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Exploring Chemical and Physical Advancements in Surface Modification Techniques of Natural Fiber Reinforced Composite: A Comprehensive Review

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ABSTRACT

This review presents a comprehensive overview of recent trends, advances, and challenges in the use of natural fiber composites. This section begins by discussing the growing adoption of bio-based fibers because of their eco-friendly nature and cost-efficiency, focusing particularly on plant-based fibers. A bibliometric analysis will be conducted to evaluate the publication frequency and research trends in this domain. Furthermore, the structural compositions of natural fibers, including cellulose, hemicellulose, lignin, pectin, and wax, were elucidated, highlighting their significance in composite material engineering. The extraction methods of natural fibers, including retting and mechanical decortication, are discussed, along with their implications for fiber quality. The limitations associated with natural fibers, including their hydrophilicity and poor mechanical properties, compared with their synthetic counterparts are addressed. Various surface-treatment methods, particularly physical and chemical ones, were explored to enhance fiber compatibility with polymer matrices. The abstract delves into the principles, techniques, and effects of physical and chemical treatments on natural fibers, emphasizing their role in improving the surface characteristics, interfacial adhesion, and overall mechanical properties of composites. Furthermore, specific studies investigating the impact of physical and chemical treatments on natural fibers are summarized, elucidating the observed changes in fiber morphology, chemical composition, and mechanical properties.

摘要

本综述全面概述了天然纤维复合材料使用的最新趋势、进展和挑战. 本节首先讨论了生物基纤维因其环保性和成本效益而越来越多地被采用，特别关注植物基纤维. 将进行文献计量分析，以评估该领域的出版频率和研究趋势. 此外，还阐明了天然纤维的结构组成，包括纤维素、半纤维素、木质素、果胶和蜡，突出了它们在复合材料工程中的意义. 讨论了天然纤维的提取方法，包括脱胶和机械去皮，以及它们对纤维质量的影响. 与合成纤维相比，天然纤维的局限性，包括亲水性和较差的机械性能，得到了解决. 探索了各种表面处理方法，特别是物理和化学方法，以提高纤维与聚合物基体的相容性. 摘要深入探讨了物理和化学处理对天然纤维的原理、

KEYWORDS

Surface modification; chemical and physical treatment; natural fiber; NFRCs; natural fiber treatment; bibliometric analysis

关键词

表面改性; 化学和物理处理; 天然纤维; 天然纤维处理; 文献计量分析

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技术和影响，强调了它们在改善复合材料的表面特性、界面粘附和整体力学性能方面的作用. 此外，总结了调查物理和化学处理对天然纤维影响的具体研究，阐明了观察到的纤维形态、化学成分和力学性能的变化.

Introduction

In recent times, bio-based fibers and polymers have been significantly adopted in composite materials owing to their environmentally friendly nature, cost efficiency, and ease of processing (Balakrishnan et al. 2024a, 2024b; Mohammadi et al. 2024). The focus has shifted toward the development of biodegradable composite materials, with natural fiber reinforcement surpassing the use of synthetic fibers (Urdanpilleta et al. 2024). The advantages of bio-based fibers compared to synthetic fibers are significant. Environmentally, they support sustainability by being sourced from renewable materials, biodegrading naturally, and requiring less energy for production. Economically, they offer benefits like reduced costs, additional revenue opportunities, and job creation. With a growing focus on sustainability among industries and consumers, the use of bio-based fibers in composite materials is expected to increase, leading to positive environmental and economic impacts (Kóczán and Pásztory 2024). Natural fibers obtained from both plant and animal sources are typically classified into three categories: animal, mineral, and plant fibers (Dejene 2024c). Among them, plant fibers are the most widely employed. With growing concerns regarding the environmental impact of nonrenewable resources, there has been a noticeable rise in the exploration and utilization of renewable plant-based resources. In Particular, in applications in which high tensile strength is not a primary requirement, economically viable natural fibers provide a practical alternative to expensive and nonrenewable synthetic fibers. In addition to their eco-friendly properties, the abundance and consequent low cost of natural fibers further enhance their attractiveness (Cárdenas-Oscanoa et al. 2024). The study conducted bibliometric analysis by combining keyword co-occurrence and author co-citation networks. Additionally, the study examined publication frequency trends across years and countries. A manual review of the search results identified significant findings. Data were sourced from ScienceDirect using the search term "natural fiber," yielding 9417 articles. Analysis and visualization were performed using VOS Viewer (version 1.6.18), a freely available software tool. A country-wise analysis of publication output identified South and East Asian nations like India, Malaysia, China, and Iran as the most prolific contributors in this field. Figure 1 provides a detailed overview of publication numbers and distribution by country, focusing on publications exceeding 20. Countries with fewer than 20 publications were excluded from the graph. Keyword analysis is pivotal for identifying research trends. VOS Viewer was employed to visualize the keyword density in the documents, with a threshold of 20 occurrences revealing 48 significant keywords. Keywords with the highest occurrence rates, starting from the threshold, included mechanical properties, natural fibers, composites, hybrid composites, thermal properties, chemical treatment, and epoxy. Figure 2 visually represents the density of these keywords. Keyword co-occurrence and author co-citation networks are indispensable tools in bibliometric analysis, providing valuable insights into the thematic and intellectual structure of natural fiber research. They help identify trends, influential researchers, collaborative networks, and research gaps, thus guiding the direction and impact of future research endeavors (Hassan and Duarte 2024).

Natural fibers consist of diverse components such as cellulose, hemicellulose, lignin, pectin, wax, and water-soluble substances (Sampaio et al. 2024). Compositional variations arise due to factors such as growth conditions and testing methodologies, even for the same fiber type (Sathishkumar et al. 2022). Cellulose, a linear semicrystalline polysaccharide, is characterized by an arrangement of anhydroglucose units linked via 1,4-β-glycoside bonds, each unit containing hydroxyl groups (Constan Lotebulo Ndruru et al. 2024). These hydroxyl groups enable the formation of intramolecular hydrogen bonds within cellulose and intermolecular hydrogen bonds between adjacent cellulose molecules (Ramachandran et al. 2022). The structure of cellulose exhibits distinct crystalline and

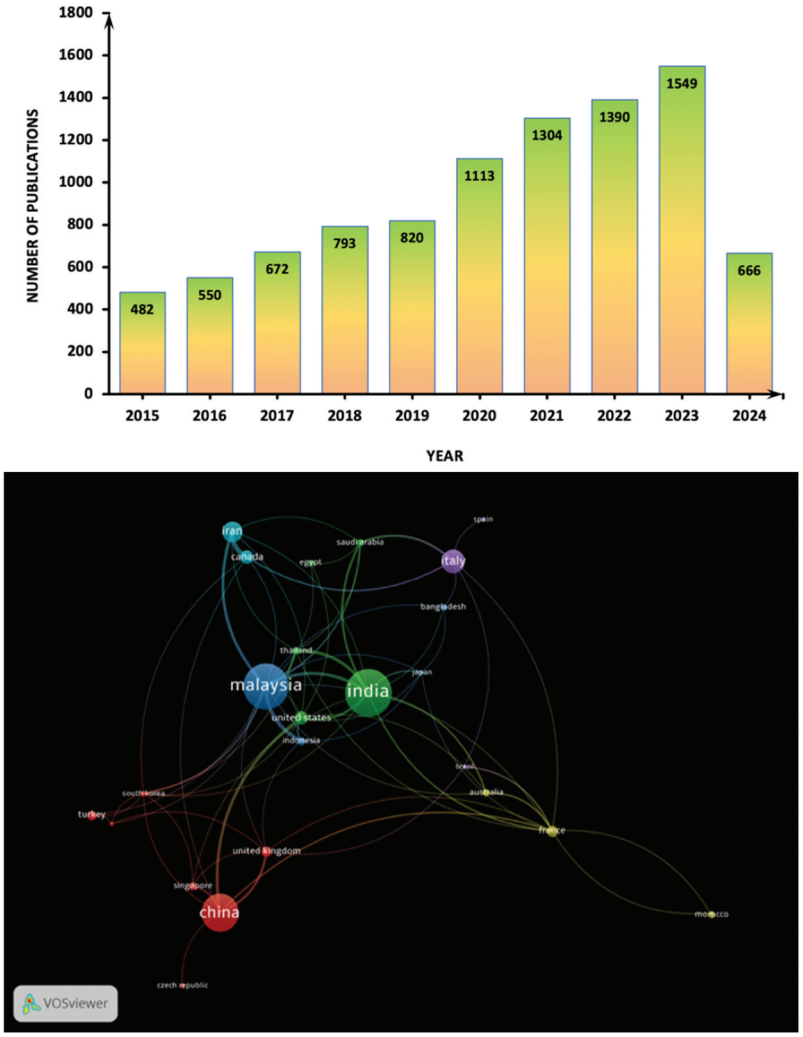

Figure 1. Number of publications per year and distribution of publications by country in the field of using natural fibers.

amorphous regions, with the crystalline fraction establishing robust intermolecular hydrogen bonds with larger molecules. These interactions occurring at the macromolecule level and in cellulose fibrils and their orientation within the cellular matrix significantly contribute to the mechanical properties of fibers. The recurring units of monomers, commonly referred to as the degree of polymerization, reflect the extent of polymer chain formation. Glucose monomers within cellulose foster hydrogen bonding interactions among adjacent fibers and associated chains, leading to the formation of a linear crystalline structure known as cellulose. This structural organization arises from the binding of both intra- and intermolecular hydrogen regions within the cellulose matrix.

In natural fiber engineering, hemicellulose emerges as a polysaccharide characterized by its intricate composition of diverse glucose monomers, in contrast with cellulose's uniform structure comprising singular 4-βD-glucopyranose repeating units (Banagar et al. 2024). The variability in hemicellulose composition among different plant species is in contrast to the consistent makeup of cellulose (Almagro-Herrera et al. 2024). The amorphous nature is underscored by a pronounced tendency toward chain branching, a feature that reinforces its intimate association with cellulose fibrils, predominantly through hydrogen bonding interactions. Hemicellulosic polymers, recognized

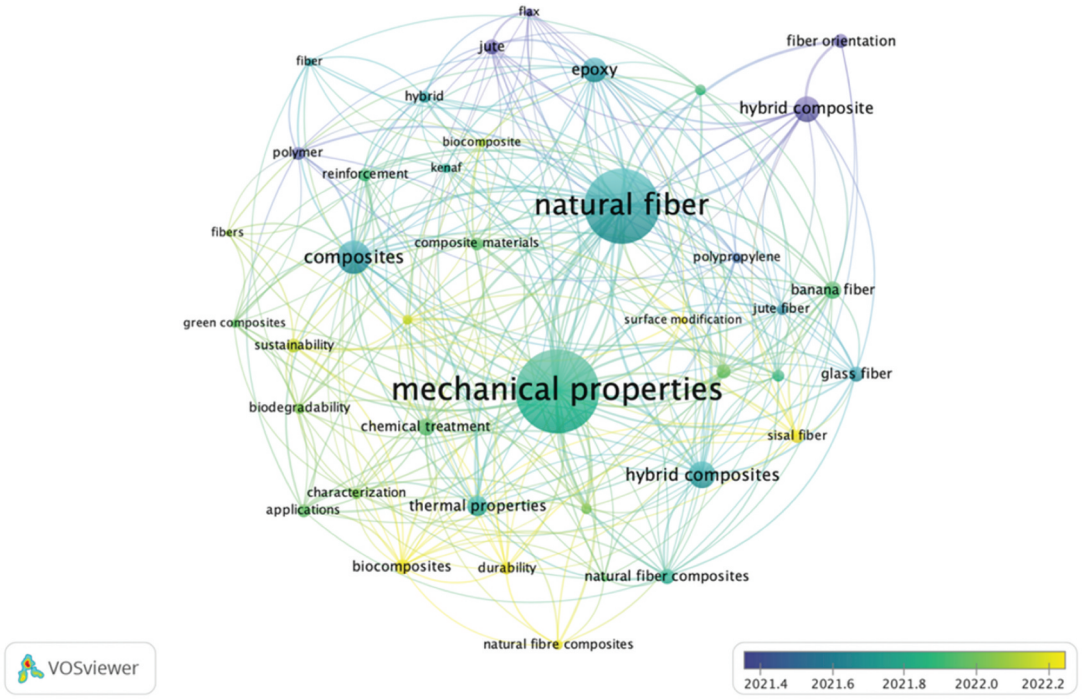

Figure 2. The graphical representation of the keywords' density.

for their branched structure and full amorphous configuration, exhibit significantly lower molecular weights than cellulose. Notably, owing to its structural characteristics, which include abundant hydroxyl and acetyl groups, hemicellulose exhibits partial solubility in water and inherent hygroscopic behavior. Cellulose and hemicellulose play crucial complementary roles in natural fibers. Cellulose imparts strength and rigidity, vital for maintaining fiber's structural integrity. On the other hand, hemicellulose adds flexibility and aids in the distribution of mechanical stress, boosting the fibers' overall durability and functionality (Dejene 2024a). Recognizing these structural differences and their mechanical roles is essential for advancing various applications, particularly for developing natural fiber-based composites and materials. However, lignin, a complex hydrocarbon polymer comprising both aliphatic and aromatic elements, plays a crucial role alongside cellulose in the composition of lignocellulosic fibrils. As a binding agent, lignin contributes to the rigidity of fiber surfaces and enhances the compression strength of plants (Sillard et al. 2024). Its chemical composition primarily consists of phenylpropane units derived from the enzyme-mediated dehydrogenative polymerization of three distinct constituents: trans-p-coumaryl, trans-coniferyl, and trans-sinapyl. Functionally, lignin forms strong associations with hemicellulose and polysaccharides, facilitating cross-linking and filling gaps within the cell wall structure composed of cellulose, hemicellulose, and pectin components, thereby enhancing overall cell wall strength. However, it is worth noting that the functional groups within lignin, cellulose, and hemicellulose are susceptible to chemical modifications during processing to improve fiber compatibility with polymer matrices. Natural fibers must provide rigidity and compression strength and enhance their mechanical and structural integrity. However, its presence poses significant challenges during chemical treatment processes aimed at improving fiber quality. Effective delignification is necessary for many applications but must be balanced against the potential loss of mechanical strength and environmental considerations. Understanding the dual role of lignin in enhancing fiber properties and complicating their processing is essential for developing natural fiber-based materials. Lignins, characterized by their amorphous, highly complex, and predominantly aromatic nature, exhibit the lowest water sorption among the components of natural

fibers. Pectin is an acidic polysaccharide that exhibits a complex structure, primarily comprising homopolymeric acid and methylated poly-α-(1-4)-D-galacturonic acid residues. When treated with an alkali or ammonium hydroxide, pectin becomes a water-soluble polymer. Its primary role is to act as a binding agent among plant fibers, thereby helping to create cohesive structures. Pectin is particularly abundant in the primary cell wall and the middle lamella of lignocellulosic fibers. During the retting process, a substantial amount of pectin is removed from natural fibers, a prerequisite for their suitability as reinforcement materials in polymer matrices. Pectin also contributes to the adhesion of cellulose fibers to other constituents in the fiber matrix. In comparison with cellulose and lignin, pectin is a weaker, amorphous polymer. Wax, a hydrocarbon compound with limited solubility in water, has diverse biological functions, including acting as a protective barrier against microbial intrusion and preventing desiccation in plants. Comprising long-chain monomers, wax segregation is governed by its melting points. However, the presence of these elements can sometimes adversely affect fiber performance and processing (Bhowmik, Kumar, and Mahakur 2024). A schematic representation of the structural hierarchy (microstructure and cell wall) in a plant fiber is presented in Figure 3.

Natural fibers are typically extracted through two main methods: retting and mechanical decortication (Badanayak, Jose, and Bose 2023). Generally, the extraction method of fibers depends on the type of plant, such as stems, leaves, seeds, fruits, or roots. Extracting fibers from plants requires the removal or dissolution of various chemical components, including pectin, hemicellulose, lignin, and other waxy substances (Hazarika et al. 2017). Retting is a process in which fibers are extracted via the natural decomposition of pectin, hemicellulose, lignin, and other wax or gummy elements present in plants. The duration of retting varies between 14 and 25 days depending on the plant category (Sanjay et al. 2019). During retting, bacteria, and moisture facilitate the breakdown of plant cellular components, including pectin, hemicellulose, lignin, and gummy substances, ultimately leaving behind fibers. The performance of the retting process directly influences the quantity and yield of the obtained fibers. The retting time, temperature, pH of water, and micronutrient content significantly affect the quality of natural fiber (Subagyo and Chafidz 2018). Retting can be performed using two methods: dew and water retting (Angulu and Gusovius 2024). Dew retting involves allowing natural sources such as sunlight, air moisture, and dew to decompose the plant's cellular components over 2–3 weeks, during which the

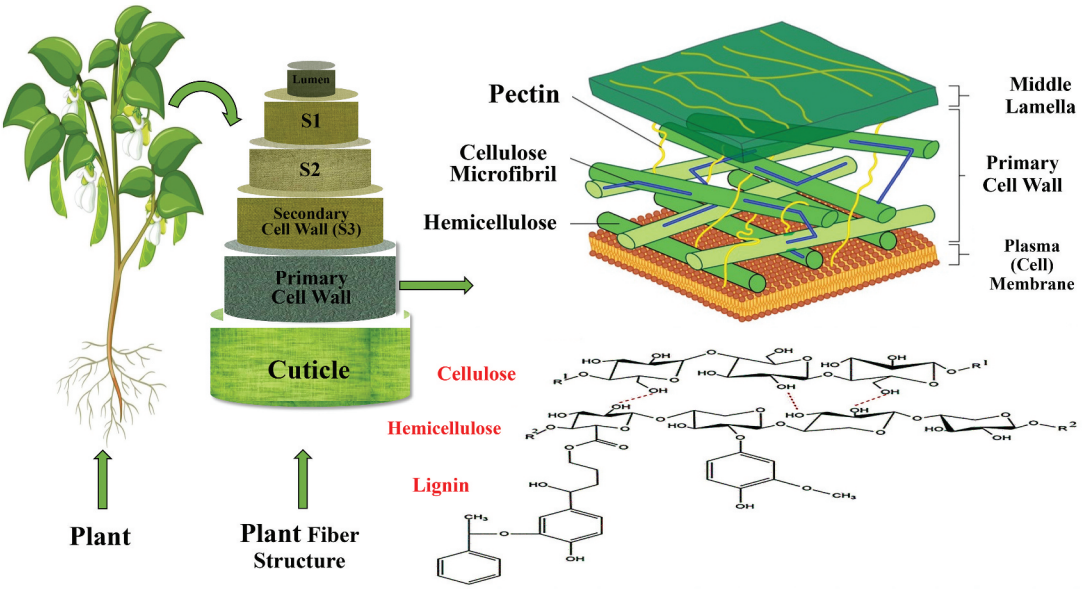

Figure 3. Diagrammatic depiction of plant fiber structure and components.

plant stems or stalks are spread out in open fields. However, fibers obtained through dew retting generally exhibit lower quality than those obtained through water retting and are often characterized by noticeable differences in fiber color (Placet, Day, and Beaugrand 2017). In the water-retting process, fermentation is used to degrade the plant's cellular components. Plant stems or stalks are submerged in water for a specific duration, allowing fermentation to occur to break down plant tissues while preserving fiber content (Dey et al. 2021). Careful attention must be paid to the retting duration during water retting to prevent fiber damage, which could lead to compromised mechanical strength. It is essential to maintain an optimum retting duration to ensure the production of high-quality fibers. Water sources such as stagnant bodies of water or flowing streams (ponds, rivers, or tank water) can be used for water retting (L. L. Zhang et al. 2008). Water and dew retting processes are commonly used to extract stem and bast fibers such as jute, hemp, roselle, and bamboo (Mazian et al. 2019). Both dew and water retting processes require a long time for fiber extraction. Therefore, the mechanical decorticator method can be employed as an alternative. After extraction from the mechanical decorticator, residual components such as pectin, hemicellulose, and lignin may remain within the fibers. These components can be removed by chemical treatment, enhancing the surface quality of the fibers. Figure 4 illustrates two main processes of extraction of natural fibers. The decision between using retting and mechanical decortication to extract natural fibers depends on the specific needs and goals of the fiber production process. When the priority is to obtain high-quality fibers with superior strength, flexibility, and uniformity, and when environmental concerns related to the process can be effectively managed, retting is preferred (Diouf and Gning 2024). Retting through its natural degradation process yields fibers that are ideal for premium applications despite the potential environmental challenges and the time and labor required. Conversely, if the focus is on achieving faster and more scalable fiber production with lower immediate environmental impact, mechanical extraction is a more suitable option. Mechanical decortication is efficient, significantly reducing the time and labor required for fiber extraction. It avoids the water pollution issues associated with retting, making it a more environmentally friendly choice in the short term (Chopra 2022). However, the quality of the fibers produced by mechanical decortication may be low, and possible damage and impurities may necessitate further processing.

The primary limitation associated with natural fibers is their hydrophilic nature (Dejene 2024b), which can lead to increased moisture absorption and compromise the bonding interactions between fibers and polymer matrices, as shown in Figure 5. Furthermore, natural fibers tend to have non-uniform characteristics, low thermal stability, and limited mechanical strength, resulting in inferior properties compared to synthetic or manufactured reinforcements in composite materials (Jeffrin et al. 2024). These drawbacks, including inadequate interfacial

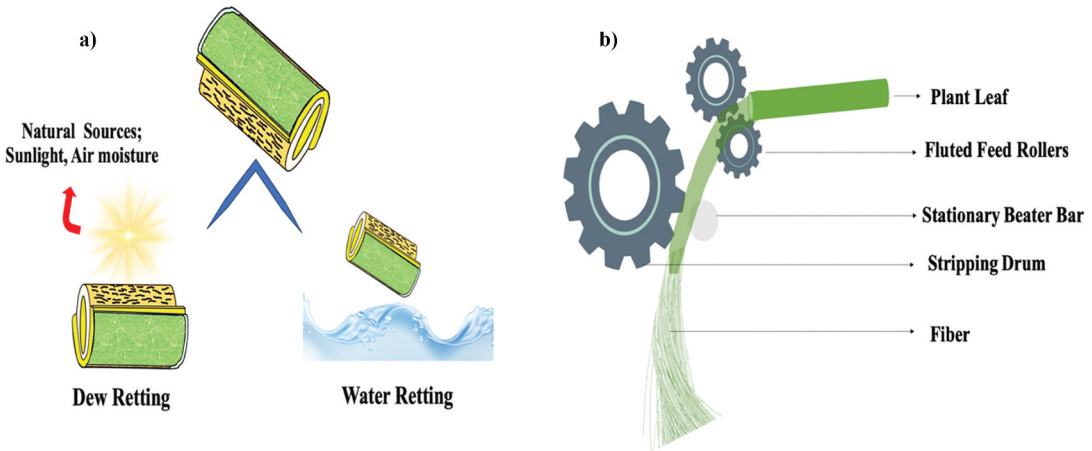

Figure 4. Two main methods of plant fiber extraction: a) retting process, b) mechanical decortication.

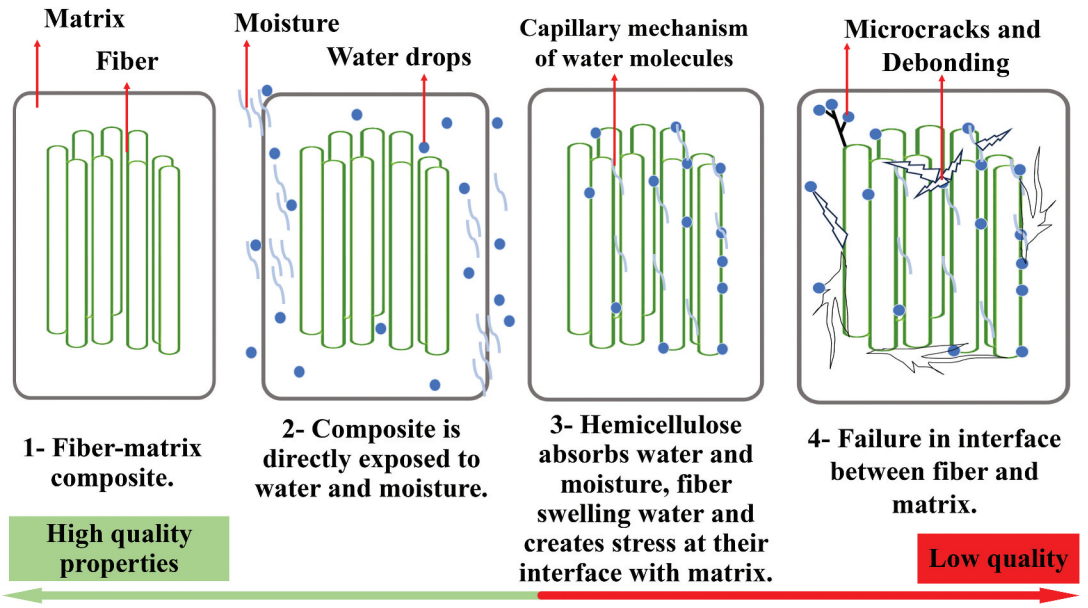

Figure 5. Schematic illustrating the impact of water on interfacial interaction between natural fiber and matrix.

bonding and hydrophilic behavior, can be mitigated through various treatments aimed at enhancing the compatibility between natural fibers and polymer matrix (Feng et al. 2024; Palanisamy et al. 2024) These treatments produce fully cured and cross-linked natural fibers, which enhance the polymeric matrix and its mechanical and thermal stability (Dejene 2024c). Enhanced compatibility between natural fibers and polymer matrices is achieved by effectively removing surface impurities and hydroxyl group components, such as pectin, lignin, and hemicellulose, from the fibers. This process promotes strong chemical bonding at the interfaces between the two phases and the formation of a robust network structure. Consequently, these improvements expand the potential applications of natural fibers, particularly in the automotive (Jabu, Alugongo, and Nkomo 0000) and construction industries (Al Hajaj 2024), and airplane (Esangbedo and Samuel 2024). Conversely, the inadequate interfacial bonding observed between the natural fibers and the matrix significantly compromised the mechanical properties of the composites. This deficiency arises from the hydrophilic nature and physicochemical heterogeneity of natural fibers, which affect their continuity and uniformity within the matrix. The natural mismatch between hydrophilic natural fibers and hydrophobic matrix polymers leads to weak fiber adhesion and uneven fiber distribution within the matrix. However, these issues can be successfully resolved using various surface treatments, chemical treatments, and other techniques (Nlandu-Mayamba et al. 2024). By employing such treatments, natural fibers can overcome issues related to moisture absorption, adhesion, fire resistance, strength, and weather dependency, thereby enhancing their consistency and performance in composite materials. The inherent hydrophilicity of fibers contrasts with the hydrophobic nature of the polymer matrix, posing challenges in establishing interfacial bonds between them. Consequently, surface modification is imperative. This process involves enhancing the fiber surface characteristics, such as roughness, wettability, and hydrophilicity, to mitigate moisture absorption, fortify interfacial bonds, and augment the tensile properties of plant fibers. Surface modification techniques encompass physical, chemical, or a combination of the two, with the overarching goal of reinforcing fibers and rectifying their undesirable characteristics. Strategies involve diminishing the polar component and impurities, modifying the crystallinity and chemical composition, improving the fiber-matrix interface, and fostering robust adhesion within the

fiber matrix. Therefore, a concerted effort toward physical, chemical, or combined modification is essential to reduce the innate properties of natural fiber surfaces, each offering distinct advantages.

