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Influence of Fiber Treatments on Water Absorption Behavior in Natural Fiber-Reinforced Polymer Composites: A Review

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ABSTRACT

Natural Fiber-Reinforced Polymer (NFRP) composites have garnered significant attention as sustainable alternatives to synthetic composites, offering lightweight, renewable, and environmentally friendly solutions for diverse engineering applications. However, the hydrophilic nature of natural fibers poses challenges, particularly in the form of water absorption, which compromises mechanical properties and durability. This review comprehensively examines the role of fiber treatments in mitigating these challenges, highlighting their impact on water absorption behavior and composite performance. The study explores various fiber treatment methods, including chemical (alkali, silane, acetylation), physical (plasma, UV irradiation, heat), and biological (enzymatic, microbial) techniques. These treatments enhance fiber hydrophobicity, improve fiber-matrix bonding, and reduce moisture uptake, leading to composites with superior tensile strength, flexural properties, and dimensional stability. Comparative analyses of treated versus untreated fibers demonstrate the significant advantages of treated composites in moisture-resistant applications. In addition to detailing experimental findings, the review addresses the challenges associated with current treatment methods, such as cost, scalability, and environmental impact, and identifies research gaps in understanding the long-term behavior and biodegradability of treated composites. The discussion extends to future directions, emphasizing the need for eco-friendly, cost-effective treatments, hybrid approaches, nano-enhancements, and standardized protocols to advance the field. This review underscores the critical role of fiber treatments in optimizing NFRP composites for practical applications, contributing to the broader goal of sustainable material development. It concludes with a call for continued innovation and collaboration to overcome existing challenges and unlock the full potential of NFRP composites as high-performance, environmentally conscious engineering materials.

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1. Introduction (Bold, 12 pt)

In recent decades, the term "nano" has garnered considerable attention from scientists worldwide. This term has profoundly altered Natural Fiber-Reinforced Polymer (NFRP) composites have emerged as a sustainable alternative to synthetic fiber composites in modern engineering applications [1]. Combining the lightweight, renewable, and biodegradable nature of natural fibers with the durability and versatility of polymer matrices, NFRP composites offer a compelling solution for industries seeking to reduce environmental impacts while maintaining high performance [2]. These composites find applications across diverse fields, including automotive, construction, and packaging, where their mechanical properties and eco-friendly nature are highly valued.

A natural fiber-reinforced polymer or natural fiber-reinforced polymer composite is a polymer matrix incorporated with natural fiber as reinforcement. It is relatively new compared to concrete and steel in the building industry [3]. natural fiber-reinforced polymer composite has been widely used in numerous engineering and industrial fields such as electrical and electronic industries, aerospace, boats, machinery, and office products due to its biodegradable nature, low specific weight but relatively high strength, and relatively low production cost [4]. Natural fibers are defined as fibers originating from plants or animals that are not synthetic or manmade. Compared to synthetic fibers, applying natural fibers as reinforcement for composite fabrication offers several advantages. The advantages and disadvantages of the natural fiber-reinforced polymer composites are summarized in Table 1.

A critical challenge in NFRP composites is their susceptibility to water absorption, primarily due to the hydrophilic nature of natural fibers [5,6]. Water absorption can significantly affect the mechanical properties of these composites, leading to swelling, reduced interfacial bonding, and long-term degradation. Understanding and mitigating this behavior is essential for ensuring the durability and reliability of NFRP composites in practical applications, particularly in humid or wet environments [7,8].

The phenomenon of water absorption in composite materials, particularly those reinforced with fibers, is a critical factor that influences their mechanical properties and overall performance [9,10]. Research indicates that the water absorbed by reinforcing materials often exceeds that of the matrix itself. This discrepancy can be attributed to several factors, including the inherent hydrophilic nature of natural fibers and the structural characteristics of the composites [11-13].

Natural fibers, such as kenaf and pineapple leaf fibers, exhibit a significant capacity for water absorption due to their high cellulose content, which is inherently hydrophilic. For instance, Mehdikhani et al. highlight that the water absorption rate in composites reinforced with kenaf fibers is influenced by the diffusion rate of water through the composite thickness, leading to micro-void formation at the interfaces between the fibers and the matrix [14]. Similarly, Kumar's et al, study on pineapple leaf fiber composites shows that treated fibers have a reduced water absorption capacity compared to untreated ones, yet still demonstrate higher absorption than the matrix itself [15]. This suggests that the fiber's surface characteristics and treatment can modulate but not eliminate the absorption tendency.

