hydrophilic character. As the fiber after treatment has lower hydrophilicity and hence has the capacity to enhanced interaction with the hydrophobic matrix is caused by the presence of benzoyl ( $\text{C}_6\text{H}_5\text{C}=\text{O}$ ) in benzoyl chloride [71]. Lignin, waxes, and surface oils are first removed during a pretreatment phase. After that, a further benzoyl chloride treatment converts the fibers' OH groups into benzoyl groups. Finally, the alteration procedure is finished by adding hydroxyl groups and attaching them to the cellulose core [67]. To accomplish this, the fibers are dipped in glacial acetic acid for one hour. They are then briefly submerged in a solution made of acetic anhydride and a few drops of strong sulphuric acid. The required alteration procedure is then finished by filtering, washing, and drying the fibers in a vented oven [3].

#### Peroxide treatment

Free radicals are created during this process as a result of the

breakdown of peroxides. The hydrogen groups found in both the cellulose fibers and the polymer matrix are then contacted by these free radicals. Natural fibers are often alkalized before being treated with peroxide. The alkaline-treated fibers are then submerged for about 30 min in an acetone solution with a 6% [72] of either benzoyl peroxide or dicumyl peroxide and after that it is decanted and dried [67, 73]. This method lowers the fibers' ability for moisture absorption, thermal stability increases, and the link strengthens at their interface.

### Maleated coupling agents

Composites are frequently strengthened by the addition of fillers and reinforcement fibers using maleated coupling agents [74]. They differ from other chemical processes in that they change both the polypropylene matrix and the fiber surface by use of maleic anhydride [75]. This contributes to strengthening the composite, improving the mechanical characteristics of the composites. Maleic anhydride grafted polypropylene: a cohesive substance created by the maleic anhydride's interaction with the polypropylene chain. Covalent bonds are created at the fiber-matrix interface when cellulose fibers are treated with hot Maleic anhydride grafted polypropylene copolymers [67]. The copolymer is heated (at 170 °C) as part of the reaction procedure before being applied to the fibers. The cellulose fibers are then subjected to esterification [76]. The cellulose fibers' surface energy is raised by this process, becoming increasingly comparable to the matrix's surface energy. As a result, the fibers display better adhesion at the interface and are wetted by the matrix material more readily.

### Permanganate treatment

The fibers can be treated with permanganate to enhance the bonding between natural fibers and the matrix in composites. In this procedure, different quantities of potassium permanganate solution, commonly in acetone, are used. The procedure comprises immersing the fibers in the potassium permanganate solution for one to three minutes following an alkaline pre-treatment. This procedure is used to increase the bond strength. At the fiber-matrix contact, potassium permanganate reacts with the cellulose hydroxyl (OH) groups and lignin components to improve chemical interlocking. The fibers' thermal stability is also improved by this process, making them more resistant to high temperatures.

### Other chemical treatments

For the purpose of decreasing the quantity of OH groups and enhance the bondage, a variety of additional chemical compounds might be applied. The interaction between the isocyanate and the OH groups is very receptive. Additionally utilised for changing the surface topography are stearic acid ( $\text{CH}_3(\text{CH}_2)_{16}\text{COOH}$ ) and acrylic acid ( $\text{CH}_2\text{CHCOOH}$ ), while sodium chlorite ( $\text{NaClO}_2$ ) is typically used for bleaching fibers [77], but it could also delignify lignocellulosics. Certain triazine derivatives, including  $\text{C}_3\text{N}_3\text{Cl}_3$ , have been discovered by researchers to be capable of forming covalent connections with cellulose fibers. In order to produce natural fiber composites, these derivatives can be used to alter vegetable fibers. The number of cellulose hydroxyl groups that are

accessible to absorb water is decreased as a result of this modification process, reducing the amount of water that the fibers absorb [76].

### Biological treatments

As alternatives to conventional chemical and physical treatments for natural fibers, various biological techniques have recently come into use. Enzymatic treatment is one such technique, which entails utilising certain enzymes to take hydrophilic elements like pectin, lignin, and hemicellulose out of the fibers in a selective manner. The cellulose fibers' inherent hydrophilicity is decreased by this focused removal. Fungal treatment is another biological strategy in which non-cellulosic substances like wax, lignin, or pectin are removed from the fiber surface using enzymes made by fungi. For instance, the oxidase lignin peroxidase, which assists in the withdrawal of lignin from natural fibers and increases roughness, is produced by the white-rot fungus *Schizophyllum commune*.