Treatment of natural fibers

Physical treatment

In general, physical treatment methods are geared toward enhancing mechanical properties like strength, modulus, and elongation, which primarily pertain to the physical structure of materials. These treatments alter the structural and surface features of plant fibers without affecting their chemical composition (Sathish et al. 2021). By doing so, they can effectively enhance the thermal properties and bonding between different components of composite materials. However, the lack of access to surface treatment equipment limits the range of approaches available to address these challenges (Mohammed et al. 2022). The physical treatment of NFRCs improves bonding at the interface between natural fibers and the matrix by refining the interface zone without changing the fiber's chemical properties. This treatment is classified into three main types: simple mechanical methods, such as stretching, calendaring, and rolling, which are applicable to mechanically treating long plant fibers; solvent extraction; and electrical discharge techniques (Molla et al. 2024). Each method – mechanical, solvent extraction, and electrical discharge – offers unique benefits and drawbacks in modifying the physical structure of natural fibers without altering their chemical composition. The selection of the method depends on specific application requirements and the desired fiber properties, as well as environmental, economic, and operational factors (Patel, Yadav, and Winczek 2023). The combination of these methods can also be explored to achieve synergistic effects and optimize the fiber modification process. Within the initial category, an optimal tensile strength can be achieved through stretching, albeit with the caveat of potential elongation. This elongation occurs as plant fibers slide past one another during stretching, resulting in additional extension. Nonetheless, this method offers the advantage of improved load distribution within the composite due to reduced fiber density and rigidity. However, rapid heating rates during stretching can induce the surface shrinkage of fibers. For shorter plant fibers and fillers, stretching is a relatively straightforward approach to augmenting the surface area and eliminating soluble impurities. Based on the solubility of compounds in mixed water and organic solvents, this method can effectively separate compounds. However, solvent extraction poses risks to ecological systems and contributes to environmental pollution. Moreover, physical alterations to fiber surfaces can be accomplished via thermal processes such as plasma treatment or non-thermal methods like electric discharge, high-frequency cold plasma, ultrasound, or ultraviolet irradiation.

Plasma treatment is an environmentally sustainable procedure for enhancing the surface characteristics of natural fibers. This technique generally avoids the use of harsh chemicals, thereby reducing the environmental impact of chemical waste and pollution (B. Zhang et al. 2021). The gases used in plasma treatment are often inert or environmentally benign, such as air, oxygen, and nitrogen, which minimize the risk of toxic emissions (Ivanovska et al. 2023). Modern plasma treatment systems are designed to be energy-efficient. Although the initial setup may require significant energy, the overall energy consumption is lower than that of traditional chemical treatments. The process typically involves short exposure times, which further reduces the energy consumption and makes the process quick and efficient. Unlike chemical treatments, plasma treatment does not produce liquid waste, thus minimizing the need for waste management and disposal infrastructure. In addition, the precision of plasma treatment reduces material waste, thereby contributing to a more efficient use of resources. Plasma treatment enhances the surface energy of fibers, thereby improving their wettability and adhesion properties. This is particularly beneficial for composite materials and coatings because it increases mechanical interlocking with matrix materials. The process can also etch the fiber surface, increasing its roughness and creating a more textured surface, which enhances mechanical bonding in

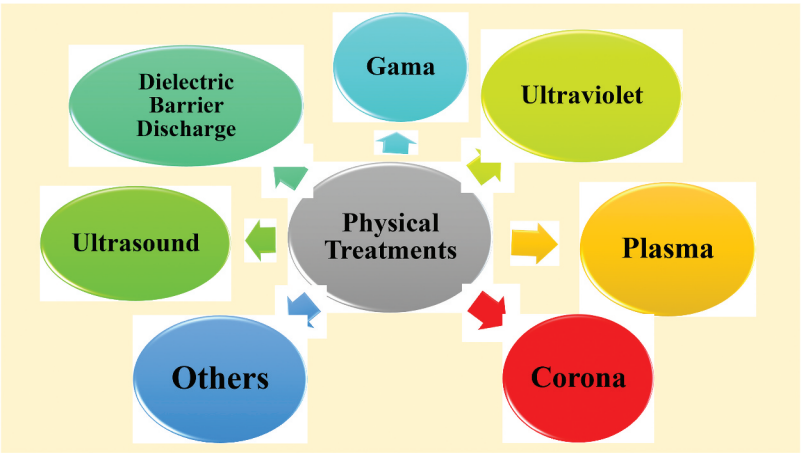

Figure 6. Different types of physical treatment for natural fibers.

composites. For biomedical applications, plasma treatment can improve the biocompatibility of natural fibers by tailoring their surface properties to promote cell adhesion and growth. Furthermore, certain plasma treatments can impart antibacterial properties to natural fibers, rendering them useful in medical textiles and hygiene products. Figure 6 shows diverse types of physical treatments suitable for natural fibers.

Plasma treatment

Plasma modification has emerged as a prominent method owing to its environmental sustainability and efficiency, and it presents a rapid approach to surface modification (Nyssanbek et al. 2024). Plasma-treated fibers exhibit rougher surfaces and greater hydrophobicity, enhancing interfacial adhesion. Consequently, this method enhances the interaction between the fiber and matrix, thereby improving the interfacial adhesion in composite materials (Molla et al. 2024). Plasma-induced changes in the physicochemical and microstructural attributes of natural fibers improve their adhesion to composite materials (R. K. Gupta, Guha, and Srivastav 2023). Plasma surface treatment involves activation and polymer grafting onto surfaces to enhance various material characteristics, including adhesion and wettability. Non-thermal or cold plasma treatment has applications in fruit treatment. This innovative non-thermal technique has substantial promise for the treatment of natural fibers because of its environmentally friendly attributes. Cold plasma has also been used to minimize microbial growth in food applications. This plasma treatment has various effects, including negative ions, positive ions, free electrons, reactive nitrogen species, reactive oxygen species, and ozone. These reactive species affect the material components, surface modification, and mechanical properties. Non-thermal plasma can be generated from multiple sources such as electric fields, heat, chemical reactions, pressure, microwaves, radio frequencies, X-rays, and electromagnetic fields, which provide energy to neutral gases (Sharafodin, Soltanizadeh, and Barahimi 2023). Plasma consists of a mixture of various energetic components, including atoms, ions, molecules, and free electrons (Pillai and Thomas 2023). The particle composition in a plasma environment varies depending on the type of plasma gas used. Within the plasma environment, free electrons interact with neutral gas molecules and transfer energy under electric field stimulation. Consequently, this interaction generates reactive species predominantly composed of ions. The interaction between these energetic ions and the solid surface initiates the chemical and physical transformation of the material surface (Sarikanat et al. 2016). Plasma treatment only altered the surface characteristics of the material, leaving its bulk properties unchanged. There are two primary types of plasma treatments: low-pressure vacuum and atmospheric pressure treatments. Vacuum-based plasma treatment requires a closed environment, whereas

atmospheric pressure plasma treatment functions in an open environment (U. S. Gupta, Dhamarikar, Dharkar, Chaturvedi, Kumrawat, et al. 2021). For years, textile plasma treatment has relied primarily on low-pressure plasma processes. However, integrating these processes, typically operating at pressures between 0.1 and 1 mbar, into continuously running textile production and finishing lines poses complexities or may even be infeasible. Furthermore, low-pressure processes are costly due to the need for vacuum technology. These methods require a controlled, enclosed environment with reduced pressure, which is facilitated by a vacuum pump to achieve the necessary conditions. Once the specimen is placed inside the chamber, gas is introduced and ionized, leading to surface modification as charged particles interact with the specimen's surface. The low-pressure plasma technique is advantageous because of its precise control and reproducibility. In contrast, atmospheric pressure plasma treatment examines the surface of a substrate or specimen under atmospheric pressure, where the operational pressure is higher than that of vacuum plasma treatment. This surface alteration technique offers significant advantages as it allows for comprehensive and uniform analysis of specimens without the limitations of a vacuum chamber. Additionally, since this approach does not rely on high maintenance and expensive vacuum systems, it is highly reliable, cost-effective, and reproducible. The four main categories of atmospheric pressure plasma treatment are dielectric barrier discharge, atmospheric pressure plasma jet, atmospheric pressure glow discharge, and corona treatment. Figure 7 shows a Schematic of the plasma treatment system.

Dielectric barrier discharge treatment (DBD)

In this method, aimed at achieving higher charge dispersion across the specimen's surface and ensuring uniformity of charge over the electrode's surface, one of two parallel metal electrodes is coated with a dielectric film. A dielectric-barrier discharge setup involves placing a glass, silica glass, or ceramic barrier between two electrodes, which is then connected to an extremely high-voltage AC generator (Adesina et al. 2024). These plasma sources operate exclusively with sine waves or pulsed high voltages due to the presence of dielectric barriers. The dielectric-barrier discharge method offers a wider power range, thus providing electrons with increased energy, leading to more effective generation of radicals and electronically excited particles. One advantage of this technique is that the electrodes are not in direct contact with the plasma. During discharge, high-energy electrons are generated by collisions, which efficiently produce radicals and electronically excited particles. This approach facilitates the activation of plant fiber surfaces. Because of alterations in the fiber surface

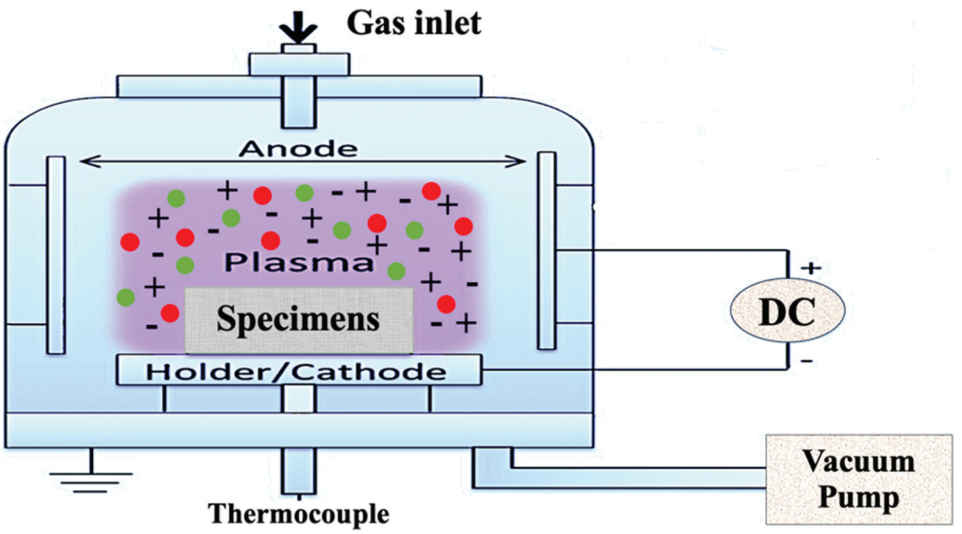

Figure 7. Schematic of the plasma treatment system.

microstructure, the surface roughness increases, enhancing the wettability while reducing the tensile strength. Fiber bundle aggregation is reduced by this treatment. Moreover, there is an increase in the number of oxygen functional groups, and the dielectric barrier discharge treatment removes the top surface films from the fiber surface. Additionally, it enhances the interfacial bonding between the epoxy matrix and fiber layers. Numerous studies have been conducted to investigate the effects of physical treatments on the NFR materials. Rachtanapun et al. (2024) investigated the effects of plasma treatment on the physical and mechanical properties of bamboo fiber-reinforced epoxy composites. The results show that after 30 min of Ar gas plasma treatment, the tensile strength increased significantly from 37 to 45 Mpa and improved the flexural properties by enhancing the polarity and surface roughness, promoting better EP-BF surface connection. The water contact angle and compatibility between the BFs and EP such that the strong bonding between EP and BFs increased water resistance. Anari Soltanizadeh, and Fathi (2024) examined the application of DBD plasma as a pretreatment method for extracting micro and nano-cellulose fibers from walnut shells. The powdered WS underwent plasma treatment at 18 and 20 kV before either sodium hydroxide alkaline treatment, sodium chlorite bleaching, or both alkaline and bleaching treatments. The findings indicated that plasma pretreatment reduced the cellulose extraction efficiency from approximately 26% to around 22%, accompanied by a decrease in the C-C/C-H and C-OH/CO-C bonds. Additionally, the plasma-treated sample exhibited a distinct weight loss pattern below 100°C compared to the control, attributed to alterations in water absorption. Gupta et al. R. K. Gupta, Guha, and Srivastav (2023) studied the impact of DBD atmospheric cold plasma treatment at three power levels (30, 32, and 34 kV) and exposure times (2, 4, and 8 min) on the functional and physicochemical properties of taro starch. Results indicated no changes in the functional groups of taro starch based on FTIR analysis following cold plasma treatments. Sawangrat et al. (2023) investigated how the properties of modified bamboo fibers were affected by dielectric barrier discharge plasma treatment using argon and oxygen gases, alongside different treatment durations, at a power output of 180 W. FTIR confirmed reduced functional groups in lignin and hemicellulose due to plasma etching. XRD showed increased crystallinity, while XPS indicated a rising oxygen/carbon ratio with longer treatment. Mechanical tests revealed high tensile strength in F(tr)RE-Ar (30) samples.

Corona treatment

Corona electrode discharge treatment is a novel technology characterized by its non-thermal nature, high efficiency, lower energy consumption, and zero-waste attributes, particularly suitable for natural fibers. Corona treatment induces a highly energetic plasma discharge composed of ions, electrons, and reactive species. When applied to natural fiber surfaces, this plasma activates the surface by disrupting chemical bonds and generating free radicals. These reactive species chemically alter the fiber surface by introducing polar functional groups like hydroxyl, carbonyl, and carboxyl groups. These functional groups enhance the fiber's affinity toward polar polymer matrices. Consequently, the surface energy of the fibers increase, enhancing their wettability and adhesion to the polymer matrix. Improved wetting facilitates better interaction between the fibers and the polymer, resulting in enhanced interfacial bonding strength. Overall, corona treatment modifies natural fiber surfaces, promoting stronger adhesion to polymer matrices through the introduction of polar functional groups and increased surface energy, ultimately enhancing interfacial bonding in composite materials. Corona treatment, along with the dielectric barrier, is a type of atmospheric plasma method involving the application of high voltage near the surface of fibers, resulting in corona discharge generation (Gholampour and Ozbakkaloglu 2020). Following this treatment, fibers undergo an increase in polarity, as well as in the quantity of hydroxyl and carboxyl groups, which contributes to enhancing fiber-matrix bonding (Nurazzi et al. 2021). Corona electrode discharge treatment is a novel technology characterized by its non-thermal nature, high efficiency, lower energy consumption, and zero-waste attributes, particularly suitable for natural fibers. Otálora et al. (Otálora González et al. 2024) studied treated starches, finding a pH drop post-corona treatment and changes in rheological properties depending on the starch form. Shifts in O-H and C-O-C FTIR bands were also noted. Corona treatment shows promise

for starch modification, primarily inducing cross-linking in dry granular starch and depolymerization in moist granular starch. The treatment improves fiber wettability by leveraging fiber surface polarity and the compatibility between hydrophilic fibers and hydrophobic matrices. Additionally, it modifies surface energy to enhance mechanical strength.

While corona treatment is effective, its adoption is limited due to several factors. Its inherent complexity poses challenges, particularly when applied to three-dimensional fibers. This method is more suited for flat or planar substrates rather than complex shapes or irregular surfaces. Treating bulkier or non-flat natural fiber materials may necessitate customized equipment or alternative surface modification techniques. Additionally, achieving consistent and reproducible treatment effects can be difficult, especially with natural fibers that exhibit variability in surface properties. Controlling factors such as treatment speed, power level, and distance from the corona discharge source is essential for desired outcomes. Moreover, corona treatment systems can be costly to purchase and operate, particularly for small-scale or low-volume applications, which may limit their adoption in smaller manufacturing facilities or research laboratories. Furthermore, the generation of ozone and other reactive species during the process poses safety hazards if proper ventilation and safety measures are not implemented. Concerns about worker safety and environmental regulations may deter some users from adopting corona treatment. Some experimental studies on the treatment of natural fiber with corona treatment are illustrated in Table 1.

Atmospheric pressure glow discharge (APGD)

Operating at atmospheric pressure, particularly when using atmospheric pressure glow discharge, decreases the distance along which the discharge extends. The APGD technique facilitates uniform surface treatment (Kogoma and Tanaka 2021). Compared with dielectric barrier discharge, APGD offers stability, homogeneity, and a more uniform discharge. This method usually starts in argon or helium gases by applying low voltages through parallel conductive electrodes at higher frequencies. APGD achieves a uniform plasma distribution and generates a current pulse for each half-cycle. This approach generates plasma at lower temperatures than other methods but yields a higher density of excited particles and energetic electrons. Kafi et al. (Kafi, Magniez, and Fox 2011) treated jute fabric with atmospheric plasma for 10 seconds, improving wetting regardless of the gas used. They observed enhancements in composite properties, including flexural strength, flexural modulus, and interlaminar shear stress, and increased storage modulus and glass transition temperature.

Table 1. Previous experimental research studies on corona treatments on the NFRCs prosperities.

Composite	Result	Ref.
Coconut/Polyurethane	The process of surface treatment removes extractives, hemicelluloses, and lignin from the fibers' surface. This causes a decrease in diameter and an increase in aspect ratio, thereby enhancing the fibers' mechanical properties.	Faria, Mendes, and Junior (2023)
Alfalfa seed	Corona discharge field treatment has the capability to modify the chemical makeup of alfalfa seed coats, consequently affecting their hydrophilicity.	Luan et al. (2020)
Cotton fabric	Cotton fabric treated with spinach leaf extract immersion and atmospheric pressure plasma pre-treatment showed better fire retardancy and absorbency. Plasma exposure duration affected fire-retardant properties.	Putra, Wijayono, and Mohamad (2020)
Cotton/polyester	Research showed that corona discharge plasma pretreatment with tip-cylinder electrodes made an anti-radiation fabric effective in absorbing smartphone radiation.	Putra et al. (2021)
Jute fiber/Polyester	All surface treatments applied demonstrated significant enhancements in the interlaminar shear strengths of the composites, flexural and tensile strengths, so indicating an overall improvement in their mechanical properties.	Sever et al. (2012)
Pine, Eucalyptus, Sugarcane/Polyester	Enhancing the impact strength in pine and bagasse composites, decreasing water absorption in eucalyptus and bagasse composites, and improving tensile strength across all reinforced composites have been happened.	Mesquita et al. (2017)
Hemp fibres/ Polypropylene	The etching effect induced by corona discharge treatment, as observed through microscopy, primarily contributes to the improved mechanical anchorage and interfacial adhesion between the compounds.	Ragoubi et al. (2010)

The atmospheric pressure glow discharge is more uniform than the dielectric barrier discharge. The ability of APGD to maintain a stable glow over a larger area, free from filamentary structures, contributes to this uniformity. This characteristic renders APGD particularly suitable for applications requiring consistent surface treatment. Conversely, a DBD typically produces fewer uniform discharges because it often operates in a filamentary mode, where multiple micro-discharges occur across the surface. These filaments can result in uneven treatment with varying degrees of exposure in different areas. In terms of discharge stability, the APGD exhibits greater stability, consistently maintaining a continuous and homogeneous plasma under various operating conditions. This stability is advantageous for applications requiring prolonged and consistent plasma exposure. On the other hand, DBDs can be less stable due to the presence of micro discharges, which can cause fluctuations in plasma properties. Although the stability of DBD can be improved by optimizing the electrode configuration and dielectric materials, it remains more variable than APGD. The uniform and stable nature of APGD leads to a more consistent modification of natural fiber surfaces. APGD can enhance fiber properties, such as wettability, dyeability, and adhesion, by introducing functional groups and etching the surface. This uniform treatment ensures that these modifications are evenly distributed across the fiber surface, resulting in enhanced overall properties. Although DBD treatment can also improve natural fiber properties, the effects may be less uniform because of the filamentary nature of the discharge. Some regions of the fiber may receive a more intense treatment, causing localized changes in surface properties. This method can be beneficial for creating specific patterns or textures; however, it may be a drawback for applications requiring uniform surface modification. In conclusion, APGD is generally preferred for applications requiring uniform and stable plasma treatment, leading to consistent enhancement of natural fiber properties. However, DBD is advantageous in specific applications where localized treatment is desirable.

Atmospheric pressure plasma jet (APPJ)

In the setup of the APPJ, two cylindrical metal electrodes are positioned apart from each other. Quartz tubes are integrated into the electrodes to allow the passage of helium or other gases, thereby initiating plasm (Tavares et al. 2020). To ensure efficient and consistent plasma generation, parameters such as wave pulse, gas flow rate, and pulse frequency were adjusted accordingly (L. Zhang et al. 2023). The plasma was directed onto the specimen via an aperture in the quartz tube. The plasma produced in APPJ contains a high concentration of free electrons. Owing to its fast gas flow and deep plasma penetration, the APPJ delivers precise outcomes (Gotoh 2020). This method allows for targeted and exact treatment, making it applicable across various fields. In industry, both low-pressure and atmospheric-pressure plasmas are increasingly being employed for pretreatment. APPJs are particularly favored for their ease of integration into current production lines and their capacity to selectively treat specific substrate sections (Zhou et al. 2020). Unlike corona treatments and dielectric barrier discharges, APPJs are not limited to two-dimensional structures but can also be applied to three-dimensional structures (Mengjin et al. 2021). Sarafpour et al. (Sarafpour, Ebrahimi, and Tanha 2021) researched the enhancement of poly para-phenylene terephthalamide fibers using an innovative plasma jet method with oxygen and argon. Varying O_2/Ar ratios, treatment times, SEM, AFM, ATR-FTIR, and mechanical tests were conducted. The surface morphology changed significantly, and COOH, NH_2, and OH groups formed, improving adhesion.

APPJ presents numerous benefits for treating three-dimensional natural fiber structures because of its operational versatility, efficacy, and plasma nature. The proposed method enables precise and localized treatment of specific areas within 3D fiber structures, which is advantageous for targeting specific surface modifications without impacting the entire structure. Operating at atmospheric pressure and generating non-thermal plasma, APPJ can treat heat-sensitive natural fibers without causing thermal damage, thereby preserving the fiber's structural integrity and inherent properties. The plasma produced by this method can effectively activate and functionalize fiber surfaces, enhancing properties such as wettability, adhesion, and dyeability by introducing polar functional groups

like hydroxyl and carboxyl. Additionally, APPJ systems are scalable and adaptable, allowing the treatment of fibers of various shapes and sizes, including complex 3D configurations, making them suitable for diverse applications in industries like textiles, biomedicine, and composites. Operation at atmospheric pressure eliminates the need for vacuum systems, thus reducing both operational costs and complexity. Furthermore, the use of inert or nontoxic gases in APPJ makes it an environmentally friendly and safe option for fiber treatment.

For APPJ to be effectively applied to three-dimensional natural fiber structures, several key parameters must be meticulously controlled. The primary considerations were power and gas flow rate. The power level of the plasma jet affects the energy density and the generation of reactive species. An optimal power setting is essential for adequate surface modification without damaging the fibers. The type and flow rate of the working gas, such as argon, helium, or air, is critical because the gas flow rate influences the plasma jet's stability, length, and concentration of reactive species. Proper adjustment is necessary to ensure uniform treatment. In addition, the duration of plasma exposure and the distance between the plasma jet nozzle and fiber surface must be optimized. An insufficient treatment time may result in inadequate surface modification, whereas excessive exposure can lead to surface etching or degradation. The standoff distance affects the plasma density and treatment area; thus, maintaining an appropriate standoff distance is crucial for uniform surface modification. Finally, environmental conditions such as humidity and temperature can affect the plasma process. Controlling these factors is essential for maintaining treatment consistency and effectiveness.