Moreover, the interaction between the matrix and the reinforcing fibers plays a crucial role in water absorption dynamics. Gawdzińska et al. discuss how the swelling of fibers upon water absorption creates interfacial stresses, which can lead to defects and degradation of the composite's mechanical properties [16]. This is further supported by the findings of Gudayu et al., who note that moisture absorption can lead to hygroscopic swelling of the matrix, exacerbating the stress at the fiber-matrix interface and potentially resulting in premature aging of the material [17]. The contrasting hydrophilic nature of natural fibers compared to the typically hydrophobic matrix materials creates a scenario where the fibers absorb more water, leading to dimensional changes that can compromise the integrity of the composite.

The mechanisms of water absorption also involve diffusion processes that are influenced by the structural characteristics of the composites. Amjad et al. describe how water molecules diffuse into the micro-gaps between polymer chains and through flaws at the fiber-matrix interface, which can significantly affect the overall water uptake of the composite [18]. This is consistent with the observations made by Al-Maharma & Al-Huniti, who emphasize that environmental conditions, such as temperature and humidity, further influence the water absorption behavior of natural fiber-reinforced composites [19].

The higher water absorption by reinforcing materials compared to the matrix is a well-documented phenomenon that can be attributed to the hydrophilic nature of natural fibers, the structural characteristics of the composites, and the interactions at the fiber-matrix interface. Understanding these dynamics is essential for optimizing the performance of composite materials in applications where moisture exposure is a concern.

Fiber treatments have emerged as a pivotal strategy to address the challenges posed by water absorption in NFRP composites [20]. These treatments modify the surface properties of natural fibers, enhancing their compatibility with polymer matrices and reducing their hydrophilicity. Various chemical, physical, and biological treatments have been developed to achieve these improvements, with notable success in reducing water uptake and improving mechanical performance [21].

The objective of this review is to explore the influence of fiber treatments on the water absorption behavior of NFRP composites. By examining the mechanisms of water absorption, the effectiveness of various treatments, and their impact on composite properties, this review aims to provide a comprehensive understanding of how fiber treatments can enhance the performance and durability of these sustainable materials.

This paper is structured as follows: Section 2 provides an overview of the composition and characteristics of NFRP composites. Section 3 delves into the mechanisms of water absorption in these materials. Section 4 discusses the various fiber treatment methods and their roles in reducing water uptake. Section 5 examines experimental findings on treated vs. untreated fibers, while Section 6 highlights the applications and implications of treated NFRP composites. Finally, Sections 7 and 8 address the challenges, limitations, and future directions, culminating in a conclusion summarizing the key insights and recommendations.

Table 1 Advantages and disadvantages of natural fiber-reinforced polymer composite

Advantages	Disadvantages
Eco-friendly, biodegradable, and renewable	High moisture absorbing property
Readily available	Not homogeneous
Relatively low in cost but high in performance	Fiber preparation is time and labor-intensive
Low in density but high specific strength and stiffness	Large areas are required for cultivation

Low emission of toxic fumes during manufacturing process and disposal at the end of service life	Lower durability and strength

2. Natural Fiber-Reinforced Polymer Composites

Natural Fiber-Reinforced Polymer (NFRP) composites are an innovative class of materials that combine the benefits of renewable natural fibers with the versatility and durability of polymer matrices [22]. These composites have gained significant attention for their potential to offer eco-friendly and cost-effective alternatives to traditional synthetic fiber composites, making them attractive for a variety of applications in industries such as automotive, construction, and marine.

NFRP composites are composed of two primary components: natural fibers and a polymer matrix. The natural fibers serve as the reinforcing phase, providing strength and stiffness, while the polymer matrix acts as a binder, offering structural integrity and environmental protection [23]. Common natural fibers used in these composites include jute, flax, sisal, hemp, and coir. Jute is known for its high tensile strength and availability, while flax is valued for its excellent mechanical properties in high-performance applications. Sisal offers durability and abrasion resistance, hemp provides strength and sustainability, and coir is a cost-effective option with resistance to microbial degradation [24]. The polymer matrices in NFRP composites can be thermoplastics, such as polypropylene and polyethylene, known for their recyclability, or thermosets, like epoxy and polyester resins, which provide superior thermal and chemical resistance.