Bacterial cellulose coating is an additional biological technique. The ability to synthesise cellulose is shared by several bacterial species, including *Salmonella*, *Escherichia coli*, *Rhizobium*, *Aerobacter*, *Gluconacetobacter (Acetobacter)*, and *Sarcina*. These microorganisms generate cellulose, which may be employed to coat the fibers with a layer of protection. These ecologically friendly biological techniques provide natural fibers the ability to have their qualities customised for a range of uses.

## Discussion

For industrial uses, natural fibers have various advantages. First, they provide advantages over synthetic materials in terms of the environment and economy. Natural fibers are a sustainable option since they are reusable and biodegradable. They don't pose the same health risks as certain synthetic fibers and are also secure to use. Natural fibers' high specific strength-to-weight ratio, which is particularly helpful in sectors like the manufacture of automobiles, is one of its main advantages. This characteristic enables lightweight yet sturdy components, improving fuel economy and lowering environmental impact. In many industrial applications, natural fibers are a tempting alternate for synthetic fibers.

In composite applications, difficulties arise from the rapport of fibers with polymeric matrix. The lack of interoperability between these two components is a significant obstacle. Natural fibers and polymeric matrices frequently vary chemically and in their surface characteristics, which can make adhesion and bonding difficult. It becomes required to use surface treatments to solve this problem. By altering the natural fibers' surface characteristics, these treatments hope to improve their compatibility with the polymeric matrix. The overall performance and mechanical qualities of natural fiber-polymer composites can be improved by increasing compatibility. Improved composites are produced as a consequence of surface treatments that aid in overcoming the incompatibility that exists naturally and encourage a stronger interface.

Natural fibers can be surface functionalized using a variety range of methods. Different substances, like sodium hydroxide,



silane etc., are used in chemical treatments. These substances have the ability to alter the fibers' surface characteristics and enhance their suitability with the polymer matrix. In chemical treatments, basically the fibers are processed with some pre-defined chemicals for a specific period of time and in a specific condition based on the type of processing. The main purpose is to decrease the moisture absorption capacity, increasing the percentage of cellulosic fiber content and to increase the surface roughness. Another strategy is to use physical treatment, such as mechanical abrasion, plasma therapy, or corona therapy. These processes modify the fibers' surface properties without using chemical agents. Additionally, biological treatments provide a different choice. Enzymatic processes entail the use of certain enzymes to remove hydrophilic substances. To reduce non-cellulosic substances from the fiber surface, fungi create enzymes. The surface qualities can be enhanced by these biological treatments.

Overall, a variety of solutions are available for functionalizing the surface of natural fibers and enhancing their suitability with polymeric matrices in composite applications using a mixture of chemical, physical, and biological approaches. Evaluating the prices of chemical agents used for surface treatments is significant when assessing the financial aspect of employing natural fibers in composites. Some chemical treatments might cost more money. It is important to keep in mind, nevertheless, that the enhanced mechanical qualities brought about by these treatments could make it possible to use less fiber. Natural fibers are also often more affordable than synthetic fibers, making them a good option in terms of economics. Therefore, using natural fibers in composite applications is still economically favourable, even though the financial impact should be taken into account.

## Conclusion and Future Direction

Natural fibers have enormous potential for the creation of polymer composites through a variety of surface modification techniques. Many studies have confirmed that by adopting different surface treatment methods, their performances are drastically increasing. Different methods have different advantages and some limitations also. From this review it is concluded that:

At present physical treatments are not so popular or not so widely adopted by researchers but slowly becoming more popular day by day and new research focus is shifting in this direction.

Chemical treatments are the most widely adopted methods often in use. As discussed, there are a number of chemical methods available at present in a variety of ways a particular method can also be applied by varying the time duration and concentration of the chemical in use. In general, it cannot be concluded that a particular chemical method is best for all applications. The best chemical method is judged by the kind of natural fiber and the type of treatment in a particular way of treatment like percent concentration of chemical, time duration of treatment, drying temperature, duration, etc.

The biological techniques are also not so widely adopted by industry or researchers but, the future developments in

biological techniques and nanoparticle treatments are also envisaged, and these should further improve the functionality and sustainability of composite materials. These continual innovations help to broaden the uses and efficiency of natural fiber-based polymer composites across a variety of sectors.