Ultrasound treatment

The ultrasound treatment involves utilizing ultrasound vibration to break down carbohydrates. Lignocellulosic fibers primarily consist of cellulose and hemicellulose, contributing to the water absorption of natural fibers. Ultrasound treatment facilitates the decomposition of carbohydrates in natural fibers (Wang et al. 2018). Ultrasound treatment employs powerful mechanical forces that help break down complex carbohydrates, such as cellulose and hemicellulose, into simpler sugars. This process can be enhanced by incorporating catalysts or enzymes that work synergistically with the ultrasound waves. The disruption of the fiber structure by ultrasound increases the surface area, facilitating easier access for enzymes or chemicals to further decompose the carbohydrates. This combined approach not only accelerates the decomposition process but also improves the efficiency of breaking down the lignocellulosic fibers into simpler components. Sifuentes-Nieves et al. (Sifuentes-Nieves et al. 2024) fabricated the polybutylene adipate terephthalate composites with plasma and ultrasound/plasma-modified Agave fibers. Their impact on processing, structure, mechanics, and water barrier properties was examined. The addition of modified AF increased processing torque and energy, signifying better matrix-fiber interaction. PBAT-AFUP composites exhibited uniform surfaces and ordered structures, enhancing fiber-matrix entanglement and reducing water interaction, as shown by changes in tensile modulus (90 to 163 MPa) and water contact angle (63 to 77°).

Applying ultrasound treatment at different temperatures removes lignin, pectin, hemicelluloses, and other surface impurities, thereby improving the bonding between fibers and the matrix in the process. composites (U. S. Gupta, Dhamarikar, Dharkar, Chaturvedi, Tiwari, et al. 2021). The composites have demonstrated greater thermal stability and reduced moisture absorption compared to untreated fibers. Hemicellulose and lignin play a role in making lignocellulosic fibers hydrophobic. However, their reduction or removal enhances the fibers' hydrophilicity, allowing them to absorb more water. Ultrasound treatment further enhances this process by increasing fiber porosity by creating microfibrils and the availability of more hydroxyl groups on cellulose chains. This increased porosity facilitates greater water absorption and retention. Additionally, the mechanical disruption caused by ultrasound alters the fiber surface, creating rougher textures with increased sites for water binding, thereby augmenting the fibers' water-absorbing capabilities. Dutta and Sit (2024) investigated biocomposite films made from potato starch reinforced with modified banana fibers. They found that combining ultrasound and enzyme treatments decreased water absorption and vapor permeability

Table 2. Previous experimental research studies on ultrasound treatments on the NFRCs prosperities.

Composite	Results	Ref.
Banana fiber	Ultra-sonication decreased the average diameter to 19.36 μm, while alkali pre-treated fiber measured 49.94 μm and untreated fiber measured 171.87 μm, as observed using a digital optical microscope.	Twebaze et al. (2022)
Sunn Hemp Fiber/ Epoxy	Lengthening ultrasonication during chemical impregnation boosted cellulose crystallinity. The irregular surface of sunn hemp fiber indicated the removal of noncellulosic components, confirmed by changes in functional groups.	Dash, Das, and Bisoyi (2022)
Rape Stalk/Polyvinyl Chloride	Composites treated with both alkali and ultrasound exhibited significant improvements in hardness, strength, stability, and resistance to wear. Compared to ultrasound treatment alone, they exhibited increases of 7.74% to 13.80% in strength. Compared to alkali treatment, the increases ranged from 1.59% to 6.48%.	X. Zhang et al. (2024)
Agave fibers/ Polyvinyl Alcohol	Treatments remove moisture, waxes, pectin, hemicellulose, and lignin from fibers to varying extents and the PVA matrix with modified fibers shows low viscosity and strong filler dispersion.	Sifuentes-Nieves et al. (2023)
Orange Bagasse	The sample treated with ultrasound for 10 minutes at 30% amplitude, along with 24-hour peracetic acid treatment, exhibited the highest crystallinity index (54%), with 0.88% hemicellulose and 2.68% lignin.	Marim et al. (2021)
Purple rice starch	Ultrasound, after heat-moisture treatment, dispersed starch granules initially clumped by HMT, resulting in a rougher surface. Higher moisture during HMT and stronger ultrasound reduced short-range order.	Su et al. (2024)
Starch/Agave fibers	Dual treatment modified fiber structure, enhancing surface polarity and secondary bonding with starch. This resulted in smoother starch films with improved mechanical properties: reduced roughness, increased melting temperature, and enhanced mechanical strength and Young's modulus.	Sifuentes-Nieves et al. (2023)
Windmill palm single fiber	Alkali-ultrasound treatment produced <90 nm CNFs with enhanced crystallinity (60%), surpassing windmill palm fibers. CNFs exhibit thermal decomposition at 469°C (crystalline) and 246°C (amorphous).	Chen et al. (2023)

(0.156 g mm m −2 h − 1 kPa − 1) of the films. Mechanical properties, such as tensile strength (5.02 MPa) and sealability (4.27 MPa), improved significantly with the use of modified fibers, leading to enhanced thermal stability. Scanning electron microscopy showed smoother surfaces and a more uniform distribution of voids in modified fibers compared to untreated ones. Table 2 shows some of the experimental research conducted using ultrasound treatment of the NFRCs in recent years.

Ultraviolet treatment

Some physical treatments are challenging to apply to three-dimensional objects, including fibrous materials like woven fabrics or strands. Recognizing these limitations has emphasized the need for alternative surface modification techniques that are more compatible with three-dimensional structures, such as ozone and/or ultraviolet radiation. UV radiation affects nearly all chemical constituents (cellulose, hemicellulose, and lignin) of natural fibers, leading to degradation. Specifically, lignin, as a surface constituent of natural fibers, undergoes rapid oxidation and degradation under UV light. However, lignin's phenolic structure also acts as a UV-absorbing agent, shielding cellulosic components from excessive photodegradation. UV treatment enhances the polarity of the fiber surface, thereby improving fiber wettability, tensile strength, and Young's modulus of both fibers and composite materials (Benedetto, Gelfuso, and Thomazini 2015).

Chemical treatment

Chemical treatments significantly impact the mechanical properties of natural fibers due to the presence of hydroxyl groups in cellulose and lignin. Cellulose, which constitutes the majority of fibers, is the primary target for chemical alteration. The non-crystalline portion of cellulose is more susceptible to chemical reactions compared to the crystalline portion. Modifying the fibers chemically can reduce moisture absorption, thereby enhancing interfacial bonding strength and resulting in composites with superior mechanical properties. There are two main methods for modifying fibers: reducing alcohol groups on the fiber surface to decrease polarity and improve

compatibility with polar polymer matrices, or exposing more reactive alcohol sites by removing compounds such as waxes, hemicelluloses, and lignins, enabling them to interact with other treatments such as alkaline and silane treatments (Elfaleh et al. 2023). Chemical treatment strategies often rely on reagent functional groups or active groups capable of effectively interacting with the structures of natural fibers while also efficiently removing non-cellulosic materials from the fibers. Additionally, hydroxyl groups produced by chemical treatments may engage in hydrogen bonding within the cellulose atoms, thereby restricting movement toward the matrix. Consequently, chemical modifications either activate these groups or introduce new moieties that can effectively interlock with the matrix, resulting in strong bonding. The choice of chemical treatment method depends on factors such as the availability of reagents, the desired modification of functional groups, and the necessity of active groups capable of interacting with natural fiber structures. Figure 8 illustrates the chemical treatment of natural fibers.

Alkaline treatment

The alkaline treatment method provides a straightforward, cost-effective, and efficient means of enhancing the water resistance, adhesion properties, and mechanical, acoustical, and thermal properties of natural fibers when used to reinforce thermoplastics and thermosets (Baskaran, Kathiresan, and Pandiarajan 2022; Bezazi et al. 2022; Boumaaza, Belaadi, and Bourchak 2021; Tenazoa et al. 2021). This treatment induces changes in fiber size, shape, and strength. Essentially, it initiates fibrillation, separating fiber bundles, increasing their aspect ratio, and exposing more cellulose sites for bonding with the polymer matrix. This promotes better wetting of fiber surfaces and reduces water absorption. Sodium hydroxide is commonly employed for its ability to convert cellulose-I to cellulose-II more thoroughly than other alternatives. Alkaline treatment involves immersing fibers in an aqueous solution of NaOH or KOH, with the specific solution composition, concentration, temperature, treatment duration, and material tension influencing the extent of swelling and subsequent alterations in fiber structure, morphology, dimensions, and mechanical properties. The treatment induces fibrillation, breaking down fiber bundles into smaller fibers and creating a rougher surface, which enhances the bond between fibers and the matrix, thereby improving mechanical properties (Sun, Pillay, and Ning 2024). Furthermore, the mercerization process increases the number of active sites on

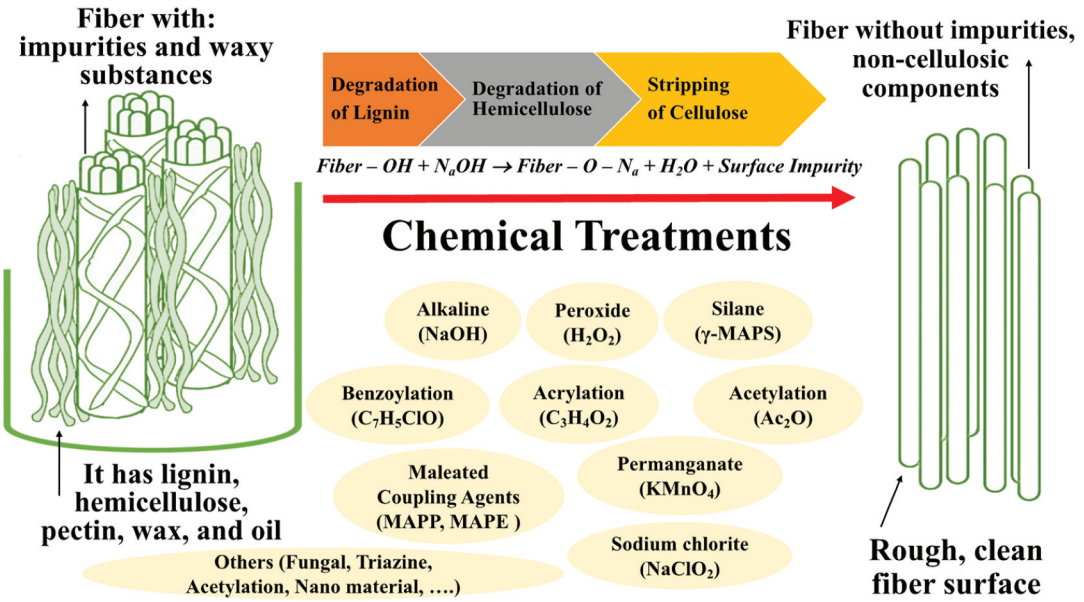

Figure 8. Schematic representation of the chemical treatment on natural fiber.

Table 3. Previous experimental research studies on alkaline treatments on the NFRCs prosperities.

Composite	Results	Ref.
Kenaf fiber/Polypropylene	A 6% concentration of NaOH for 24 h was used. Treating the composite with NaOH increased its tensile stress and reduced water absorption compared to the untreated composite. This improvement was attributed to enhanced interfacial bonding and mechanical interlocking sites.	Salehudiin et al. (2023)
Bamboo fiber/ Polyethylene	More fibrillation and surface roughness were observed on the bamboo fiber's surface, creating more contacting surfaces to improve the interfacial interaction.	Mohanta et al. (2024)
kenaf fiber/Epoxy	SEM images reveal that untreated kenaf fiber composites have impurities that cause brittleness and weak interfacial bonding, resulting in poor thermal properties. NaOH-treated composites exhibit smoother surfaces, reduced impurities, and improved adhesion with the matrix, enhancing thermal characteristics.	Muralidharan et al. (2023)
Bambusa tulda/ Epoxy resin	Composites treated with 6% NaOH showed better thermo-mechanical and interfacial properties, while those with a 30% fiber loading demonstrated the best mechanical performance. Specifically, 30% fiber weight fraction composites treated with 6% NaOH exhibited superior tensile and flexural strength, modulus, and impact strength, with lower moisture absorption.	Saha and Kumari (2023)
Jute fiber	Jute fiber treated with alkali-nano-clay exhibits substantial improvements: a 32% increase in tensile strength, a 24% rise in tensile modulus, and a 15% enhancement in fiber density compared to untreated jute fiber.	Yadav and Yadav (2024)
Coconut fiber/Unsaturated polyester	TGA analysis of the 30% fiber composite showed an 18% residual mass, indicating significant cellulose changes due to alkali treatment, which strengthened adhesion in the matrix.	Mahalingam et al. (2024)
Pinecone Scale Fiber/Vigna mungo powder/ Polypropylene	An aqueous solution of 1.6 mol/l NaOH was applied for 48 hours, resulting in increased stiffness and improved Young's modulus, attributed to enhanced distribution of tensile loading.	Negi et al. (2022)
Banana/Coir fiber/ Polylactic acid, and Unsaturated polyester resin	5 wt.% aqueous NaOH solution at room temperature for 1 h. Treated banana fibers became more thermally stable by removing hemicellulose, lignin, and waxy substances. Similarly, treated coir fibers showed altered thermal degradation likely due to the removal of hemicellulose, lignin, and pectin.	Barrera-Fajardo, Rivero-Romero, and Unfried-Silgado (2024)
Coir/Polyvinyl Alcohol/Polyethylene Glycol	The highest tensile strength of 47.21 MPa was observed for the PVOH/PEG 10%/TCo 5% film, attributed to the excellent dispersion of PVOH, PEG, and alkali-treated coir fiber.	Gond et al. (2024)
Jute fiber	Fibers treated with alkali displayed heightened crystallization, thermal endurance, and surface smoothness compared to untreated fibers, with degradation commencing at 261.23°C.	Malladi et al. (2024)
Banana fiber/Epoxy	Applying a 5% NaOH treatment improves the tensile, flexural, and impact strengths of the composite by 14.78%, 8.59%, and 29.63%, respectively. Additionally, this treatment decreases the absorption rate of the banana fiber composite.	Kadire and Joshi (2024)
Palm fiber/Polyethylene	Applying a 5% NaOH treatment improves the tensile, flexural, and impact strengths of the composite by 14.78%, 8.59%, and 29.63%, respectively. Additionally, this treatment decreases the absorption rate of the banana fiber composite.	Heraiz et al. (2024)

fibers, facilitating better wetting. Additionally, this process eliminates impurities and non-cellulosic components such as lignin, hemicellulose, pectin, wax, and oil. Removal of lignin and hemicellulose, which act as binders for microfibrils, can reduce tensile stress in natural fiber-reinforced composites (Mohammed et al. 2023). Table 3 shows some of the experimental research conducted using alkaline treatment of the NFRCs in recent years.

Silane treatment

Silanes represent a class of chemical compounds denoted by the formula SinH2n + 2, falling within the realm of inorganic chemistry alongside silicon alkoxides. These compounds exhibit hydrophilic properties and feature various groups linked to silicon. Typically, the silane treatment process begins with a silane derivative, often amine-based, dissolved in an acetone/alcohol solution. When fibers are

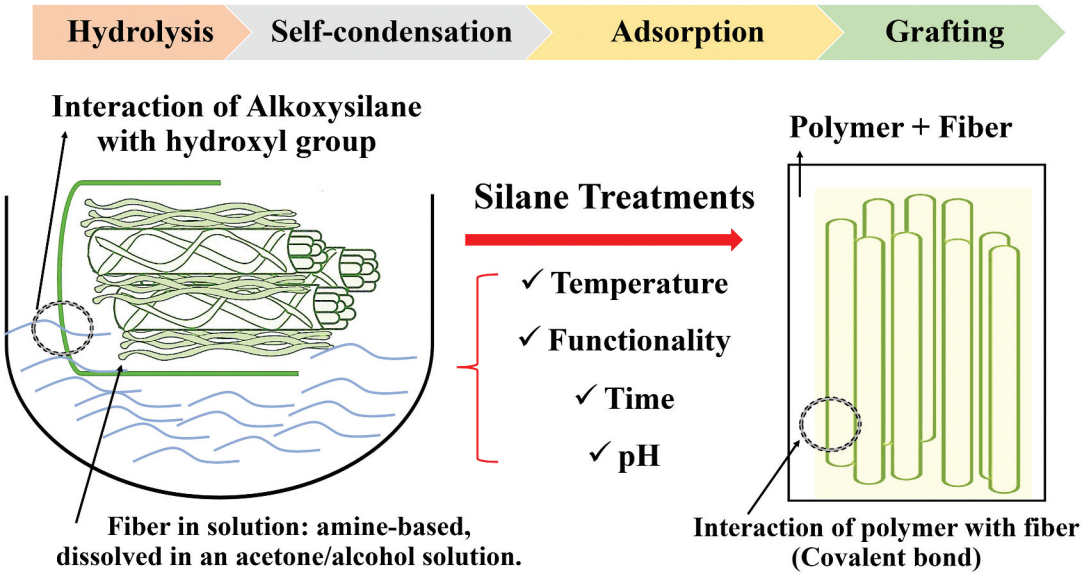

Figure 9. Schematic representation of the silane treatment on natural fiber.

immersed in this silane solution, they establish stronger interactions with the matrix compared to fibers treated with alkali, resulting in improved thermal stability, flexural stiffness, tensile strength, and tensile modulus. Alkoxysilane groups located at one end of the silane coupling agent bind with hydroxyl-rich surfaces found in natural fibers. Conversely, the opposite end interacts with the polymer matrix, enhancing adhesion between natural fibers and the polymer matrix, thereby increasing resistance to water absorption. Silane coupling agents can reduce the number of cellulose hydroxyl groups at the bond interface between natural fibers and the polymer matrix. Upon exposure to water, the hydrolyzable alkoxy group facilitates the formation of silanols. These silanols then interact with the hydroxyl groups of natural fibers, forming strong covalent bonds with the cell wall that chemically bond to the surface of the natural fibers. Figure 9 illustrates the process of silane treatment of natural fibers. Del Angel-Monroy et al. (2024) examined how chemical modification of coconut fibers using different silane agents (GLYMO, VTMS, TEOS) enhanced interaction with a polylactic acid matrix. Silanization increased interfacial interactions, raising PLA crystallinity from 48.95% to 60.08% with GLYMO, 63.94% with VTMS, and 63.35% with TEOS. Furthermore, silane treatment was also performed by Matykiewicz et al. (2024). They employed two varieties of silanes featuring distinct functional groups: 3-chloropropylmethyldimethoxysilane and *N*-(2 aminoethyl)-3-aminopropyltrimethoxysilane, each at concentrations of 1 and 2%. They highlighted the beneficial impact of silane treatment on the impact strength, impact resistance, and flexural modulus of the layered composites under examination. Fei et al. (2024) made a vitrimer matrix from hempseed oil and limonene derivatives for hemp fiber composites. Both materials exhibited higher glass transition temperatures ranging from 79.9°C to 90.8°C, similar elastic moduli exceeding 3400 MPa, and lower water absorption rates decreasing from 49% to 38%. The penetration of silanes into substrates is influenced by several factors, including temperature, pH, hydrolysis duration, and silane functionality. The actions of silanes can be divided into four stages: (a) Hydrolysis involves the initial breakdown of silane monomers in the presence of water and a catalyst, resulting in alcohol formation and the creation of reactive silanol groups, (b) Self-condensation occurs, where silanols limit condensation to maintain availability for adsorption onto natural fiber hydroxyl groups, (c) Adsorption entails the physical attachment of reactive silanol monomers or oligomers onto fiber surfaces through hydrogen bonds, either as surface coatings or within cell walls, leading to cell wall swelling. Concurrently, free silanols

polymerize to form a stable polysiloxane structure with Si-O-Si bonds, (d) Grafting occurs at elevated temperatures, promoting the transformation of hydrogen bonds between silanols and fiber hydroxyl groups into robust -Si-OC- chains, liberating water via condensation. At very high temperatures, a covalent bond forms between silanols and fiber hydroxyl groups with concurrent water evaporation.

Acetylation treatment

Acetylation of natural fibers is a widely recognized esterification process that involves the formation of ester bonds between fibrils and acetylation reagents. This process results in the plasticization of cellulosic fibers and a reduction in the hydrophilic nature of natural fiber. It enhances the dimensional stability of composites and improves the interfacial bonding between fibers and the matrix, leading to increased thermal stability. The primary purpose of acetylation treatment in natural fiber surface modification is to improve the fibers' compatibility with polymer matrices and enhance their overall properties. Acetylation is a method where acetyl groups are introduced to the hydroxyl groups found on natural fiber surfaces. This process specifically targets fiber hydroxyl groups by substituting them with acyl groups, thereby reducing the fiber's ability to absorb moisture. Acyl groups can be incorporated onto fiber surfaces through acetylation using acetate or valorization with valerate. Various acetates, such as acetic anhydride, acetic acid, and acetyl chloride, are effective agents for facilitating the acetylation process. Typically, treatment involves first soaking in acetic acid followed by exposure to acetic anhydride. Additionally, acetylation contributes to the stabilizing of the internal structure of the material. By reducing internal stresses and locking the structure in a more stable configuration, the material becomes less prone to changes in dimensions under thermal or mechanical stress. This stabilization contributes to the overall dimensional stability of the composite material.

The acetylation process involves key reagents like acetic anhydride and a catalyst, such as pyridine, which are crucial for modifying surfaces by reducing water affinity, enhancing dimensional stability, increasing durability, and improving compatibility with polymer matrices. Acetic anhydride is the main reagent, acting as the acetylating agent by donating acetyl groups to the hydroxyl groups on the surface of natural fibers. This reaction forms ester linkages and releases acetic acid as a byproduct. By replacing hydrophilic hydroxyl groups with hydrophobic acetyl groups, acetic anhydride significantly lowers the material's water absorption, thus boosting its dimensional stability. Catalysts like pyridine are used to speed up the reaction between acetic anhydride and hydroxyl groups. Pyridine, in particular, acts as a nucleophilic catalyst, creating a more reactive acyl-pyridinium intermediate, and helps neutralize the acetic acid byproduct to prevent it from reversing the acetylation or causing material degradation. In some cases, solvents like acetone or toluene are employed to dissolve the reagents and ensure better contact with the material's surface, although this depends on the specific conditions of the process. Acetylated fiber-reinforced composites exhibit decreased water absorption, enhanced mechanical properties, increased thermal stability, and improved adhesion between fibers and matrix. The process generates acetic acid as a byproduct, which can be removed through washing with water. However, a significant downside of this approach is its higher cost and the relatively toxic nature of the reagents used. Table 4 shows some of the experimental research conducted using acetylation treatment of the NFRCs in recent years.

Benzoylation treatment

Benzoyl chloride, or benzoic anhydride, is a highly effective method for enhancing the thermal stability of fibers, improving fiber-matrix adhesion, increasing composite strength, reducing water absorption, and imparting hydrophobic properties. This process involves benzoylation treatment using benzoyl compounds (Matykiewicz et al. 2021; Pradhan, Prakash, and Acharya 2022; Ramkumar et al. 2022; Sahu et al. 2023; Verma, Goh, and Vimal 2022). This approach involves alkali pretreatment to remove extractable materials other than cellulose and expose more reactive hydroxyl groups on the fiber surface. Subsequently, fibers undergo benzoylation, where benzoyl groups are introduced. Benzoyl chloride treatment enhances the hydrophobicity of the fibers by replacing hydroxyl groups with benzoyl groups. Removing extractable

Table 4. Previous experimental research studies on acetylation treatments on the NFRCs prosperities.

Composite	Results	Ref.
Corn straw/ Epoxy resin	XPS and SEM analyses confirmed the successful bonding of maleic anhydride to corn straw. The acetylated corn straw composite displayed superior impact and flexural resistance compared to the unmodified composite, particularly noticeable with a 15 wt% corn straw addition.	Jiang et al. (2023)
Corn starch/ Thermoplastic	The chemical modification of raw materials resulted in solubility levels ranging from 24.9% to 28.2%, demonstrating a decrease compared to the water solubility reported for biocomposites based on native starch.	Fitch-Vargas et al. (2023)
Coir Fiber/ Epoxy resin	The tensile strength notably rose in coir fibers treated with alkali and acetic anhydride. Among these treatments, long coir fibers treated with acetic anhydride exhibited the highest flexural strength, achieving 54.38 MPa in composites, closely followed by short coir fibers treated with acetic anhydride, which reached 53.46 MPa.	Ru et al. (2023)
Flax and Hemp/ Polylactic Acid	Alkali and acetylation treatments eliminated π–π interactions in flax samples. Furthermore, films exhibited a more textured appearance in composites with larger filler particles (149–210 μm), irrespective of the treatment.	Pokharel et al. (2024)
Natural Moso Bamboo powder	The surface micromorphology revealed that pre-treated biocomposites were less prone to cracks and holes. A denser structure is correlated with fewer cracks and holes, leading to improved mechanical properties and water resistance.	Zheng et al. (2023)
Furcraea Foetida/ Epoxy resin	Chemical treatment removes O-H groups, enhancing fiber hydrophobicity and crystallinity. Thermal stability remains unchanged, but microscopic analysis shows a uniform surface structure devoid of organic attachments.	Madival et al. (2023)
Jute fiber/ Vanillin epoxy	The biobased composite has strong mechanical properties with high tensile strength (≈83.12 MPa), Young's modulus (≈2.86 GPa), flexural strength (138.72 MPa), and modulus (8.01 GPa). It is hydrophobic, durable, and chemically resistant to acids.	Kumar, Adil, and Kim (2023)

components like oils, lignin, and waxes reveals additional reactive hydroxyl groups on the fiber surface, which are then modified with benzoyl groups. Benzoylation roughens the fiber surface, promoting fibrillation and improving adhesion to the polymer matrix, significantly increasing hydrophobicity and matrix compatibility. Benzoylation also enhances affinity with aromatic polymer matrices through electron interactions between the benzoyl group and the aromatic rings of the polymer lattice. The benzoyl group contains a benzene ring, which is nonpolar and does not interact favorably with water molecules. This nonpolar characteristic creates a hydrophobic surface on the fibers. Benzoylation treatment of natural fibers offers significant advantages, including enhanced water resistance, improved mechanical strength, increased durability, and better aesthetic qualities. However, it also presents drawbacks such as environmental and health risks, higher processing costs, possible fiber damage, and limited application scope. A careful evaluation of these factors is essential when considering benzoylation for natural fiber treatment.