NFRP composites are praised for their unique advantages. They are lightweight, with significantly lower density than synthetic composites, reducing material weight and energy consumption, particularly in transportation applications [25]. As they are derived from plant-based sources, these composites are renewable and environmentally friendly, with the added benefit of being biodegradable. Their abundant availability and lower cost compared to synthetic fibers make them an economical choice for a wide range of uses.

Despite their advantages, NFRP composites face challenges, primarily due to the hydrophilic nature of natural fibers [26]. This property makes them susceptible to water absorption, which can lead to dimensional instability, such as swelling and shrinkage, and a reduction in mechanical performance due to weakened fiber-matrix bonding. Over time, exposure to moisture can accelerate degradation and compromise the structural integrity of the composite, limiting its applicability in humid or wet environments [27]. Addressing these issues is critical to unlocking the full potential of NFRP composites, and fiber treatments have emerged as a promising solution. By modifying fiber surfaces to enhance compatibility with the polymer matrix and reduce water absorption, treatments can significantly improve the performance and durability of these sustainable materials.

3. Mechanisms of Water Absorption in NFRP Composites

Water absorption in Natural Fiber-Reinforced Polymer (NFRP) composites is a critical factor that affects their performance, particularly in humid or wet environments [28]. The behavior of water absorption in these composites is driven by a combination of primary mechanisms that involve interactions between water molecules, the polymer matrix, and the natural fibers [29].

The primary mechanism of water absorption in NFRP composites is diffusion, which is influenced by several factors including the type of natural fibers used, the polymer matrix, and environmental conditions such as temperature and humidity. Research indicates that moisture absorption typically follows Fickian diffusion behavior, characterized by a linear increase in moisture uptake with the square root of time during the initial exposure [30]. This behavior is particularly evident in composites reinforced with hydrophilic fibers, which tend to absorb water more readily due to their porous structure. Figure 1 summarises this process. For instance, studies have shown that the water absorption rate can increase significantly with temperature, as elevated temperatures enhance the diffusivity of water through the composite matrix, leading to the formation of microcracks at the fiber-matrix interface [31].

The interaction between the natural fibers and the polymer matrix also plays a critical role in moisture absorption [32]. Natural fibers, being inherently hydrophilic, can absorb moisture, which may lead to swelling and degradation of the composite's mechanical properties. For example, the presence of moisture can weaken the adhesion between the fibers and the matrix, resulting in reduced tensile and shear strength. Additionally, the structural characteristics of the fibers, such as their surface area and porosity, significantly influence the extent of water uptake. Composites with higher fiber content or those that utilize fibers with greater surface area tend to exhibit higher moisture absorption rates [33].

Several factors influence the extent of water absorption in NFRP composites. The type of natural fiber plays a significant role, as fibers such as jute, flax, and coir differ in their inherent hydrophilicity and moisture uptake characteristics [34]. The quality of the fiber-matrix interface is another critical factor, as poor bonding can create additional voids and gaps, facilitating water ingress. Environmental exposure, including humidity levels, temperature, and duration of water contact, further affects absorption behavior. Lastly, the overall composite architecture, including fiber orientation, volume fraction, and matrix type, determines the pathways and resistance to water penetration.

Moreover, the treatment of natural fibers can significantly alter their moisture absorption characteristics [35]. For instance, silane treatments have been shown to improve the interfacial adhesion between fibers and the polymer matrix, thereby reducing water uptake. Similarly, optimizing the drying process of natural fibers before their incorporation into composites can minimize moisture content and enhance the overall performance of NFRP. The development of hybrid composites, which combine different types of fibers or incorporate nanomaterials, has also been explored as a strategy to mitigate water absorption while enhancing mechanical properties [36]. In summary, the mechanisms of water absorption in NFRP composites are complex and multifaceted, involving diffusion processes influenced by fiber characteristics, polymer matrix properties, and environmental conditions. Addressing these challenges through material treatment and composite design can lead to improved performance and durability of NFRP composites in various applications.