Future developments for natural fiber polymer composites might be seen in a few different ways. First off, it may be possible to maximise the benefits of various treatments on composite performance by combining treated fillers, whether they are treated fibers or fillers. The overall qualities of the composite can be optimised by carefully blending various treated components. It is also necessary to investigate the use of biological techniques and nanoparticle therapies. Natural fiber surface modification using biological techniques, such as enzymatic or fungal treatments, offers more sustainable options. They have the capacity to deliver improved outcomes and support the manufacturing process' sustainability. Furthermore, adding nanoparticles to natural fiber composites has the potential to enhance their functional, thermal, and mechanical characteristics. The use of nanoparticles can enhance the composite material's stiffness, strength, and other desirable properties.

Researchers and business experts may promote the development of natural fiber composites by focussing on these future prospects, broadening the uses for these materials, and enhancing their general performance and sustainability.

## Acknowledgements

None.

## Conflict of Interest

None.

## References

1. Campilho RD. 2015. Natural Fiber Composites. CRC Press, Boca Raton.
2. Alix S, Colasse L, Morvan C, Lebrun L, Marais S. 2014. Pressure impact of autoclave treatment on water sorption and pectin composition of flax cellulosic-fibres. *Carbohydr Polym* 102: 21-29. <https://doi.org/10.1016/j.carbpol.2013.10.092>
3. Rohit K, Dixit S. 2016. A review-future aspect of natural fiber reinforced composite. *Polym Renew Resour* 7(2): 43-59. <https://doi.org/10.1177/204124791600700202>
4. Tsai S. 2018. Introduction to Composite Materials. Routledge, New York.
5. Poostforush M, Al-Mamun M, Fasihi M. 2013. Investigation of physical and mechanical properties of high density polyethylene/wood flour composite foams. *Res J Eng Sci* 2(1): 15-20.
6. Vigneshwaran S, Sundarakannan R, John KM, Johnson RDJ, Prasath KA, et al. 2020. Recent advancement in the natural fiber polymer composites: a comprehensive review. *J Clean Prod* 277: 124109. <https://doi.org/10.1016/j.jclepro.2020.124109>
7. Khan T, Sultan MTBH, Ariffin AH. 2018. The challenges of natural fiber in manufacturing, material selection, and technology application: a review. *J Reinf Plast Compos* 37(11): 770-779. <https://doi.org/10.1177/0731684418756762>
8. Xanthos M. 2010. Functional Fillers for Plastics. John Wiley & Sons.
9. Malkapuram R, Kumar V, Negi YS. 2009. Recent development in nat-