Benzoyl chloride is extremely toxic and corrosive, posing major health risks like severe irritation and damage to the skin, eyes, and respiratory system upon exposure. Its reaction with natural fibers produces hydrochloric acid, which is also corrosive and can damage the environment if not correctly handled. The byproducts, including any unreacted benzoyl chloride and hydrochloric acid, need to be managed as hazardous waste. Proper handling, neutralization, and disposal of these substances are essential to preventing environmental pollution. Sheeba et al. (Sheeba et al. 2023) investigated the effect of benzoyl chloride treatment on Acacia Pennata natural fiber composites in construction applications to improve mechanical and thermal characterization. The fiber underwent treatment with NaOH and benzoyl chloride solutions, enhancing the surface area and bonding with structural materials, thus improving the mechanical properties of the resulting composites. These properties, including tensile strength, thermal stability, modulus, microfibrillar angle, and elongation at break, are notably affected by benzoyl chloride concentration, fiber loading, and immersion time. XRD and SEM analyses indicate increased crystallinity and larger crystalline size in treated fibers, resulting in smoother surfaces. Thamarai et al. (Thamarai Selvi et al. 2023) studied the effect of benzoylation treatment on Gave Americana fiber composites. Agave americana fibers were initially treated with an alkaline solution to activate hydroxyl groups. Then, they were immersed in a 10% NaOH and benzoyl

chloride solution for 15 minutes, followed by ethanol soaking to remove benzoyl chloride traces. Chemical treatments reduced cellulose content (3.49% with benzoylation) and lignin (13.46% with alkalization), as well as moisture content (11.61%). Benzoylation notably improved the fiber's strength (12.16 Nmm). Thermal stability was highest with benzoylation, and surface morphology showed modification with all treatments.

Peroxide treatment

Researchers have shown keen interest in peroxide treatment for enhancing adhesion in cellulose fiber-reinforced thermoplastic composites, improving processing efficiency, boosting mechanical properties, and increasing the hydrophobicity of natural fibers. In organic chemistry, peroxides are defined by the ROOR functional group, which contains the O-O divalent ion. Organic peroxides readily decompose into RO free radicals, which react with hydrogen groups in both the matrix and cellulose fibers. Unlike oxide ions, oxygen atoms in peroxide ions have an oxidation state that makes them suitable for applications such as benzoyl peroxide and dicumyl peroxide, commonly used in modifying natural fiber surfaces. Due to their reactive nature, organic peroxides readily decompose at elevated temperatures, necessitating controlled processing conditions. The concentration of peroxide significantly impacts the reaction's effectiveness. Both benzoyl peroxide and dicumyl peroxide exhibit high reactivity and tend to degrade into free radicals of the form RO when exposed to specific conditions. Subsequently, these radicals can graft onto the cellulose macromolecule polymer chain by interacting with the hydrogen groups present in the natural fiber and polymer matrix. Consequently, robust adhesion between the natural fiber and polymer matrix is achieved along the interface region of the composite, leading to enhanced water-repellence characteristics. However, several limitations accompany this approach. For instance, natural fiber-reinforced composites coated with benzoyl peroxide, obtained from an acetone solution following alkali pre-treatments, may experience extensive damage to natural fibers due to the preferred high temperatures required for peroxide decomposition. Furthermore, peroxide-treated fiber composites exhibit limited resistance against UV deterioration, posing an additional challenge. Exposure to ultraviolet light can cause photo-oxidation in the polymer matrix. This process occurs when UV radiation is absorbed, creating free radicals within the polymer. These free radicals can break down the polymer chains, resulting in a decline in mechanical properties like tensile strength and elasticity. UV light can also cause chain scission, which breaks the polymer chains and lowers their molecular weight. This leads to the polymer becoming brittle and the composite losing its flexibility. Table 5 shows some of the experimental research conducted using peroxide treatment of the NFRCs in recent years.

Permanganate treatment

Permanganate treatment of natural fibers aims to enhance the bonding between the natural fiber and the polymer matrix. This treatment involves the interaction of potassium permanganate with cellulose hydroxyl groups and lignin components of the natural fiber, leading to improved adhesion and mechanical characteristics, as well as increased resistance to water absorption. Permanganate treatment employs potassium permanganate as an oxidizing agent to alter the surface of natural fibers such as cellulose. This oxidation introduces hydroxyl, carbonyl, and carboxyl groups, enhancing the fiber's surface properties. The process increases surface roughness, providing more physical anchoring points for the polymer matrix, which improves mechanical interlocking and adhesion of the composite materials through special mechanism. This primarily occurs due to the etching effect of the oxidizing agent on the fiber surface. The oxidative action of $KMnO_4$ partially degrades the fiber surface, resulting in a rougher texture. This etching process removes some of the amorphous regions of the fibers, creating a more pronounced surface topography. The rougher fiber surface improves mechanical interlocking with the polymer matrix. The increased surface area provides more sites for mechanical interconnections, thereby enhancing the load transfer from the matrix to the fibers under mechanical stress. In addition, the new functional groups on the fiber surface can react with the polymer matrix, forming covalent bonds or strong secondary interactions like hydrogen bonds, thereby strengthening

Table 5. Previous experimental research studies peroxide treatments on the NFRCs prosperities.

Composite	Results	Ref.
Grewia Optiva/Epoxy resin	Chemical treatment alters the degradation rate, enhances fiber-matrix bonding. BP treatment more effective than NaOH, improving surface roughness for better bonding.	Chauhan and Gope (2024)
Banana fiber/ Polypropylene	FTIR analysis revealed bond formations between dyed fibers and polypropylene matrix in composites, with slight improvements in tensile strength and modulus. Mechanical behavior was significantly enhanced compared to untreated and dye-treated fibers.	Brahma et al. (2024)
Windmill Palm fiber	The hydrogen peroxide treatment removed most lignin and hemicellulose, leaving 10.07% ± 0.83% residue. This lower lignin content exposes more active functional groups on the fiber surface, aiding in composite material formation.	Chen, Xu, and Wang (2024)
Calotropis gigantea/ PVA/PVP	The fibers exhibit a high crystallinity index of 45.01%, likely attributed to the elimination of impurities such as hemicellulose, wax, pectin, lignin, and ferulic acid during the treatment process.	Handayani et al. (2024)
Pineapple Leaf Fiber	Alkalization and bleaching treatments removed lignin and hemicellulose to different extents. Additionally, the extracted microcellulose demonstrates high thermal stability, with maximum decomposition occurring at 347°C (weight residue 16.37%).	Nawangsari et al. (2024)
Flax, Cotton /Epoxy	A two-stage surface modification of fibers leads to the production of composites with improved interfacial adhesion and enhanced mechanical properties compared to materials made with unmodified fabrics.	Barczewski, Matykiewicz, and Szostak (2020)
Snake Grass fiber/ Polyester	Treatment improved adhesion, reduced fiber pullout, and minimized debonding.	Jenish et al. (2021)
Flax linseed straw	70% cellulose yield was extracted from linseed straw fiber using 75% ethanol-toluene, 6% NaOH, and 6% H_2O_2 at specified temperatures and durations.	Feleke et al. (2023)
Palm fiber/Polyethylene	The findings reveal that the reinforced interfacial adhesion between the fibers and the matrix enhances the rigidity and uniformity of treated composites, indicating a homogeneous distribution of fibers.	Debabeche et al. (2023)
Bamboo fiber and Banana stems/ Polyester	It enhanced the fiber's mechanical properties more than alkali treatment, achieving a strength of 37.33 MPa and an elastic modulus of 5 GPa.	Suhada et al. (2023)

interfacial bonding. Moreover, the hydrophilic functional groups enhance the wettability of the fibers, facilitating better penetration and spread of the polymer matrix over the fiber surface. This expanded contact area leads to improved adhesion between the fibers and the polymer matrix.

Kudva et al. (Kudva, Gt, and Pai 2024) experimentally examined the effect of chemical treatments on the tensile strength, morphological characteristics, and degree of crystallinity of bamboo fiber reinforcement polymer composites. This study utilized sodium hydroxide, ammonium hydroxide, and potassium permanganate to modify bamboo fiber structure. Treatment with 5% sodium hydroxide, 1% ammonium hydroxide, and 0.5% potassium permanganate was found optimal based on achieved tensile strengths. Alkali-treated and Potassium Permanganate-treated fibers exhibited superior tensile strength compared to untreated fibers. The potassium permanganate treatment effectively removed impurities and contaminants, resulting in a cleaner, smoother appearance with slightly detached fibrils. Abisha et al. (Abisha et al. 2023) examined the effects of potassium permanganate treatment on the Butea parviflora fiber and analyzed its physical and chemical properties. Treated fibers show significant improvements in tensile strength (92 to 198 MPa) and Young's modulus (2.16 to 4.40 GPa). Tg-DTA thermograms indicate thermal resistance up to 240°C, with kinetic activation energy between 62.80 and 63.46 KJ/mol. SEM images show effective surface roughness for composite production, while FTIR studies reveal vibrational changes in cellulosic functional groups, correlating with increased cellulosic behavior. However, there are specific challenges associated with this technique. For instance, degradation of cellulosic NFRC can occur at concentrations exceeding 1% $KMnO_4$, resulting in the formation of polar groups between NFRC and the matrix. Additionally, treated fiber composites are susceptible to UV degradation. The process of permanganate treatment initiates radical sites in the cellulose of natural fibers, enhancing their reactivity with the polymer matrix.

Typically, this treatment involves immersing the fibers in a potassium permanganate solution in acetone at various concentrations for 1–3 minutes after alkaline pretreatment. As the $KMnO_4$ concentration increases, the hydrophilic nature of the fibers decreases, leading to reduced water absorption in the composite. However, concentrations exceeding 1% $KMnO_4$ can induce fiber degradation. The interaction between permanganate ions and cellulose hydroxyl groups results in the formation of cellulose-manganate, facilitating graft copolymerization and enhancing chemical interlinking at the fiber interface. Kulandaiyappan et al. (Kulandaiyappan et al. 2023) studied a developed palm leaf stalk, nanococonut shell powder, and polyester resin nanocomposite. Fibers treated with 5% potassium permanganate for 1 hour showed increased tensile strength in nanocomposites. The treatment cleared impurities, enhancing surface roughness for better mechanical bonding with the matrix. Additionally, it improved average impact strength due to uniform resin/filler system dispersion. Acharya et al. (Acharya, Pai, and Mahesha 2023) investigated the effect of chemical surface treatments on the physical and mechanical properties of the Helicteres isora fiber. Three chemicals-5% sodium hydroxide, 0.5% potassium permanganate, and 5% hydrogen peroxide-were used for fiber treatments. PP-treated fibers showed the best physical properties and the lowest water absorption. PP treatment enhanced fiber hydrophobicity by removing surface hydroxyl groups, as observed in FTIR spectra. This process contributes to higher thermal stability, increased mechanical properties, and reduced water absorption of the fibers. Overall, while permanganate treatment offers significant benefits in improving the properties of natural fiber composites, careful control of $KMnO_4$ concentration is necessary to avoid fiber degradation and ensure optimal performance. Additionally, further research is needed to address the susceptibility of treated fibers to UV degradation and to develop more environmentally friendly treatment methods. Experimental studies on fibers treated with potassium permanganate have shown that this method greatly enhances the bonding between natural fibers and polymer matrices. The oxidation process introduces functional groups and increases surface roughness, which improves mechanical properties like tensile strength, modulus, and impact resistance (Caren, Kenneth, and David 2022; Knežević et al. 2022; Milanovic et al. 2022; Palai and Sarangi 2022; Premalatha et al. 2021; Shenoy Heckadka et al. 2022). This treatment also enhances the wettability of the fibers, allowing for better penetration and adhesion of the polymer matrix. Moreover, treated fibers exhibit increased thermal stability, durability, and reduced water absorption, resulting in enhanced performance and longevity of the composite materials.

Maleated coupling agents

A coupling agent serves as an intermediary between the fiber's hydroxyl group and the polymer's hydrogen bond, featuring two reactive groups: one for cellulose -OH groups and another for matrix molecules. Maleic anhydride stands out from other chemical treatments by not only altering the fiber surface but also the PP matrix, aiming for enhanced interfacial bonding and mechanical properties in composites. Maleic anhydride grafted polypropylene, poly diphenylmethane diisocyanate, and polyethylene are frequently employed to bolster mechanical characteristics by improving interfacial bonding, thereby increasing resistance to water absorption. Commonly used coupling agents include isocyanates (Arasu et al. 2021), silanes (Yang et al. 2023), and modified copolymer-anhydrides, such as PP grafted with maleic anhydride (Gorgun, Ali, and Islam 2024) and acetic anhydride. The interaction of maleic anhydride groups with hydroxyl groups on fibers creates covalent ester bonds, significantly enhancing the adhesion between fibers and the polymer matrix. This strong chemical bonding at the interface improves load transfer from the matrix to the fibers, thereby increasing the composite's tensile strength and modulus. Furthermore, improved interfacial adhesion helps distribute stress more evenly across the composite, enhancing its impact resistance.

Maleic anhydride engages with cellulose or other fiber constituents in this treatment procedure, subsequently bonding with base polymers. This interaction leads to the removal of hydroxyl groups from the fiber cells due to the reaction between maleic anhydride groups and fiber hydroxyl groups. Furthermore, the maleated coupler facilitates the formation of a robust C – C connection between the polymer chain and the matrix, promoting strong adhesion. This adhesion is achieved through the

formation of covalent bonds at the interface between plant fibers and the coupling agent, as well as molecular entanglement between the coupling agent and the polymer matrix. Activation of the copolymer through heating and subsequent esterification of the fiber precedes the reaction of the coupling agent with the fiber and polymer matrix. This treatment increases the surface energy of cellulose fibers, improving wettability and interfacial adhesion. However, drawbacks include enhanced fiber – resin adhesion at the interface, potentially leading to fiber disintegration, and inadequate resistance to UV deterioration in maleated coupling-treated fiber composites. Maleic anhydride is highly reactive and can sometimes be excessively aggressive, potentially causing the degradation or disintegration of natural fibers, particularly if the treatment conditions (such as temperature, concentration, and duration) are not carefully managed. The ester bonds formed by maleated coupling agents are vulnerable to photo-degradation under UV light, which can break these chemical bonds and weaken the fiber-matrix interface. This UV-induced degradation may result in a gradual loss of the improved mechanical properties as the interfacial adhesion provided by the maleated coupling agents deteriorates. Furthermore, extended UV exposure can lead to discoloration or yellowing of the composite materials, which might be undesirable for applications where aesthetic properties are crucial. Baig et al. (Baig et al. 2024) examined the effects of maleic anhydride grafted polypropylene and the addition of UV stabilizers on the degradation of the mechanical properties of polypropylene/wood composites produced via injection molding. The experimental results showed that composites with 1 wt% maleic anhydride polypropylene exhibited better resistance to degradation compared to those with 3 wt% and 5 wt% maleic anhydride polypropylenes. UV stabilizers absorb UV rays more quickly than the polypropylene matrix, and their resistance to disintegration is generally much higher than that of the polypropylene matrix. Consequently, the presence of UV stabilizers helps extend the lifespan of the polypropylene polymer. Table 6 shows some of the experimental research conducted using maleated coupling agent treatment of the NFRCs in recent years.

Acrylation and acrylonitrile grafting

Acrylic acid serves as a means of modifying fiber surfaces to enhance bonding with the lattice. This process is initiated by the free radicals present in cellulose molecules, which can be generated through exposure to high-energy radiation, leading to chain scission. Free radicals are essential for starting the grafting process. They are usually produced by the thermal breakdown of initiators, such as benzoyl peroxide, or through irradiation techniques. These free radicals generate reactive sites on the fiber surface, which then interact with acrylate or acrylonitrile monomers to form covalent bonds, leading to the creation of grafted polymer chains. Acrylic acid interacts with the hydroxyl functional groups of fibers, facilitating the access of reactive cellulose macro-radicals to the polymerization medium during acrylation and acrylonitrile grafting (Vilay et al. 2008). During acrylation, ester bonds form between the hydroxyl groups of the cellulose in natural fibers and the acrylate monomers. These ester bonds are stable and create strong covalent connections between the fiber and the grafted polymer. The formation of ester linkages between carboxylic acids and cellulose hydroxyl groups reduces the number of hydroxyl groups in the fiber structure. Grafting with acrylic acid is initiated by peroxide radicals, enhancing the coupling between the fiber and lattice, thereby improving stress propagation under thermal and mechanical loads and reducing the fiber's hydrophilic nature, while increasing tensile and flexural strength (Iskandar et al. 2024). Grafting with acrylonitrile and subsequent polymerization results in significant alterations to the fiber surface, improving interlocking efficiency at the interface, reducing water absorption, and enhancing mechanical properties.

This technique has several benefits for the mechanical and chemical properties of natural fibers. Acrylation and acrylonitrile grafting can greatly improve the tensile strength, modulus, thermal stability of natural fibers (Sahoo et al. 2021). The creation of ester bonds and the grafting of acrylonitrile onto the fiber surface enhance the interfacial adhesion between the fibers and the matrix, leading to better load transfer. Additionally, acrylonitrile grafting can increase the toughness of natural fibers by making the surface more flexible and ductile, which aids in energy absorption during mechanical stress. Both acrylation and acrylonitrile grafting also boost the hydrophobicity of natural

Table 6. Previous experimental research studies maleated coupling agent treatments on the NFRCs prosperities.

Composite	Results	Ref.
Sugarcane Bagasse/ polyethylene	Adding 3 wt.% maleic anhydride to the sugarcane bagasse/LDPE composites raised their decomposition temperature, suggesting enhanced thermal stability due to the coupling agent.	Saber, Abdelnaby, and Abdelhaleim (2023)
Hemp strands/ Polypropylene	Unnotched polypropylene composites showed peak absorbed energy with 20–30 wt% HS and 8 wt% coupling agents, while notched samples performed best with 40 wt% HS and 4 wt% coupling agents.	Vallejos et al. (2023)
Kenaf fiber/ Polypropylene	The composite with the coupling agent has a higher tensile strength (29.3 MPa) and lower water absorption (1.05%) compared to the composite without the coupling agent (22.4 MPa and 1.31%, respectively).	Zaki et al. (2024)
Wood fiber/ Polypropylene	Analysis revealed nanolignin changes post-maleic anhydride modification, reducing its glass transition temperature to 100°C and improving nanolignin dispersion in the polymer matrix. Increasing maleated nanolignin content from 1 to 5 wt% enhanced composite properties, improving dimensional stability and mechanical strength compared unmodified nanolignin.	Younesi-Kordkheili (2023)
Jute fiber/ Polylactic Acid	Adding Fusabond as an interfacial modifier in jute fiber-reinforced polylactic acid composites enhance storage modulus and toughness by reducing the tan δ peak, and improving interfacial compatibility between the jute fiber and polylactic acid matrix.	Saeed et al. (2023)
Coconut fiber/ Thermoplastic Polyurethane (TPU)	Adding 5% RTPU enhances the adhesion between long coconut fiber and PP due to increased interfacial shear strength from chemical/ physical interactions. The impact resistance ranges from 19.8 to 24.4 J/m for PP with short coconut fibers and 39.9 to 71.7 J/m for PP with long coconut fibers.	Guillén-Mallette, Valadez-González, and Rosado-Sánchez (2023)
Agave fiber/ Polylactic acid	Initially, biodegradation may be slower with fibers, but long-term rates resemble those of neat PLA. Adding AF to PLA-based biocomposites has the potential to reduce environmental impact during production and disposal while maintaining mechanical properties.	Pérez-Fonseca et al. (2024)
Wood fibres/ Polylactic acid	Structural analysis verified the elimination of lignin and hemicellulose from the fibers. With the reinforcement and the coupling agent, the tensile and flexural moduli surged by up to 140% and 137%, respectively. In raw fiber-reinforced composites, tensile and flexural strengths each rose by 12%.	Cosse et al. (2023)
Flax fibers/ Epoxy	FTIR and SEM analyses showed isocyanate reacting with flax fibers, forming a thin polymer layer. Isocyanate treatment reduced water absorption by 4 to 18 times. FFRP strength increased by over 20% due to improved fiber-epoxy adhesion with isocyanate-treated fabrics.	Wang et al. (2020)
Cattail fiber/ Unsaturated Polyester	FTIR confirmed covalent bonds on the treated fibers. Using 10% 1,6-diisocyanatohexane and 2-hydroxyethyl acrylate significantly improved fiber properties, including reduced diameter, increased modulus and strength, lower moisture regain, and enhanced fiber-matrix bonding seen in SEM.	Shadhin et al. (2024)
Kenaf fiber/ Styrene Acrylonitrile	KNF/CF-SAN composites exhibit higher mechanical properties than CF-SAN alone. Water absorption improves properties compared to the dry matrix but reduces strength and modulus compared to dry composites. SEM and FTIR confirm improved adhesion and bonding in the composites. Thermal stability remains up to 295°C.	Tamta and Palsule (2024)

fibers, reducing moisture absorption and helping to maintain the fibers' mechanical properties and dimensional stability in humid conditions. These chemical modifications also enhance the compatibility of natural fibers with various polymer matrices, resulting in better dispersion and stronger fiber-matrix interactions, which are essential for composite materials. Despite its potential benefits, challenges arise in utilizing acrylation treatment, including variations in results among researchers. However, acrylic acid-treated fiber composites exhibit low resistance to UV degradation, which is a notable drawback (Azwa et al. 2013). In addition, the grafting process can be intricate, necessitating exact control over reaction conditions like temperature, initiator concentration, and reaction time. The chemicals involved in acrylation and acrylonitrile grafting can be costly, potentially raising the overall expense of the modified fibers. Additionally, some of the chemicals and solvents used in these

Table 7. The effect of chemical treatments on tensile and modulus of elasticity of natural fiber reinforced composites.

Composite	Treatment	Temperature (°C)	Time	Tensile strength (MPa)	Modulus strength (MPa)	Ref.
Cotton/Bamboo/Epoxy	1-3% NaOH solution	24	30 min	100	—–	(Karthik et al. 2023)
Chrysanthemum Fibre/ Unsaturated Polyester	Hydrogen peroxide	24	–	20	4900	(M. Islam et al. 2021)
Flax Fibre/Polypropylene	Acetylation	60	1-3 h	47	4500	(Bledzki et al. 2008)
Bamboo/Polyurethane	10% NaOH solution	24	48 h	510	27707	(Sánchez, Patino, and Cardenas 2020)
Bamboo/Green Polymeric Epoxy	5% NaOH solution	65 °C	1 h	180	1222	(Costa et al. 2017)
Cow Hair Fibre/Unsaturated Polyester	5% NaOH solution	60	2 h	32	1150	(Ali et al. 2024)
Date Palm Fibre, Sheep Wool/ Polyester	5% NaOH solution	24	2 h	19.6	3320	(Abdellah et al. 2024)
Jute, Hemp Fibers/Unsaturated Polyester	3, 5% NaOH solution	24	1 h	26.6	733.56	(M. Z. Islam, Sabir, and Syduzzaman 2024)
Jute/Kenaf/Glass Fibers/Epoxy resins	15% Silane	24	30 min	270	—-	(Jothi Arunachalam et al. 2024)

Note: all tensile and modulus values increased after treatment, for example in Ref. 180, the tensile strength has been increased by 32.13% compared to the untreated composite.

modification processes can be hazardous, requiring careful handling and disposal, which poses environmental and safety concerns. To address these challenges, several strategies have been identified. Firstly, integrating UV stabilizers or absorbers into either the fiber surface or the matrix can effectively reduce UV degradation. These additives absorb harmful UV rays and convert them into harmless heat energy, thereby safeguarding the fibers. Secondly, applying protective coatings containing UV-resistant materials can shield the fibers from direct exposure to UV radiation. Thirdly, incorporating antioxidants can aid in preventing the oxidation of the fiber surface, which is typically accelerated by UV exposure. Wu et al. (Wu and Tsou 2019) fabricated biocomposites based from biodegradable PLA as base polymer and rice husk as a natural filler by extrusion process. They used acrylic acid in order to enhance the mechanical and thermal properties of the biocomposites. The results show that treatment with acrylic acid improved adhesion between natural fiber with polymer. In addition, the PLA grafted-acrylic acid/treated rice husk composites showed improved thermal stability and greater resistance to moisture. The degradation temperature was found to be 4–7°C higher compared to poly lactic acid/rice husk composites. Suheyla et al. (Kocaman and Ahmetli 2020) investigated the effects of some surface treatments, including, alkali, acrylic acid, and acetic anhydride on the Hazelnut shell waste biobased composites. The findings indicated that fiber composites treated with 20 wt% acrylic acid exhibited a tensile strength of 65 MPa, which was notably higher than that of untreated composites. Additionally, these treated composites demonstrated significant thermal properties, with maximum degradation temperatures reaching up to 510°C, indicating they are more thermally stable compared to alkaline-treated and untreated composites. Nikafshar et al. (Nikafshar and Nejad 2022) studied the effectiveness of various UV stabilizers in protecting softwood organosolv lignin from UV-induced degradation. During the experiment, the photodegradation of softwood organosolv lignin was monitored over 35 days under UV exposure conditions. Eighteen different additives were mixed with the lignin and subjected to UV irradiation. Analysis using FTIR before and after UV exposure revealed that inorganic UV absorbers a combination of organic UV absorbers and the Hindered amine light stabilizers were the most effective additives in minimizing lignin degradation.