- ural fiber reinforced polypropylene composites. *J Reinf Plast Compos* 28(10): 1169-1189. <https://doi.org/10.1177/0731684407087759>
10. Geethamma VG, Kalaprasad G, Groeninckx G, Thomas S. 2005. Dynamic mechanical behavior of short coir fiber reinforced natural rubber composites. *Compos Part A Appl Sci Manuf* 36(11): 1499-1506. <https://doi.org/10.1016/j.compositesa.2005.03.004>
  11. Dhakal HN, Zhang ZA, Richardson MO. 2007. Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. *Compos Sci Technol* 67(7-8): 1674-1683. <https://doi.org/10.1016/j.compscitech.2006.06.019>
  12. Ticoalu A, Aravinthan T, Cardona F. 2010. A review of current development in natural fiber composites for structural and infrastructure applications. In Proceedings of the southern region engineering conference, Toowoomba, Australia.
  13. Faruk O, Bledzki AK, Fink HP, Sain M. 2012. Biocomposites reinforced with natural fibers: 2000-2010. *Prog Polym Sci* 37(11): 1552-1596. <https://doi.org/10.1016/j.progpolymsci.2012.04.003>
  14. Gholampour A, Ozbakkaloglu T. 2020. A review of natural fiber composites: properties, modification and processing techniques, characterization, applications. *J Mater Sci* 55(3): 829-892. <https://doi.org/10.1007/s10853-019-03990-y>
  15. Lotfi A, Li H, Dao DV, Prusty G. 2021. Natural fiber-reinforced composites: a review on material, manufacturing, and machinability. *J Thermoplast Compos Mater* 34(2): 238-284. <https://doi.org/10.1177/0892705719844546>
  16. Komuraiah A, Kumar NS, Prasad BD. 2014. Chemical composition of natural fibers and its influence on their mechanical properties. *Mech Compos Mater* 50: 359-376. <https://doi.org/10.1007/s11029-014-9422-2>
  17. Rong MZ, Zhang MQ, Liu Y, Yang GC, Zeng HM. 2001. The effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. *Compos Sci Technol* 61(10): 1437-1447. [https://doi.org/10.1016/S0266-3538\(01\)00046-X](https://doi.org/10.1016/S0266-3538(01)00046-X)
  18. Mishra T, Mandal P, Rout AK, Sahoo D. 2022. A state-of-the-art review on potential applications of natural fiber-reinforced polymer composite filled with inorganic nanoparticle. *Compos Part C* 100298. <https://doi.org/10.1016/j.jcomc.2022.100298>
  19. Razali N, Salit MS, Jawaid M, Ishak MR, Lazim Y. 2015. A study on chemical composition, physical, tensile, morphological, and thermal properties of roselle fibre: effect of fibre maturity. *BioResources* 10(1): 1803-1824.
  20. Kamp DW. 2009. Asbestos-induced lung diseases: an update. *Transl Res* 153(4): 143-152. <https://doi.org/10.1016/j.trsl.2009.01.004>
  21. Chandramohan D, Marimuthu K. 2011. A review on natural fibers. *Int J Res Rev Appl Sci* 8(2): 194-206.
  22. Suriani MJ, Ilyas RA, Zuhri MYM, Khalina A, Sultan MTH, et al. 2021. Critical review of natural fiber reinforced hybrid composites: processing, properties, applications and cost. *Polymers* 13(20): 3514. <https://doi.org/10.3390/polym13203514>
  23. Dittenber DB, Gangarao HV. 2012. Critical review of recent publications on use of natural composites in infrastructure. *Compos Part A Appl Sci Manuf* 43(8): 1419-1429. <https://doi.org/10.1016/j.compositesa.2011.11.019>
  24. Girijappa YGT, Rangappa SM, Parameswaranpillai J, Siengchin S. 2019. Natural fibers as sustainable and renewable resource for development of eco-friendly composites: a comprehensive review. *Front Mater* 6: 226. <https://doi.org/10.3389/fmats.2019.00226>
  25. Sanjay MR, Madhu P, Jawaid M, Senthamarai Kannan P, Senthil S, et al. 2018. Characterization and properties of natural fiber polymer composites: a comprehensive review. *J Clean Prod* 172: 566-581. <https://doi.org/10.1016/j.jclepro.2017.10.101>
  26. Gowda TGY, Sanjay MR, Bhat KS, Madhu P, Senthamarai Kannan P, et al. 2018. Polymer matrix-natural fiber composites: an overview. *Cogent Eng* 5(1): 1446667. <https://doi.org/10.1080/23311916.2018.1446667>