The effect of surface treatments of natural fiber on tensile and thermal properties

Tensile characterization plays a crucial role in material science, especially when evaluating the mechanical properties of natural fibers. It is essential for understanding how these fibers respond to different stresses and conditions, which directly influences their potential for use in structural applications. Tensile strength measures the force needed to break a fiber when stretched, revealing its load-bearing capacity. Fibers with high tensile strength can endure significant stress without breaking, making them ideal for applications where durability and reliability are critical. Elasticity refers to a fiber's ability to return to its original shape after being stretched. The modulus of elasticity, or Young's modulus, measures the stiffness of a fiber. A higher modulus indicates a stiffer fiber, which is advantageous in applications requiring rigidity and shape retention. The performance of natural fibers in composite materials largely depends on their compatibility with polymer matrices. Tensile characterization is used to assess how well different treatments – such as chemical, physical, or biological processes – improve the bonding between fibers and matrices. Better interfacial bonding enhances stress transfer and overall composite strength. Table 7 illustrates the effect of chemical treatments on tensile and modulus of elasticity of natural fiber reinforced composites.

Several factors directly affect the tensile properties of natural fibers, including their composition, microfibrillar angle, and, most importantly, fiber treatment. These treatments are vital for optimizing tensile properties, making fibers more suitable for various structural applications. Figure 12 shows the effect of chemical treatments on some natural fibers. By modifying surface chemistry, removing impurities, improving fiber-matrix adhesion, and altering fiber structure, treatments help natural fibers achieve better mechanical performance. Understanding the specific effects of each treatment is key to selecting the right methods to tailor fibers for particular applications, thereby promoting the use of sustainable and renewable materials in advanced composite technologies. Figure 10. Shows the effect of chemical treatment on the physical and mechanical properties of bamboo fibers as potential reinforcement for polymer composites (Kudva, Gt, and Pai 2024).

Madhu et al. (Madhu et al. 2020) investigated the effect of various chemical treatments, including NaOH, stearic acid, benzoyl peroxide and potassium permanganate on Agave Americana fiber for composite reinforcement. They reported that chemical analysis shows that various chemical treatments significantly reduce amorphous contents such as hemicellulose, lignin, and other impurities, making the fibers less resistant to water. FT-IR analysis confirms the removal of these amorphous contents. TGA and DSC indicate improved thermal behavior in chemically treated fibers. The tensile test demonstrates major improvements in tensile strength and elongation at break for all treated fibers, though this comes with a decrease in Young's modulus due to variations in fiber dimensions after treatment. SEM measurements reveal significant details about the hydrophilic nature of raw fibers linked to different chemical treatments. Jing et al. (Jing et al. 2023) examined how alkali treatment affects the microstructural changes and mechanical properties of palm fiber cell walls. They reported that imaging technologies provided detailed insights into the fiber's cellular structure. The tensile strength of palm fiber was significantly enhanced following alkali treatment, which also induced microstructural changes in the fiber's cell walls. Furthermore, the treatment led to the removal of hemicellulose and lignin, contributing to increased crystallinity. Figure 11. Illustrates the results of this paper.

Analyzing the thermal properties of natural fiber-reinforced composites that have undergone surface treatments involves several techniques. These methods, including Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), Thermal Conductivity Measurement, Dynamic Mechanical Analysis (DMA), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR), help evaluate the effects of surface treatments on the composites' thermal stability, conductivity, and other behaviors. Figure 13. Illustrates the effect of FTIR spectra of some natural fibers before and after chemical treatment. TGA measures the change in mass of a composite as it is heated, providing insights into thermal stability and decomposition. Surface-treated composites are expected to show a higher onset temperature for degradation and reduced weight loss compared to

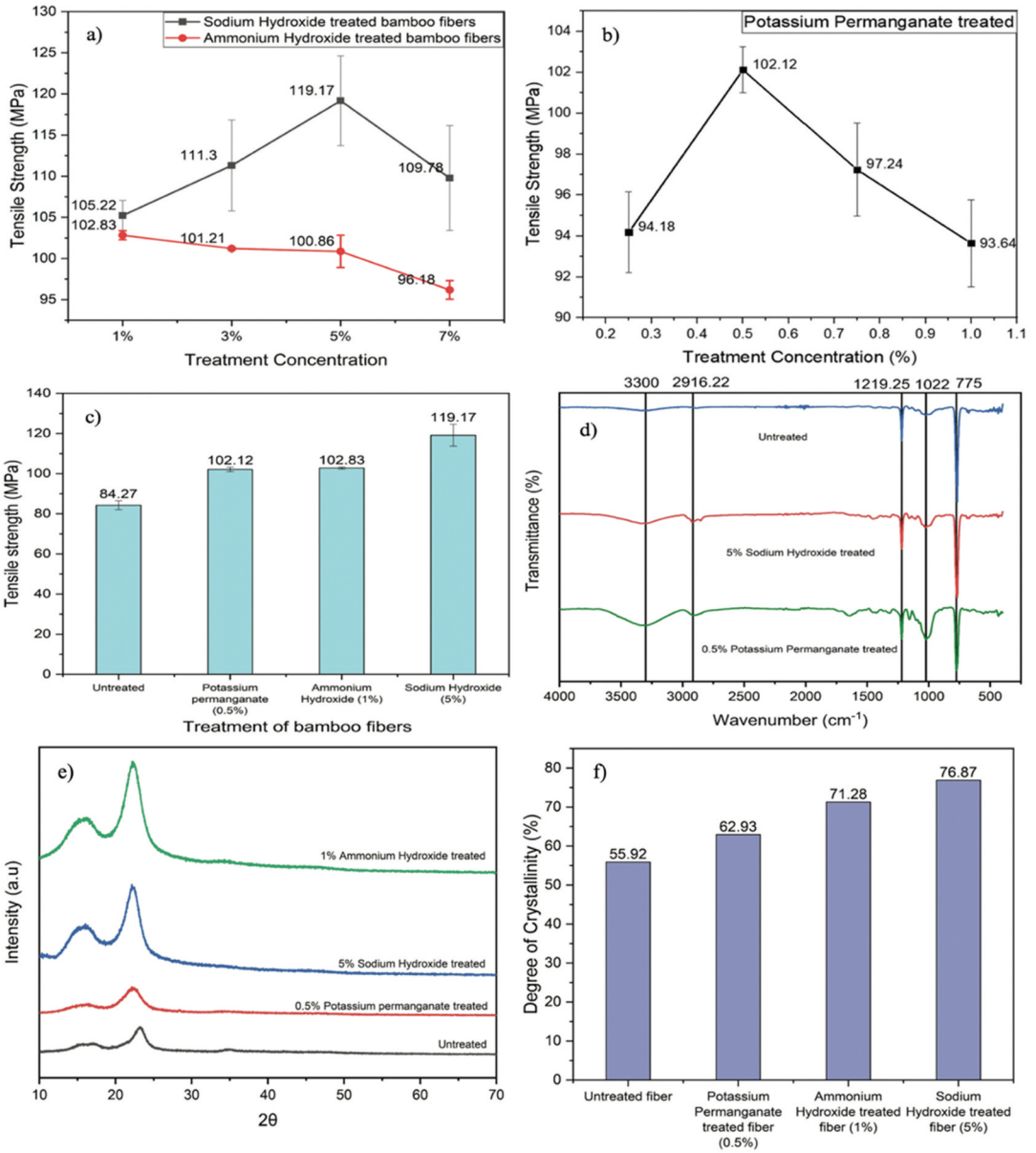

Figure 10. Effect of 3 different chemical treatments on mechanical and physical properties of bamboo fiber, a) tensile strength of sodium hydroxide treated and ammonium hydroxide treated bamboo fibers, b) tensile strength of potassium permanganate treated bamboo fibers, c) comparison of tensile strength of treated and untreated bamboo fibers, d) FTIR spectrum of treated and untreated bamboo fibers, e) XRD spectrum of treated and untreated bamboo fibers, f) degree of crystallinity of treated and untreated bamboo fibers (Kudva, Gt, and Pai 2024).

untreated ones, indicating improved stability. The TGA curve for treated composites may display a delayed onset of weight loss and a more gradual weight loss profile, suggesting enhanced thermal stability. DSC measures heat flow related to transitions in the composite material, such as glass transition, melting, and crystallization. Surface-treated composites might show shifts in the glass transition temperature (Tg), melting temperature (Tm), or crystallization temperature (Tc), reflecting changes in the polymer matrix or fiber-matrix interactions. After treatment, DSC curves may indicate increased Tg and Tm, sharper peaks, and shifts in crystallization temperature, which suggest better

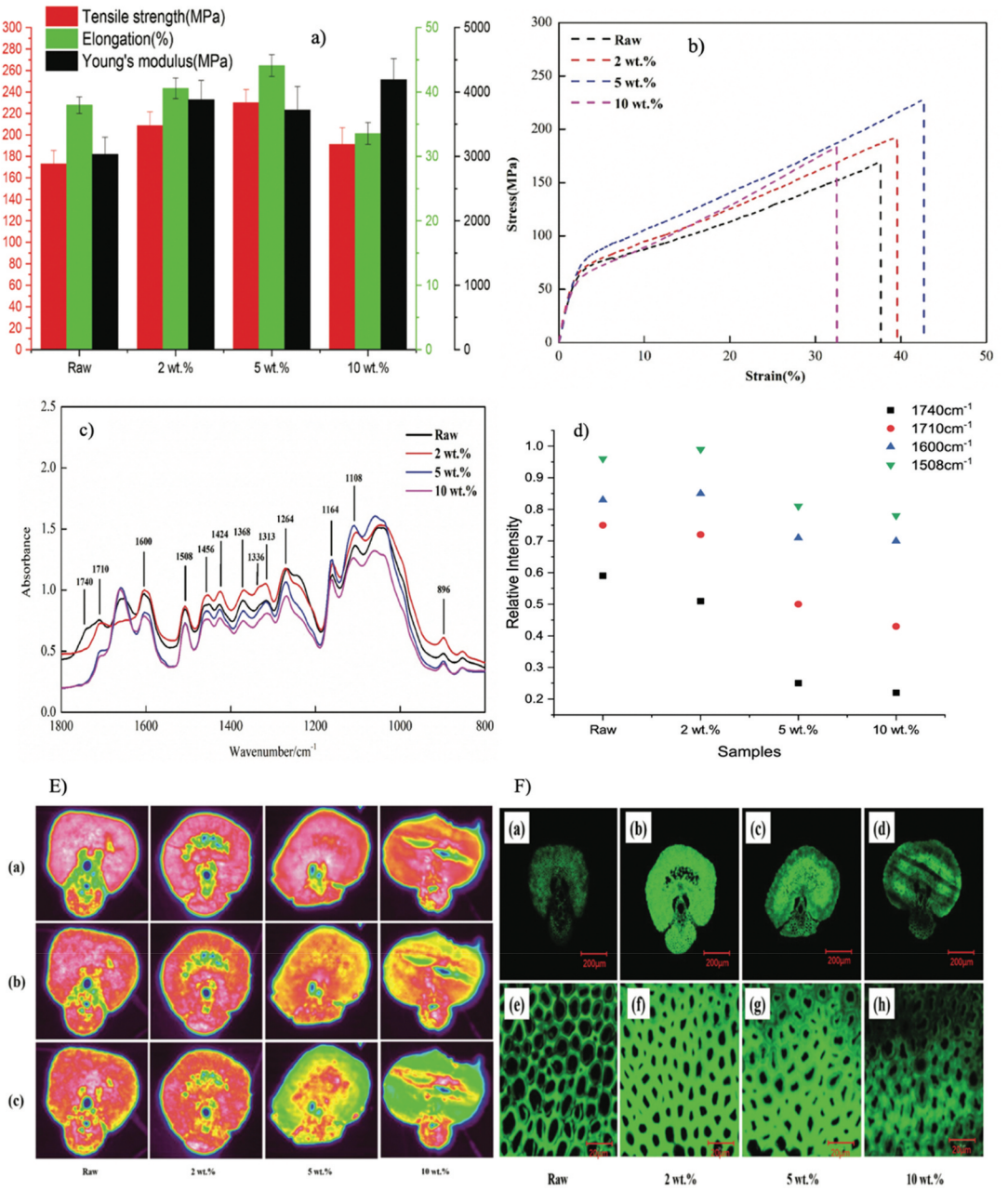

Figure 11. a, b) mechanical properties and tensile stress–strain curves of raw and alkali treatment palm fiber at different conditions, respectively, c) FTIR spectra of the cell wall of fibers in the fingerprint region, d) the relative intensities of the absorption peaks at 1740, 1710, 1600, and 1508 cm^{-1} in palm as a function of treatments, e) the relative concentration and distribution of cellulose (a), lignin (b) and hemicelluloses (c) at peak 1240 cm^{-1}, 1508 cm^{-1} and 1710 cm^{-1}, F) fluorescence images of transverse section of raw, alkali-treated at 2 wt.%, alkali-treated at 5 wt.%, and alkali-treated at 10 wt.% palm cells (Jing et al. 2023).

thermal stability and crystallinity. Thermal Conductivity Measurement assesses how well the composite conducts heat, which is crucial for heat transfer and insulation applications. Changes in thermal conductivity post-treatment can signal modifications in fiber structure, fiber-matrix interface, or density. An increase in thermal conductivity after treatment might indicate improved heat transfer

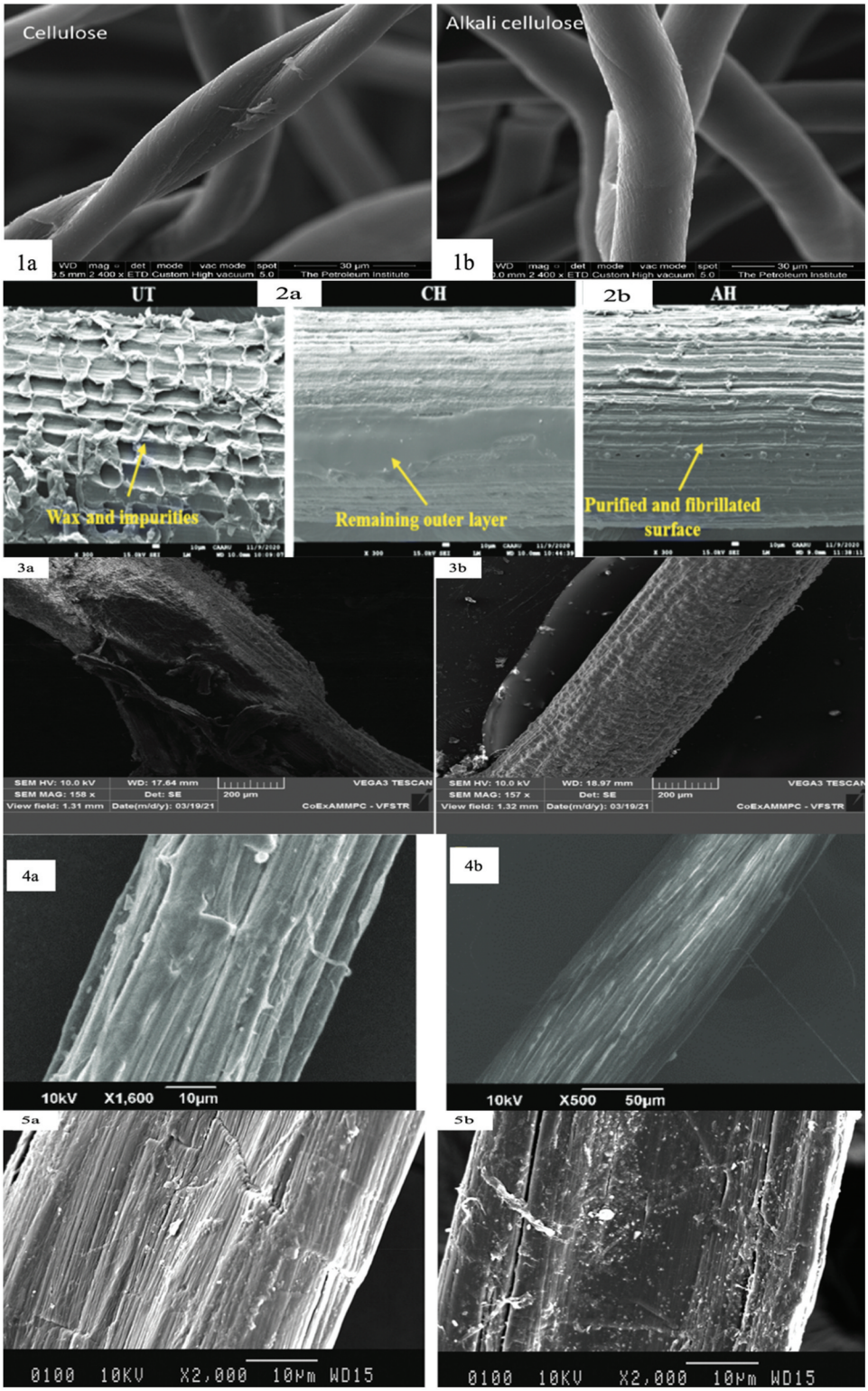

Figure 12. The effect of different physical and chemical treatments on natural fiber-reinforced composites: SEM and FE-SEM images. 1a,b) cotton without and with alkaline treatment, 20% aqueous NaOH for 3 h at room temperature (Marzouki et al. 2019), 2a,b) SEM images of untreated and treated (mercerized) date palm fiber (Nassar et al. 2023), 3a,b) surface morphology of (a) untreated hemp fiber and (b) treated hemp fiber with 6% NaOH solution (Narayana and Rao 2023), 4a,b) SEM images of banana fiber (a) raw surface (b) degummed surface (Badanayak, Jose, and Bose 2023), 5. a) SEM images of untreated nettle fiber, b) NaOH (6%) treated nettle fiber (Pankaj and Kant 2023).

due to enhanced fiber-matrix bonding and increased crystallinity. DMA evaluates the mechanical properties of composites as a function of temperature, providing insights into viscoelastic behavior. Improved thermal stability in treated composites is often reflected in a higher Tg and a more stable storage modulus at elevated temperatures. DMA graphs for treated composites may show increased storage modulus, higher Tg, and a reduced peak in loss modulus, indicating stronger fiber-matrix bonding and enhanced stability. A less pronounced tan δ peak may suggest reduced damping. XRD examines the crystalline structure of the composite, revealing changes in crystallinity due to surface treatment. Higher crystallinity, which often accompanies improved thermal stability and conductivity, may be shown by sharper and more intense peaks in the XRD pattern, reflecting a more ordered structure and the removal of amorphous components. Balaji et al. (Balaji et al. 2024) investigated the mechanical, water absorption, and thermal properties of banana fiber and particle-reinforced epoxy biocomposites. They treated the fibers and particles with a 5% sodium hydroxide solution for 1 day and then dried them in an oven at 100°C for 18 hours. Their study found that the epoxy and banana fiber (E-BF) composites had a strong OH group (3700–3100 cm^{-1}), which generally indicates high mechanical strength. The E-BF composites demonstrated notably superior thermal stability compared to the other three composites. The Differential Scanning Calorimetry curves revealed both endothermic and exothermic activities. Endothermic peaks were observed at 82°C and 390–400°C. An exothermic peak around 150°C was noted in all composite DSC curves, reflecting exceptional performance, while another exothermic peak at 350°C was linked to cellulose degradation across all samples. Setswalo et al. (Setswalo et al. 2023) investigated water absorption and thermal properties of green pterocarpus angolensis (Mukwa)-polylactide composites and potential of enhancing the mukwa/polylactide interface through an economic and ecological surface modification of recycled mukwa wood fibers via alkali-laccase modification. They reported that the less-dense (1.09 g/cm^3) alkali-laccase treated composites showed better chemical resistance. Much swelling of the composites was observed on the 40% nitric acid (HNO^3), while 60%NaOH shrunk the composites and PLA by < 3.5%. The laccase/PLA bio-composite showed a maximum thermal stability of 733°C. The activation energy (Ea) optimized on the laccase/PLA composite with the highest of 104 kJmol – 1. Maximum crystallinity of 45.8% was achieved on the untreated/PLA composites. The alkali-laccase modification maximized the hardness of compo-sites with 35.45 hV on alkali-laccase/PLA. Figure 14. Illustrates data obtained of this research.

Majka et al. (Majka et al. 2024) investigated the influence of Urtica dioica and Vitis vinifera fibers on the thermal properties and flammability of polylactide composites. In this study, fibers were subjected to two types of modifications: mercerization in NaOH solution (M1 route) and encapsulation in an organic PLA solution (M2 route). In a further step, PLA composites containing 5, 10, and 15 wt% of unmodified and chemically treated fibers were obtained. They reported that Chemical modification primarily removes fatty compounds responsible for the ability to absorb moisture during the processing process. Thus, chemical modification helps to increase the hydrophobicity of the surface of natural fibers and, consequently, compatibility with the PLA matrix. In addition, only biocomposites containing mercerized fibers had a nearly 20% reduced flammability compared to that of PLA. Moreover, the biofiller obtained in this way belongs to the group of flame retardants that generate char residue during combustion, which was also confirmed by TGA tests. Figure 15 Illustrates data obtained of this research.

Conclusion and future scope

In this review, we have explored the dynamic landscape of surface modification techniques for natural fiber-reinforced composites, with a focus on chemical and physical advancements. Through meticulous bibliometric analysis integrating keyword co-occurrence and author co-citation networks on the ScienceDirect platform, we gained insights into the evolving trends and key contributors in this field. Our exploration began with an examination of the constituents of natural fibers, emphasizing their

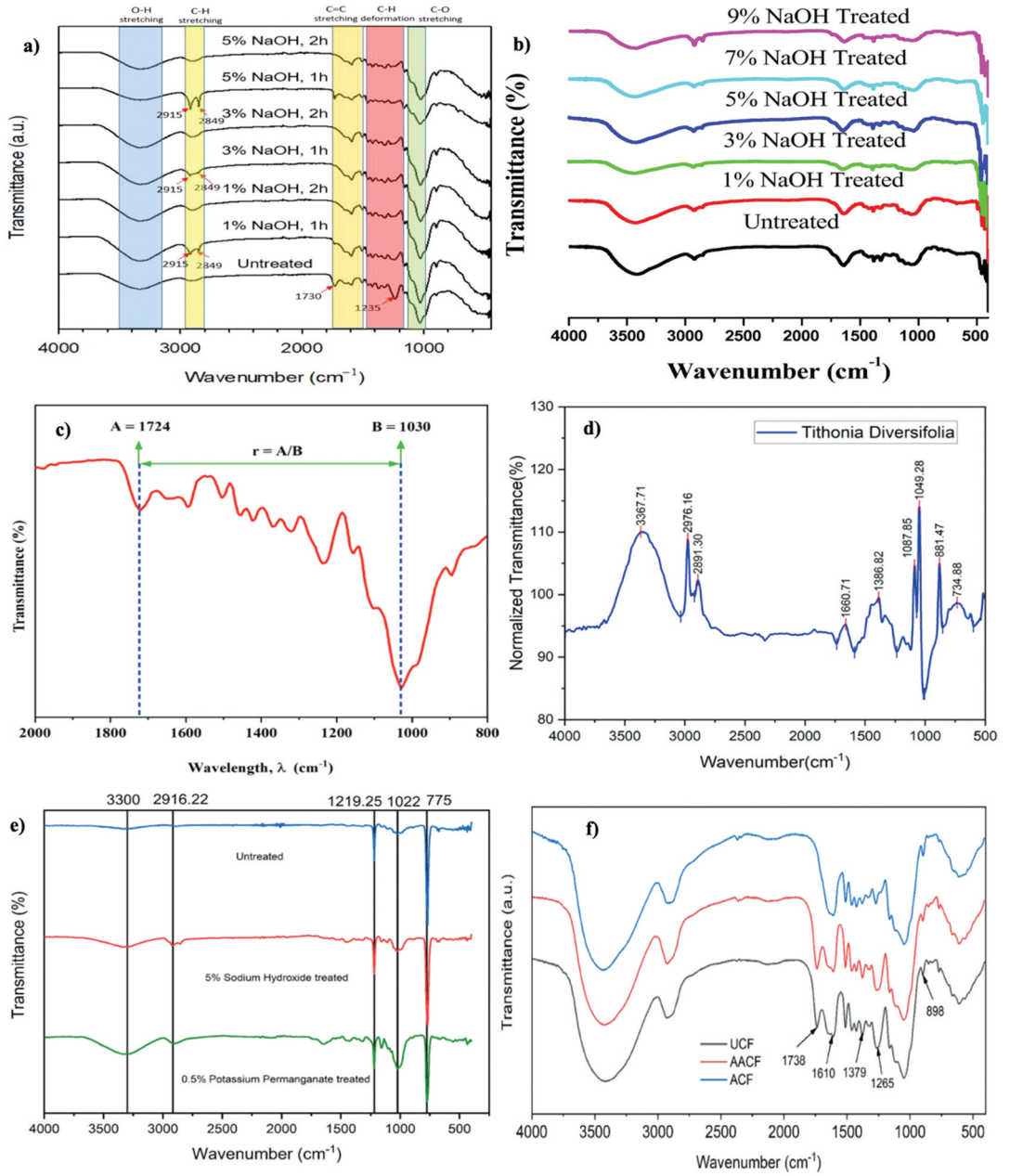

Figure 13. The effect of FTIR spectra of some natural fibers before and after chemical treatment, a) banana fiber before and after NaOH solution treatment (Parre et al. 2020), b) cytostachys renda fibre before and after NaOH solution treatment (Loganathan et al. 2020), c) FTIR spectrum of acetylated date palm fiber using accelerated heating (Nassar et al. 2023), d) FTIR spectrum of tithonia diversifolia fiber (Selvaraj, Mylsamy, and Mylsamy 2023), e) FTIR spectrum of treated and untreated bamboo fibers before sodium hydroxide and potassium permanganate treatment (Kudva, Gt, and Pai 2024), f) FTIR spectra of untreated coir fibers (black), acetic anhydride-treated coir fibers (red) and alkali-treated coir fibers (blue) under optimal conditions (Ru et al. 2023).

abundance, renewability, and potential as reinforcements in composite materials. However, despite their numerous advantages, the inherent limitations of natural fibers, including hydrophilicity, poor adhesion with matrix materials, and susceptibility to environmental factors, necessitate effective surface modification strategies. We then delved into the core of our study, discussing a myriad of chemical and physical treatments aimed at enhancing the surface properties of natural fibers. These

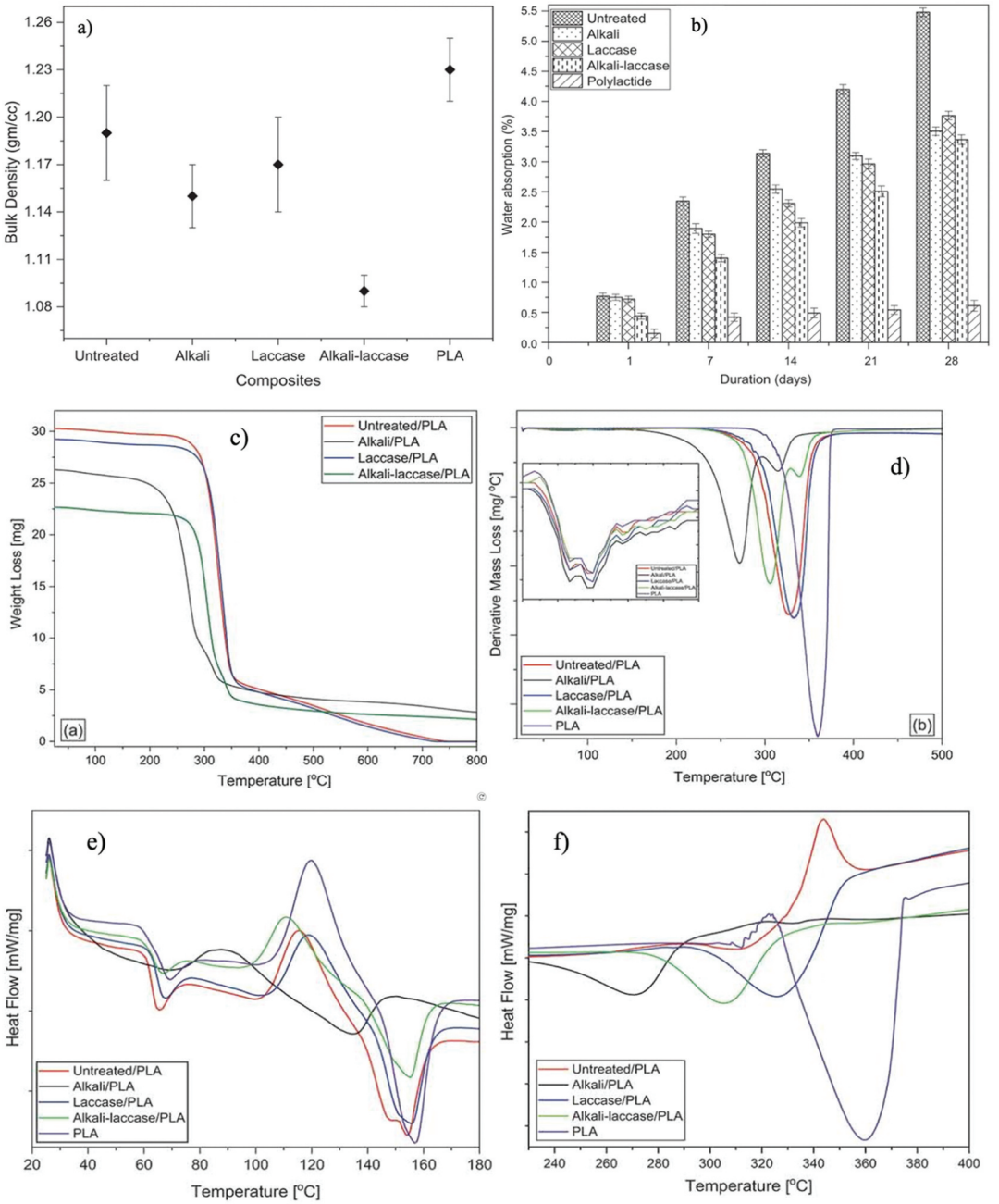

Figure 14. a) the effect of surface modification on the bulk density of the composites, b) the water absorption of the polylactide, untreated, treated mukwa wood/pla composites, c) the TGA curves of untreated and treated mukwa/pla composites, d) the DTA curves of untreated and treated mukwa/pla composites, e,f) the DSC curves of untreated and treated mukwa/pla composites (Setswalo et al. 2023).

treatments serve to improve interfacial adhesion between fibers and matrices, mitigate moisture absorption, and enhance the mechanical and thermal properties of NFRCs. From alkali and silane treatments to plasma and ultrasound techniques, a diverse array of methodologies has emerged, each

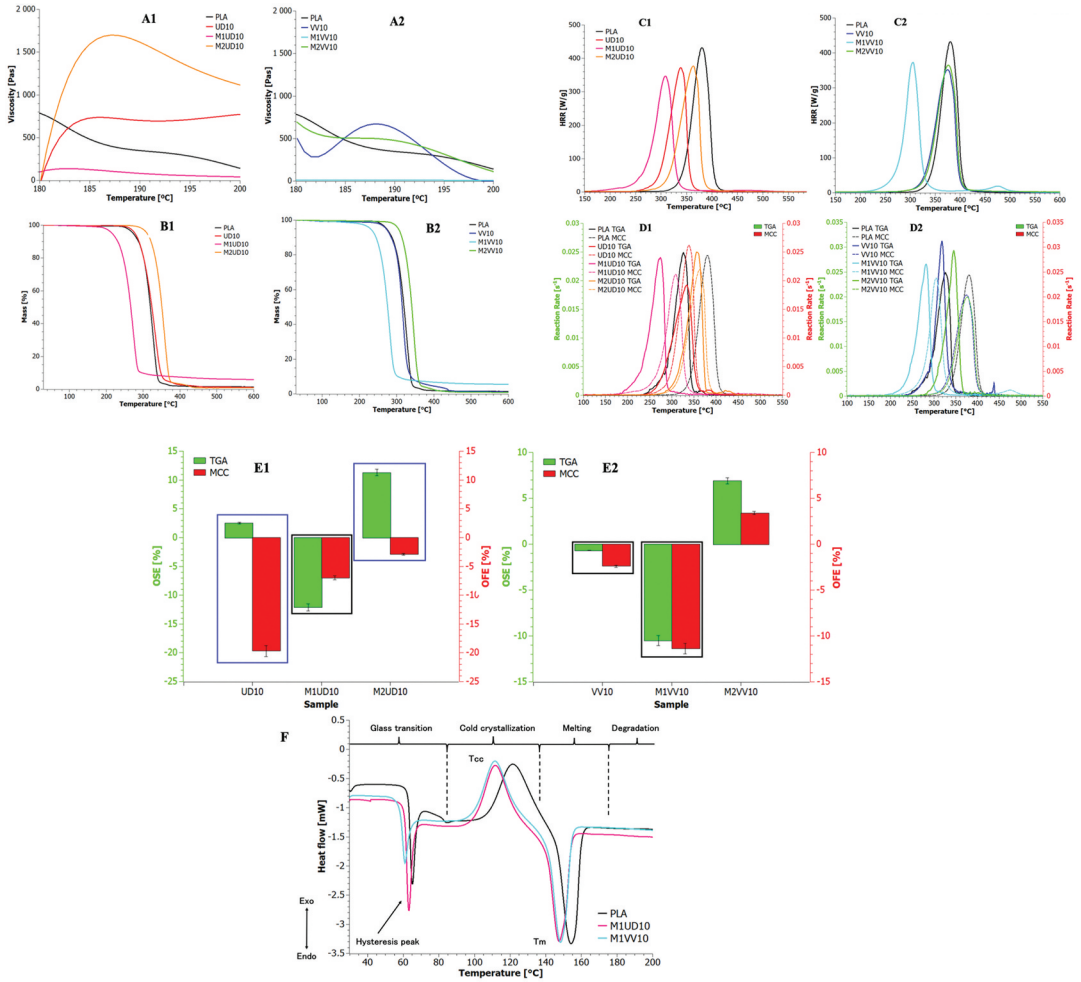

Figure 15. A1,2) viscosity versus temperature curves for PLA composites with urtica dioica and vitis vinifera 10% of unmodified fibers, fibers modified with route M1, and fibers modified with route M2 respectively, B1,2) TGA curves for PLA composites with urtica dioic and vitis vinifera 10%, C1,2) heat release rate versus temperature for PLA composites with urtica dioica and vitis vinifera 10%, D1,2) reaction rate for polylactide composites with urtica dioica and dioic and vitis vinifera 10%, E1,2) overall thermal stabilization effect (OSE) and overall flammability effect (OFE) for PLA composites with modified and pure urtica dioica and vitis vinifera 10%, and F) DSC indicators: melting temperature (tm), melting enthalpy (Δhm), degree of crystallinity (X_C) crystallization temperature (T_C), cold crystallization temperature (T_{CC}), and glass transition temperature (tg) (Majka et al. 2024).

offering unique advantages and applications in tailoring the properties of NFRCs to meet specific performance requirements.

By synthesizing the findings from our bibliometric analysis and literature review, it is evident that surface modification holds immense promise in advancing the performance and applicability of NFRCs across various industries, including automotive, construction, and packaging. Furthermore, it will aid researchers in better comprehending the many characteristics of natural fiber composites, thereby facilitating the development of novel green materials with enhanced performance. However, as with any burgeoning field, several crucial research gaps and important future scopes for further research should be seriously taken into consideration, including hybrid treatments, nanotechnology treatment, bio-based and eco-friendly treatments, and computational modeling, which will be discussed.

Hybrid treatments

Integrating multiple treatment techniques, such as combining physical treatments like surface modifications with chemical treatments like grafting or coating, could lead to synergistic effects, resulting in NFRCs with tailored properties suitable for specific applications. Exploring novel combinations of treatments and their effects on composite performance will be crucial. For example, Plasma treatment is used to introduce reactive functional groups onto the surface of natural fibers, enhancing their wettability and adhesion to polymer matrices. Following plasma treatment, chemical grafting is performed to covalently attach coupling agents or compatibilizers onto the fiber surface, leading to enhanced bonding between fibers and the matrix, enhancing moisture resistance, imparting flame retardancy, or increasing compatibility with different types of matrices. These improvements contribute to the overall performance and durability of natural fiber-reinforced composites in real-world applications. Consequently, this is a perfect research area for future researchers' work.

Nanotechnology treatment

The nano-coating serves multiple functions, creating a compatible interface between the hydrophilic natural fibers and hydrophobic polymer matrices, facilitating better wetting and interlocking between the two phases, providing barrier properties against moisture and UV radiation, and imparting additional functionalities such as antimicrobial or flame-retardant properties, enhancing the moisture resistance and dimensional stability of fibers. Depending on the desired properties, different types of nano-coatings may be selected, including silica (for mechanical properties and moisture resistance), carbon nanotubes (to enhance electrical conductivity and thermal stability), TiO_2, ZnO, Al_2O_3, and other materials. Nano-coatings can be applied to natural fibers using various techniques, including dip coating, spray coating, chemical vapor deposition, physical vapor deposition, electrospinning, and layer-by-layer deposition. The choice of coating technique depends on factors such as the desired coating thickness, uniformity, adhesion to the fiber surface, and scalability for industrial production. Achieving uniform and durable nano-coatings on natural fibers while maintaining their structural integrity and biocompatibility can be challenging. Optimization of coating parameters, such as coating thickness, deposition temperature, and precursor concentration, is necessary to ensure good adhesion and coverage without compromising fiber properties. There is less information and research in this field in the literature, so this is a very potential field of work for those who are interested.

Bio-based and eco-friendly treatments

Bio-based and sustainable treatment approaches for NFRCs (such as plant extracts, natural oils, or bio-based polymers) aim to reduce environmental impact, minimize dependence on fossil resources, and promote the use of renewable and biodegradable materials throughout the composite manufacturing process. These approaches emphasize the use of eco-friendly treatments, bio-based chemicals, and sustainable processing techniques. Natural extracts derived from plants, fruits, seeds, or leaves contain bioactive compounds that can be utilized as treatment agents for natural fibers. Examples include tannins, lignin derivatives, flavonoids, and saponins, which possess properties such as antimicrobial activity, UV resistance, flame retardancy, or antioxidant properties. Eco-friendly processing techniques, such as microwave-assisted treatment, ultrasound-assisted treatment, or electrospinning, reduce energy consumption, minimize waste generation, and enable precise control over treatment parameters. Utilizing these materials and techniques reduces reliance on costly chemicals and equipment, making it a promising area for future researchers due to the scarcity of resources and information available.

Computational modeling

Modeling plays a significant role in understanding and optimizing the treatment of the NFRCs. It provides valuable insights into the underlying mechanisms of treatment processes, predicts the effects of various parameters, and facilitates the design and optimization of treatment methodologies. Modeling helps elucidate the complex physicochemical processes involved in treating natural fibers, such as surface modification, chemical grafting, or nano-coating. Computational models can simulate the interactions between treatment agents and fiber surfaces at the molecular level, providing insights into adsorption mechanisms, reaction kinetics, and the formation of functional groups. Understanding these mechanisms enables researchers to optimize treatment protocols, enhance treatment efficiency, and tailor the properties of treated fibers to meet specific application requirements. Modeling allows researchers to predict the effects of treatment parameters, such as temperature, concentration, reaction time, and pH, on the properties of treated natural fibers and their compatibility with polymer matrices. Computational models can simulate the impact of different treatment conditions on surface morphology, chemical composition, and interfacial adhesion, guiding experimental optimization and process control. Predictive modeling helps identify optimal treatment conditions that maximize the desired properties of NFRCs while minimizing resource consumption, energy expenditure, and environmental impact. Computational fluid dynamics models can simulate fluid flow and mass transport phenomena during treatment processes, guiding the design of reactors, impregnation baths, or coating chambers for efficient and uniform treatment of natural fibers. Process optimization models consider factors such as residence time, agitation intensity, solvent usage, and energy consumption to minimize costs and maximize productivity while maintaining treatment efficacy. Finite element analysis and multiscale modeling techniques predict the mechanical behavior, structural integrity, and durability of NFRCs based on the properties of treated fibers and their interactions with polymer matrices. Predictive modeling enables the selection of optimal fiber treatments, matrix formulations, and composite architectures to meet specific performance requirements in diverse applications, such as automotive, aerospace, construction, and consumer goods. Modeling complements experimental research by reducing the need for costly and time-consuming trial-and-error experiments. Virtual experimentation through computational models allows researchers to explore a wide range of treatment scenarios, evaluate alternative approaches, and identify promising candidates for further experimental validation.

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No potential conflict of interest was reported by the author(s).

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References

Abdellah, M. Y., M. G. Sadek, H. Alharthi, and G. T. Abdel-Jaber. 2024. "Mechanical, Thermal, and Acoustic Properties of Natural Fibre-Reinforced Polyester." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 238 (3): 1436–1448. https://doi.org/10.1177/09544089231157638.

Abisha, M., R. K. Priya, K. P. Arunachalam, S. Avudaiappan, E. I. Saavedra Flores, and P. F. Parra. 2023. "Biodegradable Green Composites: Effects of Potassium Permanganate (KMnO4) Treatment on Thermal, Mechanical, and Morphological Behavior of Butea Parviflora (BP) Fibers." *Polymers* 15 (9): 2197. https://doi.org/10.3390/polym15092197.

Acharya, P., D. Pai, and G. T. Mahesha. 2023. "Effect of Chemical Treatments on Physical and Mechanical Characteristics of Helicteres Isora Natural Fiber." *Materials Today: Proceedings*. Singapore.

Adesina, K., T. C. Lin, Y. W. Huang, M. Locmelis, and D. Han. 2024. "A Review of Dielectric Barrier Discharge Cold Atmospheric Plasma for Surface Sterilization and Decontamination." *IEEE Transactions on Radiation and Plasma Medical Sciences*. Florida, USA: Tampa Convention Center.

Al Hajaj, Z. 2024. "The Influence of Incorporating Natural Fiber on the Mechanical Performance of Natural Fiber Reinforced Concrete." *Journal of Engineering Research* 15(3): 874. https://doi.org/10.3390/ma15030874 .

Ali, M. F., M. S. Hossain, S. Ahmed, and A. S. Chowdhury. 2024. "The Effect of Chemical Treatment on Mechanical Properties of Composites of Unsaturated Polyester Resin with Cow Hair Fibre and Chicken Feather Fibre." *Chapter* 1 (3): 45–51. *AccessEdited by: Jun*.

Almagro-Herrera, N., S. Lozano-Calvo, A. Palma, J. C. García, and M. J. Díaz. 2024. "Assessing the Influence of Biomass Origin and Fractionation Methods on Pyrolysis of Primary Biomass Fractions." *Fuel* 367:131501. https://doi.org/10.1016/j.fuel.2024.131501.

Anari, E. S., N. Soltanizadeh, and M. Fathi. 2024. "The Potential of DBD Plasma Pretreatment for the Isolation of Micro-And Nano-Cellulose Fibers from the Walnut Shells." *Carbohydrate Polymers* 327:121692. https://doi.org/10.1016/j.carbpol.2023.121692.

Angulu, M., and H. J. Gusovius. 2024. "Retting of Bast Fiber Crops Like Hemp and Flax—A Review for Classification of Procedures." *Fibers* 12 (3): 28. https://doi.org/10.3390/fib12030028.

Arasu, P. T., P. S. Seenidurai, A. Murugan, and S. Elangovan. 2021. "Functional Modification of Borassus Flabellifer Shealth Fibers Using Isocyanate." *Letters in Applied NanoBiosci* 10 (1): 1889–1895.

Azwa, Z. N., B. F. Yousif, A. C. Manalo, and W. Karunasena. 2013. "A Review on the Degradability of Polymeric Composites Based on Natural Fibres." *Materials & Design* 47:424–442. https://doi.org/10.1016/j.matdes.2012.11.025.

Badanayak, P., S. Jose, and G. Bose. 2023. "Banana Pseudostem Fiber: A Critical Review on Fiber Extraction, Characterization, and Surface Modification." *Journal of Natural Fibers* 20 (1): 2168821. https://doi.org/10.1080/15440478.2023.2168821.

Baig, M., B. Almeshari, A. Aabid, H. Junaedi, and A. Almajid. 2024. "The Effect of Maleic Anhydride Grafted Polypropylene Addition on the Degradation in the Mechanical Properties of the PP/Wood Composites." *Heliyon* 10 (9): e30510. https://doi.org/10.1016/j.heliyon.2024.e30510.

Balaji, A., S. Kannan, R. Purushothaman, S. Mohanakannan, A. H. Maideen, J. Swaminathan, B. Karthikeyan, and P. Premkumar. 2024. "Banana Fiber and Particle-Reinforced Epoxy Biocomposites: Mechanical, Water Absorption, and Thermal Properties Investigation." *Biomass Conversion and Biorefinery* 14 (6): 7835–7845. https://doi.org/10.1007/s13399-022-02829-y.

Balakrishnan, T. S., M. T. H. Sultan, F. S. Shahar, S. Y. Nayak, A. U. M. Shah, T. A. Sebaey, and A. A. Basri. 2024a. "Hybridization of Woven Kenaf and Unidirectional Glass Fibre Roving for Unsaturated Polyester Composite." *Iranian Polymer Journal* 33 (9): 1–14. https://doi.org/10.1007/s13726-024-01319-4.

Balakrishnan, T. S., M. T. H. Sultan, F. S. Shahar, S. Y. Nayak, A. U. M. Shah, T. A. Sebaey, and A. A. Basri. 2024b. "Plant Fiber Reinforcements as Alternatives in Pultruded FRP Composites Manufacturing: A Review." *Journal of Natural Fibers* 21 (1): 2298396. https://doi.org/10.1080/15440478.2023.2298396.

Banagar, A. R., G. R. Patel, C. V. Srinivasa, S. Dhanalakshmi, Hemaraju, and B. T. Ramesh. 2024. "Extraction and Characterization of Hemicellulose and Lignin Contents of Areca Fiber." *Journal of the Indian Academy of Wood Science* 21 (1): 1–11. https://doi.org/10.1007/s13196-024-00330-9.

Barczewski, M., D. Matykiewicz, and M. Szostak. 2020. "The Effect of Two-Step Surface Treatment by Hydrogen Peroxide and Silanization of Flax/Cotton Fabrics on Epoxy-Based Laminates Thermomechanical Properties and Structure." *Journal of Materials Research and Technology* 9 (6): 13813–13824. https://doi.org/10.1016/j.jmrt.2020.09.120.

Barrera-Fajardo, I., O. Rivero-Romero, and J. Unfried-Silgado. 2024. "Investigation of the Effect of Chemical Treatment on the Properties of Colombian Banana and Coir Fibers and Their Adhesion Behavior on Polylactic Acid and Unsaturated Polyester Matrices." *Fibers* 12 (1): 6. https://doi.org/10.3390/fib12010006.

Baskaran, P. G., M. Kathiresan, and P. Pandiarajan. 2022. "Effect of Alkali-Treatment on Structural, Thermal, Tensile Properties of Dichrostachys Cinerea Bark Fiber and Its Composites." *Journal of Natural Fibers* 19 (2): 433–449. https://doi.org/10.1080/15440478.2020.1745123.

Benedetto, R. M. D., M. V. Gelfuso, and D. Thomazini. 2015. "Influence of UV Radiation on the Physical-Chemical and Mechanical Properties of Banana Fiber." *Materials Research* 18 (suppl 2): 265–272. https://doi.org/10.1590/1516-1439.371414.

Bezazi, A., H. Boumediri, G. Garcia Del Pino, B. Bezzazi, F. Scarpa, P. N. Reis, and A. Dufresne. 2022. "Alkali Treatment Effect on Physicochemical and Tensile Properties of Date Palm Rachis Fibers." *Journal of Natural Fibers* 19 (10): 3770–3787. https://doi.org/10.1080/15440478.2020.1848726.

Bhowmik, S., S. Kumar, and V. K. Mahakur. 2024. "Various Factors Affecting the Fatigue Performance of Natural Fiber-Reinforced Polymer Composites: A Systematic Review." *Iranian Polymer Journal* 33 (2): 249–271. https://doi.org/10.1007/s13726-023-01243-z.

Bledzki, A. K., A. A. Mamun, M. Lucka-Gabor, and V. S. Gutowski. 2008. "The Effects of Acetylation on Properties of Flax Fibre and Its Polypropylene Composites." *Express Polymer Letters* 2 (6): 413–422. https://doi.org/10.3144/expresspolymlett.2008.50.

Boumaaza, M., A. Belaadi, and M. Bourchak. 2021. "The Effect of Alkaline Treatment on Mechanical Performance of Natural Fibers-Reinforced Plaster: Optimization Using RSM." *Journal of Natural Fibers* 18 (12): 2220–2240. https://doi.org/10.1080/15440478.2020.1724236.

Brahma, S., S. M. Raafi, S. N. Arju, and J. U. Rehman. 2024. "Dyeability and Mechanical Properties of Banana Fiber Reinforced Polypropylene Composite." *SPE Polymers* 5 (3): 353–365. https://doi.org/10.1002/pls2.10129.

Cárdenas-Oscanoa, A. J., J. L. Tene Tayo, C. Huang, C. Huang, and M. Euring. 2024. "Discovering Natural Fiber-Insulation Boards and Natural Adhesives, Focused on a Polylactic Acid (PLA) Application–A Review." *Journal of Natural Fibers* 21 (1): 2343371. https://doi.org/10.1080/15440478.2024.2343371.

Caren, K. J., N. D. Kenneth, and M. M. David. 2022. "Strength Properties of Surface-Modified Giant Cavendish (Musa Acuminata) Banana Fibers." *Journal of Natural Fibers* 19 (16): 12746–12759. https://doi.org/10.1080/15440478.2022.2073507.

Chauhan, S., and P. C. Gope. 2024. "Effects of Fiber Treatment and Humidity on the Mechanical, Fracture Toughness, Dynamic and Thermal Properties of Grewia Optiva Natural Fiber-Reinforced Epoxy Composites." *Journal of Engineering Materials and Technology* 146 (3): 1–36. https://doi.org/10.1115/1.4064373.

Chen, C., D. Huang, Q. Yang, G. Wang, and X. Wang. 2023. "Structure and Thermal Properties of Cellulose Nanofibrils Extracted from Alkali–Ultrasound Treated Windmill Palm Fibers." *International Journal of Biological Macromolecules* 253:126645. https://doi.org/10.1016/j.ijbiomac.2023.126645.

Chen, C., P. Xu, and X. Wang. 2024. "Structure and Mechanical Properties of Windmill Palm Fiber with Different Delignification Treatments." *Journal of Bioresources & Bioproducts* 9 (1): 102–112. https://doi.org/10.1016/j.jobab.2023.12.001.

Chopra, L. 2022. "Extraction of Cellulosic Fibers from the Natural Resources: A Short Review." *Materials Today: Proceedings*, India, 1265–1270, *48*.

Constan Lotebulo Ndruru, S. T., V. Ariva Asta, R. Al Razi Hidayat, R. Siti Mawarni, A. Marlina, E. Yulianti, A. Sri Handayani, et al. 2024. "Isolation, Modification, and Characterization of Local Indonesia's Sugarcane Bagasse Cellulose for Dye-Adsorbent Application." *Chemistry Select* 9 (2): e202302812. https://doi.org/10.1002/slct.202302812.