  27. Ahmad R, Hamid R, Osman SA. 2019. Physical and chemical modifications of plant fibres for reinforcement in cementitious composites. *Adv Civ Eng* 2019: 5185806. <https://doi.org/10.1155/2019/5185806>
  28. Pickering KL, Efendy MA, Le TM. 2016. A review of recent developments in natural fibre composites and their mechanical performance. *Compos Part A Appl Sci Manuf* 83: 98-112. <https://doi.org/10.1016/j.compositesa.2015.08.038>
  29. Manimaran P, Senthamarai Kannan P, Murugananthan K, Sanjay MR. 2018. Physicochemical properties of new cellulosic fibers from *Azadirachta indica* plant. *J Nat Fibers* 15(1): 29-38. <https://doi.org/10.1080/15440478.2017.1302388>
  30. Rangappa SM, Siengchin S. 2018. Natural fibers as perspective materials. *Int J Appl Sci Technol* 11(4): 233. <https://doi.org/10.14416/ijast.2018.09.001>
  31. Mukhopadhyay S, Figueiro R. 2009. Physical modification of natural fibers and thermoplastic films for composites—a review. *J Thermoplast Compos Mater* 22(2): 135-162. <https://doi.org/10.1177/0892705708091860>
  32. Ma C, Ni L, Guo Z, Zeng H, Wu M, et al. 2022. Principle and application of steam explosion technology in modification of food fiber. *Foods* 11(21): 3370. <https://doi.org/10.3390/foods11213370>
  33. Eichhorn SJ, Sirichaisit J, Young RJ. 2001. Deformation mechanisms in cellulose fibres, paper and wood. *J Mater Sci* 36: 3129-3135. <https://doi.org/10.1023/A:1017969916020>
  34. Kessler RW, Becker U, Kohler R, Goth B. 1998. Steam explosion of flax—a superior technique for upgrading fibre value. *Biomass Bioenergy* 14(3): 237-249. [https://doi.org/10.1016/S0961-9534\(97\)10040-X](https://doi.org/10.1016/S0961-9534(97)10040-X)
  35. Vitrone F, Ramos D, Vitagliano V, Ferrando F, Salvadó J. 2022. All-lignocellulosic fiberboards from giant reed (*Arundo donax* L.): effect of steam explosion pre-treatment on physical and mechanical properties. *Constr Build Mater* 319: 126064. <https://doi.org/10.1016/j.conbuildmat.2021.126064>
  36. Brett CT, Waldron KW. 1996. Physiology and Biochemistry of Plant Cell Walls. Springer.
  37. Avella M, Casale L, Dell'era R, Focher B, Martuscelli E, et al. 1998. Broom fibers as reinforcing materials for polypropylene-based composites. *J Appl Polym Sci* 68(7): 1077-1089. [https://doi.org/10.1002/\(SICI\)1097-4628\(19980516\)68:7<1077::AID-APP5>3.0.CO;2-C](https://doi.org/10.1002/(SICI)1097-4628(19980516)68:7<1077::AID-APP5>3.0.CO;2-C)
  38. Pires C, Motta LADC, Ferreira RADR, Caixeta CDO, Savastano H. 2021. Thermomechanical and thermo-hydro-mechanical treatments of luffa cylindrical fibers. *J Nat Fibers* 18(12): 2351-2363. <https://doi.org/10.1080/15440478.2020.1726245>
  39. Marais S, Gouanvé F, Bonnesoeur A, Grenet J, Poncin-Epaillard F, et al. 2005. Unsaturated polyester composites reinforced with flax fibers: effect of cold plasma and autoclave treatments on mechanical and permeation properties. *Compos Part A Appl Sci Manuf* 36(7): 975-986. <https://doi.org/10.1016/j.compositesa.2004.11.008>
  40. Leone G, D'Angelo GA, Russo P, Ferraro P, Pagliarulo V. 2022. Plasma treatment application to improve interfacial adhesion in polypropylene-flax fabric composite laminates. *Polym Compos* 43(3): 1787-1798. <https://doi.org/10.1002/pc.26497>
  41. Izdebska J. 2016. Corona Treatment. In Izdebska J, Thomas S (eds) *Printing on Polymers: Fundamentals and Applications*. Elsevier.
  42. Ferreira DP, Cruz J, Figueiro R. 2019. Surface Modification of Natural Fibers in Polymer Composites. In Koronis G, Silva A (eds) *Green Composites for Automotive Applications*. Woodhead Publishing, pp 3-41.
  43. Żenkiewicz M, Richert J, Rytlewski P, Moraczewski K. 2009. Some effects of corona plasma treatment of polylactide/montmorillonite nanocomposite films. *Plasma Process Polym* 6(S1): S387-S391. <https://doi.org/10.1002/ppap.200930901>
  44. Tuominen M, Lahti J, Lavonen J, Penttinen T, Räsänen JP, et al. 2010. The influence of flame, corona and atmospheric plasma treatments on surface properties and digital print quality of extrusion coated paper.