Cosse, R. L., V. S. Voet, R. Folkersma, and K. Loos. 2023. "The Effect of Size and Delignification on the Mechanical Properties of Polylactic Acid (PLA) Biocomposites Reinforced with Wood Fibres via Extrusion." *RSC Sustainability* 1 (4): 876–885. https://doi.org/10.1039/D3SU00039G.

Costa, M. M., S. L. Melo, J. V. M. Santos, E. A. Araújo, G. P. Cunha, E. P. Deus, and N. Schmitt. 2017. "Influence of Physical and Chemical Treatments on the Mechanical Properties of Bamboo Fibers." *Procedia Engineering* 200:457–464. https://doi.org/10.1016/j.proeng.2017.07.064.

Dash, C., A. Das, and D. K. Bisoyi. 2022. "High-Intensity Ultrasonication (HIU) Effect on Sunn Hemp Fiber-Reinforced Epoxy Composite: A Physicochemical Treatment Toward Fiber." In *Natural Polymers*, edited by C. Dash, A. Das, and D. K. Bisoyi, 193–224. Apple Academic Press.

Debabeche, N., O. Kribaa, H. Boussehel, B. Guerira, M. Jawaid, H. Fouad, and M. A. Azeem. 2023. "Effect of Fiber Surface Treatment on the Mechanical, Morphological, and Dynamic Mechanical Properties of Palm Petiole Fiber/LLDPE Composites." *Biomass Conversion and Biorefinery* 14 (17): 1–14. https://doi.org/10.1007/s13399-023-04197-7.

Dejene, B. K. 2024a. "Advancing Natural Fiber-Reinforced Composites Through Incorporating ZnO Nanofillers in the Polymeric Matrix: A Review." *Journal of Natural Fibers* 21 (1): 2356015. https://doi.org/10.1080/15440478.2024.2356015.

Dejene, B. K. 2024b. "Exploring the Potential of ZnO Nanoparticle-Treated Fibers in Advancing Natural Fiber Reinforced Composites: A Review." *Journal of Natural Fibers* 21 (1): 2311304. https://doi.org/10.1080/15440478.2024.2311304.

Dejene, B. K. 2024c. "False Banana (Enset Ventricosum) Fibers: An Emerging Natural Fiber with Distinct Properties, Promising Potentials, Challenges and Future Prospects–A Critical Review." *Journal of Natural Fibers* 21 (1): 2311303. https://doi.org/10.1080/15440478.2024.2311303.

Del Angel-Monroy, M., V. Escobar-Barrios, M. G. Peña-Juarez, L. E. Lugo-Uribe, J. Navarrete-Damian, E. Perez, and J. A. Gonzalez-Calderon. 2024. "Effect of Coconut Fibers Chemically Modified with Alkoxysilanes on the Crystallization, Thermal, and Dynamic Mechanical Properties of Poly (Lactic Acid) Composites." *Polymer Bulletin* 81 (1): 843–870. https://doi.org/10.1007/s00289-023-04740-6.

Dey, P., B. S. Mahapatra, B. Pramanick, A. Kumar, M. S. Negi, J. Paul, D. K. Shukla, and S. P. Singh. 2021. "Quality Optimization of Flax Fibre Through Durational Management of Water Retting Technology Under Sub-Tropical Climate." *Industrial Crops and Products* 162:113277. https://doi.org/10.1016/j.indcrop.2021.113277.

Diouf, G., and P. B. Gning. 2024. "Influence of the Extraction Process on the Mechanical and Morphological Properties of Technical Fibers from Typha domingensis." *Journal of Natural Fibers* 21 (1): 2357744. https://doi.org/10.1080/15440478.2024.2357744.

Dutta, D., and N. Sit. 2024. "Preparation and Characterization of Potato Starch-Based Composite Films Reinforced by Modified Banana Fibers and Its Application in Packaging of Grapes." *International Journal of Biological Macromolecules* 254:127791. https://doi.org/10.1016/j.ijbiomac.2023.127791.

Elfaleh, I., F. Abbassi, M. Habibi, F. Ahmad, M. Guedri, M. Nasri, and C. Garnier. 2023. "A Comprehensive Review of Natural Fibers and Their Composites: An Eco-Friendly Alternative to Conventional Materials." *Results in Engineering* 19:101271. https://doi.org/10.1016/j.rineng.2023.101271.

Esangbedo, M. O., and B. O. Samuel. 2024. "Application of Machine Learning and Grey Taguchi Technique for the Development and Optimization of a Natural Fiber Hybrid Reinforced Polymer Composite for Aircraft Body Manufacture." *Oxford Open Materials Science* 4 (1). https://doi.org/10.1093/oxfmat/itae004.

Faria, D. L., L. M. Mendes, and J. B. G. Junior. 2023. "Effect of Surface Treatment on the Technological Properties of Coconut Fiber–Reinforced Plant Polyurethane Composites." *Environmental Science and Pollution Research* 30 (18): 52124–52140. https://doi.org/10.1007/s11356-023-25946-1.

Fei, M., W. Liu, L. Shao, Y. Cao, B. J. Bliss, B. Zhao, and J. Zhang. 2024. "Hemp Fiber Reinforced Dual Dynamic Network Vitrimer Biocomposites with Direct Incorporation of Amino Silane." *Chemical Engineering Journal* 480:148091. https://doi.org/10.1016/j.cej.2023.148091.

Feleke, K., G. Thothadri, H. Beri Tufa, A. A. Rajhi, and G. M. S. Ahmed. 2023. "Extraction and Characterization of Fiber and Cellulose from Ethiopian Linseed Straw: Determination of Retting Period and Optimization of Multi-Step Alkaline Peroxide Process." *Polymers* 15 (2): 469. https://doi.org/10.3390/polym15020469.

Feng, Y., H. Hao, H. Lu, C. L. Chow, and D. Lau. 2024. "Exploring the Development and Applications of Sustainable Natural Fiber Composites: A Review from a Nanoscale Perspective." *Composites Part B Engineering* 276:111369. https://doi.org/10.1016/j.compositesb.2024.111369.

Fitch-Vargas, P. R., I. L. Camacho-Hernández, F. J. Rodríguez-González, F. Martínez-Bustos, A. Calderón-Castro, J. de Jesús Zazueta-Morales, and E. Aguilar-Palazuelos. 2023. "Effect of Compounding and Plastic Processing Methods on the Development of Bioplastics Based on Acetylated Starch Reinforced with Sugarcane Bagasse Cellulose Fibers." *Industrial Crops and Products* 192:116084. https://doi.org/10.1016/j.indcrop.2022.116084.

Gholampour, A., and T. Ozbakkaloglu. 2020. "A Review of Natural Fiber Composites: Properties, Modification and Processing Techniques, Characterization, Applications." *Journal of Materials Science* 55 (3): 829–892. https://doi.org/10.1007/s10853-019-03990-y.

Gond, D. K., B. K. Yadav, S. Priyadarshan, and V. L. Yadav. 2024. "Characterization and Synthesis of Biocomposite Film with Coir and Polyvinyl Alcohol/Polyethylene Glycol." *Journal of Scientific & Industrial Research (JSIR) volume* 83:146–152. https://doi.org/10.56042/jsir.v83i2.4482.

Gorgun, E., A. Ali, and M. S. Islam. 2024. "Biocomposites of Poly (Lactic Acid) and Microcrystalline Cellulose: Influence of the Coupling Agent on Thermomechanical and Absorption Characteristics." *American Chemical Society Omega* 9 (10): 11523–11533. https://doi.org/10.1021/acsomega.3c08448.

Gotoh, K. 2020. "Application of Atmospheric Pressure Plasma Oxidation and Plasma-Induced Polymer Coating to Surface Functionalization of Textiles." *Journal of Fiber Science and Technology* 76 (9): 275–287. https://doi.org/10.2115/fiberst.2020-0034.

Guillén-Mallette, J., A. Valadez-González, and S. I. Rosado-Sánchez. 2023. "Recycled Thermoplastic Polyurethane as a Coupling Agent in Automotive Polypropylene Compounds with Coconut Fibers." *Journal of Thermoplastic Composite Materials* 36 (6): 2674–2697. https://doi.org/10.1177/08927057221083489.

Gupta, R. K., P. Guha, and P. P. Srivastav. 2023. "Effect of High Voltage Dielectric Barrier Discharge (DBD) Atmospheric Cold Plasma Treatment on Physicochemical and Functional Properties of Taro (Colocasia Esculenta) Starch." *International Journal of Biological Macromolecules* 253:126772. https://doi.org/10.1016/j.ijbiomac.2023.126772.

Gupta, U. S., M. Dhamarikar, A. Dharkar, S. Chaturvedi, A. Kumrawat, N. Giri, S. Tiwari, and R. Namdeo. 2021. "Plasma Modification of Natural Fiber: A Review." *Materials Today: Proceedings*, 451–457, *43*. New Delhi, India: National Institute of Technology Delhi.

Gupta, U. S., M. Dhamarikar, A. Dharkar, S. Chaturvedi, S. Tiwari, and R. Namdeo. 2021. "Surface Modification of Banana Fiber: A Review." *Materials Today: Proceedings*, 904–915, *43*.

Handayani, L., S. Aprilia, N. Arahman, and M. R. Bilad. 2024. "Assessment of Fibers from Different Part of the Calotropis Gigantea Biomass as a Filler of Composites Foam PVA/PVP." *South African Journal of Chemical Engineering* 49:189–198. https://doi.org/10.1016/j.sajce.2024.03.016.

Hassan, W., and A. E. Duarte. 2024. "Bibliometric Analysis: A Few Suggestions." *Current Problems in Cardiology* 49 (8): 102640. https://doi.org/10.1016/j.cpcardiol.2024.102640.

Hazarika, D., N. Gogoi, S. Jose, R. Das, and G. Basu. 2017. "Exploration of Future Prospects of Indian Pineapple Leaf, an Agro Waste for Textile Application." *Journal of Cleaner Production* 141:580–586. https://doi.org/10.1016/j.jclepro.2016.09.092.

Heraiz, H., C. Farsi, H. Makri, S. Amroune, A. Belaadi, K. Saada, M. Zaoui, and M. I. Beddiar. 2024. "Assessment of Mechanical and Physicochemical Properties of Palm Fiber Composites: Effect of Alkaline Treatment and Volume Alterations." *Journal of Composite Materials* 58 (15): 1789–1800. https://doi.org/10.1177/00219983241246614.

Iskandar, W. M. E., H. R. Ong, M. M. R. Khan, and F. S. Toma. 2024. "Effect of Bio-Based Nanosilica on the Mechanical Properties of Single Empty Fruit Bunch Fibre." *AIP Conference Proceedings* 3014 (1). https://doi.org/10.1063/5.0192522. AIP Publishing.

Islam, M., C. M. Yeng, K. S. Chun, and H. S. Huey. 2021. "The Influence of Fibre Orientation and Chemical Treatment on the Performance of Unsaturated Polyester/Chrysanthemum Stem Fibre Composites." *Polymers & Polymer Composites* 29 (8): 1103–1113. https://doi.org/10.1177/0967391120954067.

Islam, M. Z., E. C. Sabir, and M. Syduzzaman. 2024. "Experimental Investigation of Mechanical Properties of Jute/Hemp Fibers Reinforced Hybrid Polyester Composites." *SPE Polymers* 5 (2): 192–205. https://doi.org/10.1002/pls2.10119.

Ivanovska, A., M. Milošević, B. Obradović, Z. Svirčev, and M. Kostić. 2023. "Plasma Treatment as a Sustainable Method for Enhancing the Wettability of Jute Fabrics." *Sustainability* 15 (3): 2125. https://doi.org/10.3390/su15032125.

Jabu, M. A., A. A. Alugongo, and N. Z. Nkomo. "Application of Natural Fibre Composites in Interior Panels in the Automotive Industry: A Review."

Jeffrin, J. R., R. Ganesamoorthy, N. Balaji, J. Parthiban, and K. R. Padmavathi. 2024. "A Study on Different Chemical Treatments for Natural Fiber Reinforced Composites." *No. 2023-01-5179*. SAE Technical Paper.

Jenish, I., A. Felix Sahayaraj, M. Appadurai, E. Fantin Irudaya Raj, P. Suresh, T. Raja, S. H. Salmen, S. Alfarraj, and V. Manikandan. 2021. "Fabrication and Experimental Analysis of Treated Snake Grass Fiber Reinforced with Polyester Composite." *Advances in Materials Science and Engineering* 2021 (1): 6078155. https://doi.org/10.1155/2021/6078155.

Jiang, S., C. Lou, Y. Zhou, X. Gu, and X. Kong. 2023. "Biobased Epoxy Composites Reinforced with Acetylated Corn Straw." *American Chemical Society Omega* 8 (14): 12644–12652. https://doi.org/10.1021/acsomega.2c06947.

Jing, L., Y. Jiang, L. Li, and T. Zhang. 2023. "Influence of Alkali Treatment on Microstructure Transformation and Mechanical Properties of Palm-Fiber Cell Wall." *Journal of Natural Fibers* 20 (2): 2237681. https://doi.org/10.1080/15440478.2023.2237681.

Jothi Arunachalam, S., R. Saravanan, T. Sathish, S. Haider, and J. Giri. 2024. "Investigation of Chemically Treated Jute/Kenaf/Glass Fiber with TiO2 Nano-Filler for Tensile and Impact Characteristics." *AIP Advances* 14 (4). https://doi.org/10.1063/5.0206141.

Kadire, T., and S. N. Joshi. 2024. "Effects of Alkaline Treatment and Manufacturing Process on Mechanical and Absorption Properties of Wild Abyssinia Banana Fiber Reinforced Epoxy Composite." *Materials Today: Proceedings*, India, 212–218, *98*.

Kafi, A. A., K. Magniez, and B. L. Fox. 2011. "A Surface-Property Relationship of Atmospheric Plasma Treated Jute Composites." *Composites Science and Technology* 71 (15): 1692–1698. https://doi.org/10.1016/j.compscitech.2011.07.011.

Karthik, A., J. Daniel, P. S. Sampath, and V. Thirumurugan. 2023. "Effect of Alkali Treatment on Cotton/Bamboo Fibres for Application as a Reinforcement Material." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, United States, 09544089231162292.

Knežević, M., A. Kramar, T. Hajnrih, M. Korica, T. Nikolić, A. Žekić, and M. Kostić. 2022. "Influence of Potassium Permanganate Oxidation on Structure and Properties of Cotton." *Journal of Natural Fibers* 19 (2): 403–415. https://doi.org/10.1080/15440478.2020.1745120.

Kocaman, S., and G. Ahmetli. 2020. "Effects of Various Methods of Chemical Modification of Lignocellulose Hazelnut Shell Waste on a Newly Synthesized Bio-Based Epoxy Composite." *Journal of Polymers and the Environment* 28 (4): 1190–1203. https://doi.org/10.1007/s10924-020-01675-1.

Kóczán, Z., and Z. Pásztory. 2024. "Overview of Natural Fiber-Based Packaging Materials." *Journal of Natural Fibers* 21 (1): 2301364. https://doi.org/10.1080/15440478.2023.2301364.

Kogoma, M., and K. Tanaka. 2021. "Low-Temperature Atmospheric Discharge Plasma and Its Applications for the Surface Treatment." *Reviews of Modern Plasma Physics* 5 (1): 3. https://doi.org/10.1007/s41614-021-00050-4.

Kudva, A., M. Gt, and D. Pai. 2024. "Influence of Chemical Treatment on the Physical and Mechanical Properties of Bamboo Fibers as Potential Reinforcement for Polymer Composites." *Journal of Natural Fibers* 21 (1): 2332698. https://doi.org/10.1080/15440478.2024.2332698.

Kulandaiyappan, N. K., V. Raja, C. A. Saleel, M. Alwetaishi, B. S. Arputharaj, A. M. H. Deif, and H. A. AL-Bonsrulah. 2023. "Manufacturing and Experimental Characterization of New-Developed Natural Fiber Reinforced Polymer Nanocomposite." *Journal of Materials Research and Technology* 26:6084–6095. https://doi.org/10.1016/j.jmrt.2023.08.187.

Kumar, B., S. Adil, and J. Kim. 2023. "Adhesion Improvement of Bio-Based Epoxy in Environmentally Friendly and High-Performance Natural Fiber-Reinforced Composites." *Macromolecular Materials and Engineering* 308 (8): 2300003. https://doi.org/10.1002/mame.202300003.

Loganathan, T. M., M. T. H. Sultan, Q. Ahsan, M. Jawaid, J. Naveen, A. U. M. Shah, and L. S. Hua. 2020. "Characterization of Alkali Treated New Cellulosic Fibre from Cyrtostachys Renda." *Journal of Materials Research and Technology* 9 (3): 3537–3546. https://doi.org/10.1016/j.jmrt.2020.01.091.

Luan, X., Z. Song, W. Xu, Y. Li, C. Ding, and H. Chen. 2020. "Spectral Characteristics on Increasing Hydrophilicity of Alfalfa Seeds Treated with Alternating Current Corona Discharge Field." *Spectrochimica Acta Part A, Molecular and Biomolecular Spectroscopy* 236:118350. https://doi.org/10.1016/j.saa.2020.118350.

Madhu, P., M. R. Sanjay, M. Jawaid, S. Siengchin, A. Khan, and C. I. Pruncu. 2020. "A New Study on Effect of Various Chemical Treatments on Agave Americana Fiber for Composite Reinforcement: Physico-Chemical, Thermal, Mechanical and Morphological Properties." *Polymer Testing* 85:106437. https://doi.org/10.1016/j.polymertesting.2020.106437.

Madival, A. S., S. Maddasani, R. Shetty, and D. Doreswamy. 2023. "Influence of Chemical Treatments on the Physical and Mechanical Properties of Furcraea Foetida Fiber for Polymer Reinforcement Applications." *Journal of Natural Fibers* 20 (1): 2136816. https://doi.org/10.1080/15440478.2022.2136816.

Mahalingam, J., S. Rajendran, N. Shanmugasundram, H. Kuppuswamy, and R. Thirumurugan. 2024. "Investigation of Acoustic, Mechanical, Thermal, and Moisture Properties of Milled Alkali-Treated Coconut Tree Secondary Flower Leaf Stalk Fiber-Reinforced Polymer Composite." *Polymer Composites* 45 (5): 4221–4232. https://doi.org/10.1002/pc.28054.

Majka, T. M., R. Piech, M. Piechaczek, and K. A. Ostrowski. 2024. "The Influence of Urtica Dioica and Vitis Vinifera Fibers on the Thermal Properties and Flammability of Polylactide Composites." *Materials* 17 (6): 1256. https://doi.org/10.3390/ma17061256.

Malladi, A., S. Kaliappan, L. Natrayan, and V. Mahesh. 2024. "Effectiveness of Thermal and Mechanical Properties of Jute Fibers Under Different Chemical Treatment for Automotive Interior Trim." *No. 2024-01-5008*. SAE Technical Paper.

Marim, B. M., J. Mantovan, G. A. Giraldo, and S. Mali. 2021. "Environmentally Friendly Process Based on a Combination of Ultrasound and Peracetic Acid Treatment to Obtain Cellulose from Orange Bagasse." *Journal of Chemical Technology & Biotechnology* 96 (3): 630–638. https://doi.org/10.1002/jctb.6576.

Marzouki, R., A. Brahmia, S. Bondock, S. M. Keshk, M. F. Zid, A. G. Al-Sehemi, A. Koschella, and T. Heinze. 2019. "Mercerization Effect on Structure and Electrical Properties of Cellulose: Development of a Novel Fast Na-Ionic Conductor." *Carbohydrate Polymers* 221:29–36. https://doi.org/10.1016/j.carbpol.2019.05.083.

Matykiewicz, D., M. Barczewski, O. Mysiukiewicz, and K. Skórczewska. 2021. "Comparison of Various Chemical Treatments Efficiency in Relation to the Properties of Flax, Hemp Fibers and Cotton Trichomes." *Journal of Natural Fibers* 18 (5): 735–751. https://doi.org/10.1080/15440478.2019.1645792.

Matykiewicz, D., B. Dudziec, K. Skórczewska, and K. Sałasińska. 2024. "The Effect of Silanes Treatments on Thermal and Mechanical Properties of Nettle Fibre/Bio Epoxy Composites." *Journal of Natural Fibers* 21 (1): 2332913. https://doi.org/10.1080/15440478.2024.2332913.

Mazian, B., S. Cariou, M. Chaignaud, J. L. Fanlo, M. L. Fauconnier, A. Bergeret, and L. Malhautier. 2019. "Evolution of Temporal Dynamic of Volatile Organic Compounds (VOCs) and Odors of Hemp Stem During Field Retting." *Planta* 250 (6): 1983–1996. https://doi.org/10.1007/s00425-019-03280-6.

Mengjin, W. U., J. I. A. Lixia, L. U. Suling, Q. I. N. Zhigang, W. E. I. Sainan, and Y. A. N. Ruosi. 2021. "Interfacial Performance of High-Performance Fiber-Reinforced Composites Improved by Cold Plasma Treatment: A Review." *Surfaces and Interfaces* 24:101077. https://doi.org/10.1016/j.surfin.2021.101077.

Mesquita, R. G. D. A., A. A. D. S. César, R. F. Mendes, L. M. Mendes, J. M. Marconcini, G. Glenn, and G. H. D. Tonoli. 2017. "Polyester Composites Reinforced with Corona-Treated Fibers from Pine, Eucalyptus and Sugarcane Bagasse." *Journal of Polymers and the Environment* 25 (3): 800–811. https://doi.org/10.1007/s10924-016-0864-6.

Milanovic, J. Z., M. Milosevic, I. Jankovic-Castvan, and M. M. Kostic. 2022. "Capillary Rise and Sorption Ability of Hemp Fibers Oxidized by Non-Selective Oxidative Agents: Hydrogen Peroxide and Potassium Permanganate." *Journal of Natural Fibers* 19 (12): 4567–4582. https://doi.org/10.1080/15440478.2020.1870609.

Mohammadi, M., E. Taban, W. H. Tan, N. B. C. Din, A. Putra, and U. Berardi. 2024. "Recent Progress in Natural Fiber Reinforced Composite as Sound Absorber Material." *Journal of Building Engineering* 84:108514. https://doi.org/10.1016/j.jobe.2024.108514.

Mohammed, M., A. J. A. M. Jawad, A. M. Mohammed, J. K. Oleiwi, T. Adam, A. F. Osman, O. S. Dahham, B. O. Betar, S. C. Gopinath, and M. Jaafar. 2023. "Challenges and Advancement in Water Absorption of Natural Fiber-Reinforced Polymer Composites." *Polymer Testing* 124:108083. https://doi.org/10.1016/j.polymertesting.2023.108083.

Mohammed, M., R. Rahman, A. M. Mohammed, T. Adam, B. O. Betar, A. F. Osman, and O. S. Dahham. 2022. "Surface Treatment to Improve Water Repellence and Compatibility of Natural Fiber with Polymer Matrix: Recent Advancement." *Polymer Testing* 115:107707. https://doi.org/10.1016/j.polymertesting.2022.107707.

Mohanta, S., P. Mahalik, G. P. Hota, B. B. Sahoo, S. S. Pradhan, and S. P. Mohanty. 2024. "Influence of Surface-Treatment of Bamboo Fiber on the Physico-Mechanical Properties of Bamboo Fiber Composites with Virgin and Recycled High-Density Polyethylene." *Polymer Composites* 45 (1): 914–923. https://doi.org/10.1002/pc.27825.

Molla, A., A. A. Moyeen, R. Mashfiqua Mahmud, and M. J. Haque. 2024. "Plant Fiber-Reinforced Green Composite: A Review on Surface Modification, Properties, Fabrications and Applications." *Materials Open Research* 3:6. https://doi.org/10.12688/materialsopenres.17651.1.

Muralidharan, N. D., J. Subramanian, S. K. Rajamanickam, and V. Gopalan. 2023. "An Experimental Investigation of Flame Retardancy and Thermal Stability of Treated and Untreated Kenaf Fiber Reinforced Epoxy Composites." *Journal of Polymer Engineering* 43 (10): 865–874. https://doi.org/10.1515/polyeng-2023-0128.

Narayana, V. L., and L. B. Rao. 2023. "Influence of Alkali Treatment and Stacking Sequence on Mechanical, Physical, and Thermal Characteristics of Hemp and Palmyra-Reinforced Hybrid Composites." *Journal of Natural Fibers* 20 (2): 2213908. https://doi.org/10.1080/15440478.2023.2213908.

Nassar, M. M., K. I. Alzebdeh, N. Al-Hinai, and T. Pervez. 2023. "A New Multistep Chemical Treatment Method for High Performance Natural Fibers Extraction." *Journal of Natural Fibers* 20 (1): 2150922. https://doi.org/10.1080/15440478.2022.2150922.

Nawangsari, P., W. Fatra, A. Kusuma, M. Badri, and D. Masnur. 2024. "Microcellulose from Pineapple Leaf Fiber as a PotentialSustainable Material: Extraction and Characterization." *Jurnal Polimesin* 22 (1): 83. https://doi.org/10.30811/jpl.v22i1.4522.

Negi, R. S., L. Prasad, A. Yadav, and J. Winczek. 2022. "Physical and Mechanical Properties of Pinecone Scale Fiber/Vigna Mungo Powder Reinforced Polypropylene Based Hybrid Composites." *Journal of Natural Fibers* 19 (15): 11458–11468. https://doi.org/10.1080/15440478.2022.2025983.

Nikafshar, S., and M. Nejad. 2022. "Evaluating Efficacy of Different UV-Stabilizers/absorbers in Reducing UV-Degradation of Lignin." *Holzforschung* 76 (3): 235–244. https://doi.org/10.1515/hf-2021-0147.