- J Adhes Sci Technol* 24(3): 471-492. <https://doi.org/10.1163/016942409X12561252292224>
45. Dixon D, Meenan BJ. 2012. Atmospheric dielectric barrier discharge treatments of polyethylene, polypropylene, polystyrene and poly (ethylene terephthalate) for enhanced adhesion. *J Adhes Sci Technol* 26(20-21): 2325-2337. <https://doi.org/10.1163/156856111X599481>
  46. Pascual M, Sanchis R, Sánchez L, García D, Balart R. 2008. Surface modification of low density polyethylene (LDPE) film using corona discharge plasma for technological applications. *J Adhes Sci Technol* 22(13): 1425-1442. <https://doi.org/10.1163/156856108X305723>
  47. Shishoo R. 2007. Plasma Technologies for Textiles. Elsevier.
  48. Pankaj SK, Bueno-Ferrer C, Misra NN, O'Neill L, Tiwari BK, et al. 2015. Dielectric barrier discharge atmospheric air plasma treatment of high amylose corn starch films. *LWT Food Sci Technol* 63(2): 1076-1082. <https://doi.org/10.1016/j.lwt.2015.04.027>
  49. Wagner HE, Brandenburg R, Kozlov KV, Sonnenfeld A, Michel P, et al. 2003. The barrier discharge: basic properties and applications to surface treatment. *Vacuum* 71(3): 417-436. [https://doi.org/10.1016/S0042-207X\(02\)00765-0](https://doi.org/10.1016/S0042-207X(02)00765-0)
  50. Kogelschatz U. 2003. Dielectric-barrier discharges: their history, discharge physics, and industrial applications. *Plasma Chem Plasma Process* 23: 1-46. <https://doi.org/10.1023/A:1022470901385>
  51. Stegmaier T, Dinkelmann A, Von Arnim V, Rau A. 2007. Corona and Dielectric Barrier Discharge Plasma Treatment of Textiles for Technical Applications. In Shishoo R (ed) Plasma Technologies for Textiles. Woodhead Publishing, pp 129-157.
  52. Graham WG. 2007. The Physics and Chemistry of Plasmas for Processing Textiles and Other Materials. In In Shishoo R (ed) Plasma Technologies for Textiles. Woodhead Publishing, pp 3-24.
  53. Li Q, Lin T, Wang X. 2012. Effects of ultrasonic treatment on wool fibre and fabric properties. *J Text Inst* 103(6): 662-668. <https://doi.org/10.1080/00405000.2011.597569>
  54. Willems P. 1962. Kinematic high-frequency and ultrasonic treatment of pulp. *Pulp Paper Magaz Canada* 63: T455-T462.
  55. Rosales SGS, Naranjo LN, Fonseca-Florido HA, González-Morones P, Hernández ZG, et al. 2022. Alkali/ultrasound treatment as alternative to modify structural and thermal properties of *Agave tequilana* fibers. *J Nat Fibers* 19(14): 9309-9322. <https://doi.org/10.1080/15440478.2021.1982822>
  56. Koronis G, Silva A. 2018. Green Composites for Automotive Applications. Woodhead Publishing.
  57. Mahzan S, Fitri M, Zaleha M. 2017. UV radiation effect towards mechanical properties of natural fibre reinforced composite material: a review. *IOP Conf Ser Mater Sci Eng* 165(1): 012021. <https://doi.org/10.1088/1757-899X/165/1/012021>
  58. Gassan J, Gutowski VS. 2000. Effects of corona discharge and UV treatment on the properties of jute-fibre epoxy composites. *Compos Sci Technol* 60(15): 2857-2863. [https://doi.org/10.1016/S0266-3538\(00\)00168-8](https://doi.org/10.1016/S0266-3538(00)00168-8)
  59. Abdullah-Al-Kafi, Abedin MZ, Beg MDH, Pickering KL, Khan MA. 2006. Study on the mechanical properties of jute/glass fiber-reinforced unsaturated polyester hybrid composites: effect of surface modification by ultraviolet radiation. *J Reinf Plast Compos* 25(6): 575-588. <https://doi.org/10.1177/0731684405056437>
  60. Benedetto RMD, Gelfuso MV, Thomazini D. 2015. Influence of UV radiation on the physical-chemical and mechanical properties of banana fiber. *Mater Res* 18: 265-272. <https://doi.org/10.1590/1516-1439.371414>
  61. Singh B, Gupta M, Verma A. 1996. Influence of fiber surface treatment on the properties of sisal-polyester composites. *Polym Compos* 17(6): 910-918. <https://doi.org/10.1002/pc.10684>
  62. Prabhu L, Krishnaraj V, Sathish S, Gokulkumar S, Karthi N, et al. 2021. A review on natural fiber reinforced hybrid composites: chemical treatments, manufacturing methods and potential applications. *Mater Today Proc* 45: 8080-8085. <https://doi.org/10.1016/j.matpr.2021.01.280>
  63. Nayak S, Mohapatra J, Muduli K, Khuntia SK, Malla C, et al. 2023. Mechanical and thermal properties of *Careya arborea* bast fiber-reinforced chitosan composites for packaging industries. *Biomass Convers Bioref* 1-8. <https://doi.org/10.1007/s13399-023-04328-0>
  64. Nayak S, Samal P, Malla C, Pradhan MK, Khuntia SK, et al. 2023. Enhancement of mechanical, thermal and morphological properties of *Eleusine indica* grass fiber reinforced epoxy composites. *J Nat Fibers* 20(1): 2163029. <https://doi.org/10.1080/15440478.2022.2163029>
  65. Sahu S, Sahu SB, Nayak S, Mohapatra J, Khuntia SK, et al. 2023. Characterization of natural fiber extracted from *Bauhinia vahlii* bast subjected to different surface treatments: a potential reinforcement in polymer composite. *J Nat Fibers* 20(1): 2162185. <https://doi.org/10.1080/15440478.2022.2162185>
  66. Agrawal R, Saxena NS, Sharma KB, Thomas S, Sreekala MS. 2000. Activation energy and crystallization kinetics of untreated and treated oil palm fibre reinforced phenol formaldehyde composites. *Mater Sci Eng A* 277(1-2): 77-82. [https://doi.org/10.1016/S0921-5093\(99\)00556-0](https://doi.org/10.1016/S0921-5093(99)00556-0)
  67. Li X, Tabil LG, Panigrahi S. 2007. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review. *J Polym Environ* 15: 25-33. <https://doi.org/10.1007/s10924-006-0042-3>
  68. Kalia S, Dufresne A, Cherian BM, Kaith BS, Avérous L, et al. 2011. Cellulose-based bio- and nanocomposites: a review. *Int J Polym Sci* 2011: 837875. <https://doi.org/10.1155/2011/837875>
  69. Ravindran S, Sozhamannan GG, Venkatachalapathy VSK. 2022. Mechanical and water absorption behaviour on silane treated jute fiber based natural composites. *Mater Today Proc* 68: 2134-2141. <https://doi.org/10.1016/j.matpr.2022.08.398>
  70. Gudayy AD, Steuernagel L, Meiners D, Gideon R. 2022. Effect of surface treatment on moisture absorption, thermal, and mechanical properties of sisal fiber. *J Ind Text* 51(2\_suppl): 2853S-2873S. <https://doi.org/10.1177/1528083720924774>
  71. Kabir MM, Wang H, Lau KT, Cardona F. 2012. Chemical treatments on plant-based natural fibre reinforced polymer composites: an overview. *Compos Part B Eng* 43(7): 2883-2892. <https://doi.org/10.1016/j.compositesb.2012.04.053>
  72. Paul A, Joseph K, Thomas S. 1997. Effect of surface treatments on the electrical properties of low-density polyethylene composites reinforced with short sisal fibers. *Compos Sci Technol* 57(1): 67-79. [https://doi.org/10.1016/S0266-3538\(96\)00109-1](https://doi.org/10.1016/S0266-3538(96)00109-1)
  73. Sreekala MS, Kumaran MG, Thomas S. 2002. Water sorption in oil palm fiber reinforced phenol formaldehyde composites. *Compos Part A Appl Sci Manuf* 33(6): 763-777. [https://doi.org/10.1016/S1359-835X\(02\)00032-5](https://doi.org/10.1016/S1359-835X(02)00032-5)
  74. Keener TJ, Stuart RK, Brown TK. 2004. Maleated coupling agents for natural fibre composites. *Compos Part A Appl Sci Manuf* 35(3): 357-362. <https://doi.org/10.1016/j.compositesa.2003.09.014>
  75. Joseph PV, Joseph K, Thomas S, Pillai CKS, Prasad VS, et al. 2003. The thermal and crystallisation studies of short sisal fibre reinforced polypropylene composites. *Compos Part A Appl Sci Manuf* 34(3): 253-266. [https://doi.org/10.1016/S1359-835X\(02\)00185-9](https://doi.org/10.1016/S1359-835X(02)00185-9)
  76. Bledzki AK, Reihmane S, Gassan J. 1996. Properties and modification methods for vegetable fibers for natural fiber composites. *J Appl Polym Sci* 59(8): 1329-1336. [https://doi.org/10.1002/\(SICI\)1097-4628\(19960222\)59:8<1329::AID-APP17>3.0.CO;2-0](https://doi.org/10.1002/(SICI)1097-4628(19960222)59:8<1329::AID-APP17>3.0.CO;2-0)
  77. Jose C, Thomas MS, Deepa B, Pothan LA, Thomas S. 2015. Adhesion and Surface Issues in Biocomposites and Bionanocomposites. In Mittal KL (ed) Progress in Adhesion and Adhesives. Scrivener Publishing, pp 169-217.