Nlandu-Mayamba, H., A. Taguet, D. Perrin, S. Joannès, F. Delor-Jestin, H. Askanian, and J. M. Lopez-Cuesta. 2024. "Influence of Surface Treatments and Addition of a Reactive Agent on the Properties of PLA/Flax and PLA/Bamboo Composites." *Journal of Thermoplastic Composite Materials*: 08927057241231733. https://doi.org/10.1177/08927057241231733.

Nurazzi, N. M., M. R. M. Asyraf, A. Khalina, N. Abdullah, H. A. Aisyah, S. A. Rafiqah, F. A. Sabaruddin, et al. 2021. "A Review on Natural Fiber Reinforced Polymer Composite for Bullet Proof and Ballistic Applications." *Polymers* 13 (4): 646. https://doi.org/10.3390/polym13040646.

Nyssanbek, M., N. Kuzina, V. Kondrashchenko, and A. Azimov. 2024. "Effects of Plasma Treatment on Biodegradation of Natural and Synthetic Fibers." *Npj Materials Degradation* 8 (1): 23. https://doi.org/10.1038/s41529-024-00437-x.

Otálora González, C. M., M. Felix, C. Bengoechea, S. Flores, and L. N. Gerschenson. 2024. "Development and Characterization of Edible Films Based on Cassava Starch Modified by Corona Treatment." *Foods* 13 (3): 468. https://doi.org/10.3390/foods13030468.

Palai, B. K., and S. K. Sarangi. 2022. "Characterization of Chemical Treated Eichhornia Crassipes Fibers and Its Composites." *Journal of Natural Fibers* 19 (15): 10883–10896. https://doi.org/10.1080/15440478.2021.2002777.

Palanisamy, S., K. Vijayananth, T. M. Murugesan, M. Palaniappan, and C. Santulli. 2024. "The Prospects of Natural Fiber Composites: A Brief Review." *International Journal of Lightweight Materials and Manufacture* 7 (4): 496–506. https://doi.org/10.1016/j.ijlmm.2024.01.003.

Pankaj, J. C., and S. Kant. 2023. "Study on Mechanical Properties and Delamination Factor Evaluation of Chemically Treated Nettle Fiber Reinforced Polymer Composites." *Journal of Natural Fibers* 20 (1): 2135053. https://doi.org/10.1080/15440478.2022.2135053.

Parre, A., B. Karthikeyan, A. Balaji, and R. Udhayasankar. 2020. "Investigation of Chemical, Thermal and Morphological Properties of Untreated and NaOH Treated Banana Fiber." *Materials Today: Proceedings*, India, 347–352, *22*.

Patel, R. V., A. Yadav, and J. Winczek. 2023. "Physical, Mechanical, and Thermal Properties of Natural Fiber-Reinforced Epoxy Composites for Construction and Automotive Applications." *Applied Sciences* 13 (8): 5126. https://doi.org/10.3390/app13085126.

Pérez-Fonseca, A. A., D. Rodrigue, A. S. Martín Del Campo, and J. R. Robledo-Ortíz. 2024. "Polylactic Acid-Agave Fiber Biocomposites: Processing, Properties, Weathering Performance, and Biodegradation." In *Polylactic Acid Composites*, edited by A. A. Pérez-Fonseca, D. Rodrigue, A. S. Martín del Campo and J. R. Robledo-Ortíz, 13–30. Deutschland: De Gruyter.

Pillai, R. R., and V. Thomas. 2023. "Plasma Surface Engineering of Natural and Sustainable Polymeric Derivatives and Their Potential Applications." *Polymers (Basel)* 15 (2): 400. https://doi.org/10.3390/polym15020400.

Placet, V., A. Day, and J. Beaugrand. 2017. "The Influence of Unintended Field Retting on the Physicochemical and Mechanical Properties of Industrial Hemp Bast Fibres." *Journal of Materials Science* 52 (10): 5759–5777. https://doi.org/10.1007/s10853-017-0811-5.

Pokharel, A., K. J. Falua, A. Babaei-Ghazvini, M. Nikkhah Dafchahi, L. G. Tabil, V. Meda, and B. Acharya. 2024. "Development of Polylactic Acid Films with Alkali-And Acetylation-Treated Flax and Hemp Fillers via Solution Casting Technique." *Polymers* 16 (7): 996. https://doi.org/10.3390/polym16070996.

Pradhan, S., V. Prakash, and S. K. Acharya. 2022. "Influence of Chemical Modification on Structural, Morphological, Thermal, and Weathering Behavior of Eulaliopsis Binata Fiber and Its Composites." *Journal of Natural Fibers* 19 (15): 11870–11884. https://doi.org/10.1080/15440478.2022.2044966.

Premalatha, N., S. S. Saravanakumar, M. R. Sanjay, S. Siengchin, and A. Khan. 2021. "Structural and Thermal Properties of Chemically Modified Luffa Cylindrica Fibers." *Journal of Natural Fibers* 18 (7): 1037–1043. https://doi.org/10.1080/15440478.2019.1678546.

Putra, V. G. V., J. N. Mohamad, D. R. Arief, and Y. Yusuf. 2021. "Surface Modification of Polyester-Cotton (TC 70%) Fabric by Corona Discharged Plasma with Tip-Cylinder Electrode Configuration-Assisted Coating Carbon Black Conductive Ink for Electromagnetic Shielding Fabric." *Arab Journal of Basic and Applied Sciences* 28 (1): 272–282. https://doi.org/10.1080/25765299.2021.1889116.

Putra, V. G. V., A. Wijayono, and J. N. Mohamad. 2020. "Novel Method for Fire Retardancy of Cotton Fabrics Coated by Spinach Leaf Extract Assisted by Corona Discharge Plasma." *Dinamika Kerajinan Dan Batik* 37 (2): 369359. https://doi.org/10.22322/dkb.v37i2.6038.

Rachtanapun, P., C. Sawangrat, T. Kanthiya, P. Thipchai, K. Kaewapai, J. Suhr, P. Worajittiphon, N. Tanadchangsaeng, P. Wattanachai, and K. Jantanasakulwong. 2024. "Effect of Plasma Treatment on Bamboo Fiber-Reinforced Epoxy Composites." *Polymers* 16 (7): 938. https://doi.org/10.3390/polym16070938.

Ragoubi, M., D. Bienaimé, S. Molina, B. George, and A. Merlin. 2010. "Impact of Corona Treated Hemp Fibres Onto Mechanical Properties of Polypropylene Composites Made Thereof." *Industrial Crops and Products* 31 (2): 344–349. https://doi.org/10.1016/j.indcrop.2009.12.004.

Ramachandran, A., S. Mavinkere Rangappa, V. Kushvaha, A. Khan, S. Seingchin, and H. N. Dhakal. 2022. "Modification of Fibers and Matrices in Natural Fiber Reinforced Polymer Composites: A Comprehensive Review." *Macromolecular Rapid Communications* 43 (17): 2100862. https://doi.org/10.1002/marc.202100862.

Ramkumar, T., K. Hariharan, M. Selvakumar, and M. Jayaraj. 2022. "Effect of Various Surface Modifications on Characterization of New Natural Cellulosic Fiber from Coconut Tree Secondary Flower Leaf Stalk Fiber (CSF)." *Journal of Natural Fibers* 19 (16): 13362–13375. https://doi.org/10.1080/15440478.2022.2091715.

Ru, S., R. Yang, S. Yang, and C. Zhao. 2023. "Effects of Physical and Mechanical Properties of Coir Fiber and Reinforced Epoxy Composites Treated with Acetic Anhydride and Alkali." *Journal of Natural Fibers* 20 (2): 2285819. https://doi.org/10.1080/15440478.2023.2285819.

Saber, D., A. H. Abdelnaby, and A. M. Abdelhaleim. 2023. "Fabrication of Ecofriendly Composites Using Low-Density Polyethylene and Sugarcane Bagasse: Characteristics' Degradation." *Textile Research Journal* 93 (15–16): 3666–3679. https://doi.org/10.1177/00405175231161281.

Saeed, U., A. A. Taimoor, S. U. Rathur, H. Alhumade, H. AlTuraif, H. S. Bamufleh, E. Siddiqui, and B. Al-Zaitone. 2023. "Sustainable Jute Fiber Reinforced Polylactic Acid Composite: Thermochemical and Thermomechanical Characteristics." *Journal of Composite Materials* 57 (7): 1363–1376. https://doi.org/10.1177/00219983231152552.

Saha, A., and P. Kumari. 2023. "Effect of Alkaline Treatment on Physical, Structural, Mechanical and Thermal Properties of Bambusa Tulda (Northeast Indian Species) Based Sustainable Green Composites." *Polymer Composites* 44 (4): 2449–2473. https://doi.org/10.1002/pc.27256.

Sahoo, S. K., J. R. Mohanty, S. Nayak, and B. Behera. 2021. "Chemical Treatment on Rattan Fibers: Durability, Mechanical, Thermal, and Morphological Properties." *Journal of Natural Fibers* 18 (11): 1762–1771. https://doi.org/10.1080/15440478.2019.1697995.

Sahu, S., S. B. Sahu, S. Nayak, J. Mohapatra, S. K. Khuntia, C. Malla, P. Samal, S. K. Patra, and S. Swain. 2023. "Characterization of Natural Fiber Extracted from Bauhinia Vahlii Bast Subjected to Different Surface Treatments: A Potential Reinforcement in Polymer Composite." *Journal of Natural Fibers* 20 (1): 2162185. https://doi.org/10.1080/15440478.2022.2162185.

Salehudiin, N. M., N. Salim, R. Roslan, N. H. A. Bakar, and S. N. Sarmin. 2023. "Improving the Properties of Kenaf Reinforced Polypropylene Composite by Alkaline Treatment." *Materials Today: Proceedings*, Malaysia, 156–162, *75*.

Sampaio, T. Q., F. S. Cunha, L. M. Campos, and C. A. Pires. 2024. "Evaluation of the Influence of Hydrophilic Extractives on the Formation of Bio-Oil from the Micro-Pyrolysis of Biomass Waste." *Journal of Analytical and Applied Pyrolysis* 178:106417. https://doi.org/10.1016/j.jaap.2024.106417.

Sánchez, M. L., W. Patino, and J. Cardenas. 2020. "Physical-Mechanical Properties of Bamboo Fibers-Reinforced Biocomposites: Influence of Surface Treatment of Fibers." *Journal of Building Engineering* 28:101058. https://doi.org/10.1016/j.jobe.2019.101058.

Sanjay, M. R., S. Siengchin, J. Parameswaranpillai, M. Jawaid, C. I. Pruncu, and A. Khan. 2019. "A Comprehensive Review of Techniques for Natural Fibers as Reinforcement in Composites: Preparation, Processing and Characterization." *Carbohydrate Polymers* 207:108–121. https://doi.org/10.1016/j.carbpol.2018.11.083.

Sarafpour, M., I. Ebrahimi, and N. R. Tanha. 2021. "Improving the Interfacial Properties of Para Aramid Fibers by Surface Treatment via Plasma Jet Method in Atmospheric Pressure." *The European Physical Journal Applied Physics* 93 (1): 11301. https://doi.org/10.1051/epjap/2020200277.

Sarikanat, M., Y. Seki, K. Sever, E. Bozaci, A. Demir, and E. Ozdogan. 2016. "The Effect of Argon and Air Plasma Treatment of Flax Fiber on Mechanical Properties of Reinforced Polyester Composite." *Journal of Industrial Textiles* 45 (6): 1252–1267. https://doi.org/10.1177/1528083714557057.

Sathish, S., L. Prabhu, S. Gokulkumar, N. Karthi, D. Balaji, and N. Vigneshkumar. 2021. "Extraction, Treatment and Applications of Natural Fibers for Bio-composites–a Critical Review." *International Polymer Processing* 36 (2): 114–130. https://doi.org/10.1515/ipp-2020-4004.

Sathishkumar, G. K., M. Ibrahim, M. Mohamed Akheel, G. Rajkumar, B. Gopinath, R. Karpagam, P. Karthik, M. Martin Charles, G. Gautham, and G. Gowri Shankar. 2022. "Synthesis and Mechanical Properties of Natural Fiber Reinforced

Epoxy/Polyester/Polypropylene Composites: A Review." *Journal of Natural Fibers* 19 (10): 3718–3741. https://doi.org/10.1080/15440478.2020.1848723.

Sawangrat, C., P. Thipchai, K. Kaewapai, K. Jantanasakulwong, J. Suhr, P. Wattanachai, and P. Rachtanapun. 2023. "Surface Modification and Mechanical Properties Improvement of Bamboo Fibers Using Dielectric Barrier Discharge Plasma Treatment." *Polymers* 15 (7): 1711. https://doi.org/10.3390/polym15071711.

Selvaraj, M., A. Mylsamy, and B. Mylsamy. 2023. "Characterization of New Natural Fiber from the Stem of Tithonia Diversifolia Plant." *Journal of Natural Fibers* 20 (1): 2167144. https://doi.org/10.1080/15440478.2023.2167144.

Setswalo, K., O. P. Oladijo, M. Namoshe, E. T. Akinlabi, R. M. Sanjay, S. Siengchin, and R. Srisuk. 2023. "The Water Absorption and Thermal Properties of Green Pterocarpus Angolensis (Mukwa)-Polylactide Composites." *Journal of Natural Fibers* 20 (1): 2124217. https://doi.org/10.1080/15440478.2022.2124217.

Sever, K., M. Sarikanat, Y. Seki, G. Erkan, Ü. H. Erdoğan, and S. Erden. 2012. "Surface Treatments of Jute Fabric: The Influence of Surface Characteristics on Jute Fabrics and Mechanical Properties of Jute/Polyester Composites." *Industrial Crops and Products* 35 (1): 22–30. https://doi.org/10.1016/j.indcrop.2011.05.020.

Shadhin, M., R. Jayaraman, M. Rahman, and D. Mann. 2024. "Effect of Fiber Surface Treatment on Mechanical, Interfacial, and Moisture Absorption Properties of Cattail Fiber-Reinforced Composites." *Journal of Applied Polymer Science* 141 (1): e54765. https://doi.org/10.1002/app.54765.

Sharafodin, H., N. Soltanizadeh, and M. S. Barahimi. 2023. "Conjugation of Soy Protein Isolate with Carboxymethyl Cellulose Through Dielectric Barrier Discharge (DBD) Plasma." *Food Chemistry* 407:135059. https://doi.org/10.1016/j.foodchem.2022.135059.

Sheeba, K. J., R. K. Priya, K. P. Arunachalam, S. Avudaiappan, E. S. Flores, and P. Kozlov. 2023. "Enhancing Structural, Thermal, and Mechanical Properties of Acacia Pennata Natural Fibers Through Benzoyl Chloride Treatment for Construction Applications." *Case Studies in Construction Materials* 19:e02443. https://doi.org/10.1016/j.cscm.2023.e02443.

Shenoy Heckadka, S., S. Y. Nayak, T. Joe, N. J. Zachariah, S. Gupta, A. Kumar Nv, and M. Matuszewska. 2022. "Comparative Evaluation of Chemical Treatment on the Physical and Mechanical Properties of Areca Frond, Banana, and Flax Fibers." *Journal of Natural Fibers* 19 (4): 1531–1543. https://doi.org/10.1080/15440478.2020.1784817.

Sifuentes-Nieves, I., J. F. Hernandez-Gamez, P. C. Flores-Silva, J. Gudiño-Rivera, J. E. Rivera-Salinas, E. Saucedo-Salazar, and E. Hernández-Hernández. 2023. "Effect of Treatment Type of Natural Fibers on the Rheological and Micromechanical Behavior of Polyvinyl Alcohol Composites." *Journal of Applied Polymer Science* 140 (37): e54416. https://doi.org/10.1002/app.54416.

Sifuentes-Nieves, I., J. F. Hernandez-Gamez, M. Salinas-Hernández, Z. Garcia-Hernandez, A. Herrera-Guerrero, E. Hernandez-Hernandez, and P. C. Flores-Silva. 2024. "Biopolymer Composites Based on Ultrasound/plasma-Modified Fiber Waste and Polybutylene Adipate Terephthalate (PBAT): Physicochemical and Functional Performance." *Polymer Composites* 45 (8): 7564–7573. https://doi.org/10.1002/pc.28287.

Sifuentes-Nieves, I., R. Yáñez-Macías, P. C. Flores-Silva, P. Gonzalez-Morones, C. A. Gallardo-Vega, E. Ramírez-Vargas, and E. Hernández-Hernández. 2023. "Ultrasound/plasma-Modified Agave Fibers as Alternative Eco-Sustainable Raw Material to Reinforce Starch-Based Films." *Journal of Polymers and the Environment* 31 (2): 595–607. https://doi.org/10.1007/s10924-022-02645-5.

Sillard, C., E. Castro, J. Kaima, Q. Charlier, J. Viguié, M. Terrien, I. Preechawuttipong, R. Peyroux, E. Mauret, and A. Dufresne. 2024. "Bio-Based Composites Made from Bamboo Fibers with High Lignin Contents: A Multiscale Analysis." *Composite Interfaces* 31 (3): 287–304. https://doi.org/10.1080/09276440.2023.2253640.

Su, Q., S. Cai, Q. Duan, W. Huang, Y. Huang, P. Chen, and F. Xie. 2024. "Combined Effect of Heat Moisture and Ultrasound Treatment on the Physicochemical, Thermal and Structural Properties of New Variety of Purple Rice Starch." *International Journal of Biological Macromolecules* 261:129748. https://doi.org/10.1016/j.ijbiomac.2024.129748.

Subagyo, A., and A. Chafidz. 2018. "Banana Pseudo-Stem Fiber: Preparation, Characteristics, and Applications." *Banana Nutrition-Function and Processing Kinetics* 20 (4): 1–19.

Suhada, F. P., A. A. Rosidah, V. A. Setyowati, and S. Suheni. 2023. "The Influence of Fiber Orientation and Treatment Variation of Natural Fiber Reinforced Composites on Tensile Strength and Toughness." *Journal of Applied Sciences, Management and Engineering Technology* 4 (1): 21–28. https://doi.org/10.31284/j.jasmet.2023.v4i1.4461.

Sun, S., S. Pillay, and H. Ning. 2024. "Mechanical Behaviors of Composites Made of Natural Fibers Through Environmentally Friendly Treatment." *Journal of Thermoplastic Composite Materials*: 08927057241239954. https://doi.org/10.1177/08927057241239954.

Tamta, N., and S. Palsule. 2024. "Kenaf Fiber Reinforced Chemically Functionalized Styrene-Acrylonitrile Composites." *Journal of Thermoplastic Composite Materials* 37 (1): 5–27. https://doi.org/10.1177/08927057231168560.

Tavares, T. D., J. C. Antunes, F. Ferreira, and H. P. Felgueiras. 2020. "Biofunctionalization of Natural Fiber-Reinforced Biocomposites for Biomedical Applications." *Biomolecules* 10 (1): 148. https://doi.org/10.3390/biom10010148.

Tenazoa, C., H. Savastano, S. Charca, M. Quintana, and E. Flores. 2021. "The Effect of Alkali Treatment on Chemical and Physical Properties of Ichu and Cabuya Fibers." *Journal of Natural Fibers* 18 (7): 923–936. https://doi.org/10.1080/15440478.2019.1675211.

Thamarai Selvi, S., R. Sunitha, L. Ammayappan, and C. Prakash. 2023. "Impact of Chemical Treatment on Surface Modification of Agave Americana Fibres for Composite Application–A Futuristic Approach." *Journal of Natural Fibers* 20 (1): 2142726. https://doi.org/10.1080/15440478.2022.2142726.

Twebaze, C., M. Zhang, X. Zhuang, M. Kimani, G. Zheng, and Z. Wang. 2022. "Banana Fiber Degumming by Alkali Treatment and Ultrasonic Methods." *Journal of Natural Fibers* 19 (16): 12911–12923. https://doi.org/10.1080/15440478.2022.2079581.

Urdanpilleta, M., R. Del Rey, I. Leceta, J. C. Rodríguez, J. Alba, and P. Guerrero. 2024. "Empirical Modelling of the Acoustic Behavior of Sheep Wool/Soy Protein Biocomposites." *Journal of Building Engineering* 89:109290. https://doi.org/10.1016/j.jobe.2024.109290.

Vallejos, M. E., F. Vilaseca, J. A. Méndez, F. X. Espinach, R. J. Aguado, M. Delgado-Aguilar, and P. Mutjé. 2023. "Response of Polypropylene Composites Reinforced with Natural Fibers: Impact Strength and Water-Uptake Behaviors." *Polymers* 15 (4): 900. https://doi.org/10.3390/polym15040900.

Verma, D., K. L. Goh, and V. Vimal. 2022. "Interfacial Studies of Natural Fiber-Reinforced Particulate Thermoplastic Composites and Their Mechanical Properties." *Journal of Natural Fibers* 19 (6): 2299–2326. https://doi.org/10.1080/15440478.2020.1808147.

Vilay, V., M. Mariatti, R. M. Taib, and M. Todo. 2008. "Effect of Fiber Surface Treatment and Fiber Loading on the Properties of Bagasse Fiber–Reinforced Unsaturated Polyester Composites." *Composites Science and Technology* 68 (3–4): 631–638. https://doi.org/10.1016/j.compscitech.2007.10.005.

Wang, W., W. Chen, M. Zou, R. Lv, D. Wang, F. Hou, H. Feng, et al. 2018. "Applications of Power Ultrasound in Oriented Modification and Degradation of Pectin: A Review." *Journal of Food Engineering* 234:98–107. https://doi.org/10.1016/j.jfoodeng.2018.04.016.

Wang, W., R. Fu, Q. Deng, X. Wang, Y. Wang, Z. Zhang, and G. Xian. 2020. "Surface Modification of Flax Fibers with Isocyanate and Its Effects on Fiber/Epoxy Interfacial Properties." *Fibers and Polymers* 21 (12): 2888–2895. https://doi.org/10.1007/s12221-020-9722-1.

Wu, C. S., and C. H. Tsou. 2019. "Fabrication, Characterization, and Application of Biocomposites from Poly (Lactic Acid) with Renewable Rice Husk as Reinforcement." *Journal of Polymer Research* 26 (2): 44. https://doi.org/10.1007/s10965-019-1710-z.

Yadav, B. K., and V. L. Yadav. 2024. "Nano-Clay Treatment of Jute Fiber for Reinforcement in Polymer Composites: Mechanical, Morphological, and Thermo-Kinetic Analysis." *Journal of Reinforced Plastics & Composites*: 07316844241233420. https://doi.org/10.1177/07316844241233420.

Yang, M., J. Su, Y. Zheng, C. Fang, W. Lei, and L. Li. 2023. "Effect of Different Silane Coupling Agents on Properties of Waste Corrugated Paper Fiber/Polylactic Acid Composites." *Polymers* 15 (17): 3525. https://doi.org/10.3390/polym15173525.

Younesi-Kordkheili, H. 2023. "Maleated Nanolignin as a New Coupling Agent for Wood-Plastic Composites." *Journal of Composite Materials* 57 (30): 4649–4658. https://doi.org/10.1177/00219983231215422.

Zaki, S. Z. S. M., N. Salim, N. H. A. Bakar, R. Roslan, N. A. Samah, S. M. Kabeb, and S. N. Sarmin. 2024. "Investigation of the Effect of Coupling Agent on the Properties of Kenaf Fiber/Polypropylene Composites." *Journal of Physics: Conference Series* 2688 (1): 012006. IOP Publishing.https://doi.org/10.1088/1742-6596/2688/1/012006.

Zhang, B., L. Jia, M. Tian, N. Ning, L. Zhang, and W. Wang. 2021. "Surface and Interface Modification of Aramid Fiber and Its Reinforcement for Polymer Composites: A Review." *European Polymer Journal* 147:110352. https://doi.org/10.1016/j.eurpolymj.2021.110352.

Zhang, L. L., R. Y. Zhu, J. Y. Chen, J. M. Chen, and X. X. Feng. 2008. "Seawater-Retting Treatment of Hemp and Characterization of Bacterial Strains Involved in the Retting Process." *Process Biochemistry* 43 (11): 1195–1201. https://doi.org/10.1016/j.procbio.2008.06.019.

Zhang, L., Z. Xia, Y. He, C. Xin, Y. Yu, F. Ren, and R. Wang. 2023. "Fiber Reinforced Polypropylene Composites Interfacial Behavior Improvement Fabricated by Cold Plasma Jet SiOx Nanoparticles Deposition." *Journal of Composite Materials* 57 (6): 1185–1198. https://doi.org/10.1177/00219983221149793.

Zhang, X., K. Zhang, J. Yang, Y. Zhang, D. Chen, and Z. Yang. 2024. "Mechanical and Abrasive Wear Properties of Rape Stalk Reinforced Polyvinyl Chloride Composites Synergistically Treated by Alkali and Ultrasound." *Polymer Testing* 134:108419. https://doi.org/10.1016/j.polymertesting.2024.108419.

Zheng, G., H. Ye, Y. Liang, X. Jin, C. Xia, W. Fan, Y. Shi, Y. Xie, J. Li, and S. Ge. 2023. "Pre-Treatment of Natural Bamboo for Use as a High-Performance Bio-Composites via Acetic Acid Ball Milling Technology." *Construction and Building Materials* 367:130350. https://doi.org/10.1016/j.conbuildmat.2023.130350.

Zhou, S., L. Wen, Z. Tian, K. C. Yan, J. Cheng, L. Xia, H. Wang, J. Chu, and G. Zou. 2020. "Parameter Optimization of O2/He Atmospheric Pressure Plasma for Surface Modification of Poly (L-Lactic) Acid Oriented Fiber Membranes: Improving Cell Adhesion and Proliferation." *Vacuum* 182:109763. https://doi.org/10.1016/j.vacuum.2020.109763.