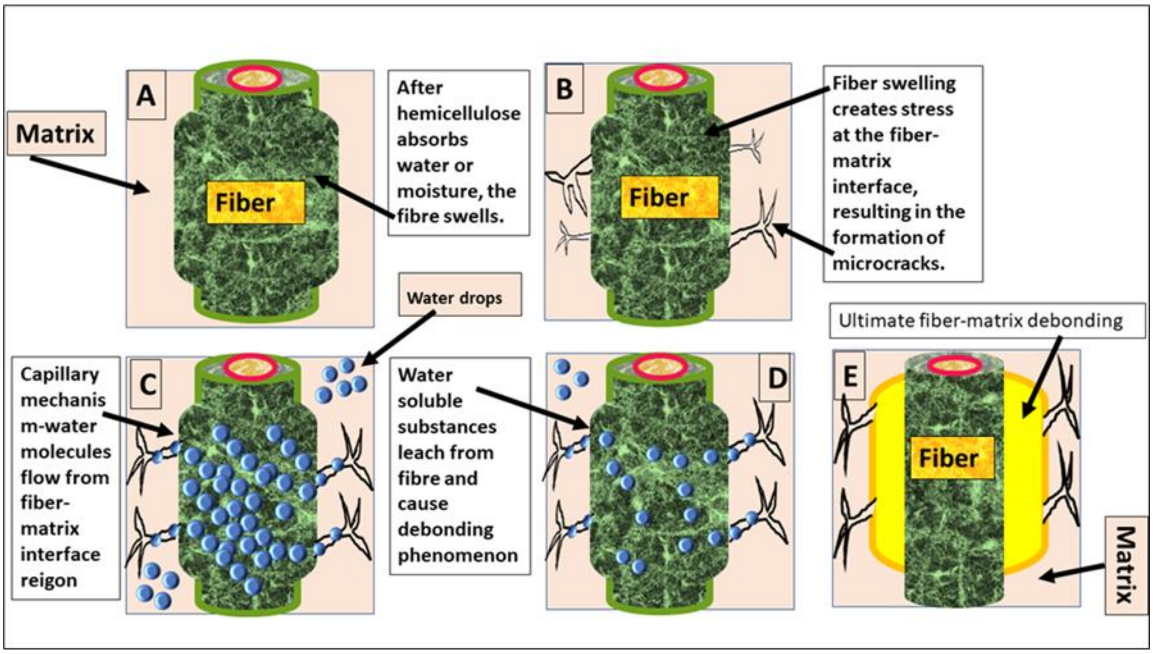

Figure 1: Schematic Representation of Effect of Water on Fiber-Matrix Interface.

4. Fiber Treatments for NFRP Composites

Fiber treatments are essential in addressing the challenges posed by water absorption and poor fiber-matrix bonding in Natural Fiber-Reinforced Polymer (NFRP) composites [37]. The primary purpose of these treatments is to enhance the hydrophobicity of natural fibers and improve their compatibility with polymer matrices. By modifying the fiber surface, these treatments reduce moisture uptake, improve fiber dispersion within the matrix, and strengthen the interfacial bonding, ultimately leading to composites with better mechanical properties and durability [38].

There are three main categories of fiber treatments: chemical, physical, and biological. Chemical treatments are the most widely used and include methods such as alkali treatment, silane coupling, acetylation, and benzoylation. Alkali treatment, or mercerization, removes impurities such as lignin, hemicellulose, and oils from the fiber surface, increasing roughness and exposing cellulose for better bonding [39]. Silane treatments enhance the chemical compatibility between fibers and matrices, forming covalent bonds that improve interfacial adhesion [40]. Acetylation and benzoylation reduce the hydrophilicity of fibers by replacing hydroxyl groups with hydrophobic functional groups, further enhancing water resistance. The silane treatment of NFR is depicted pictorially in Figure 2, which contains a schematic illustration of the process.

Physical treatments, such as plasma treatment, UV irradiation, and heat treatments, modify the fiber surface through non-chemical means [41]. Plasma treatment introduces functional groups onto the fiber surface, increasing roughness and enhancing wettability. UV irradiation alters the chemical composition of the fiber surface, promoting better bonding with the polymer matrix. Heat treatments improve thermal stability and reduce moisture content in the fibers, contributing to enhanced composite performance. Figure 3 is a schematic representation of the plasma treatment that is applied in order to remove surface impurities (the cleaning effect).

Biological treatments, including enzymatic and microbial methods, represent an eco-friendly alternative to traditional chemical treatments [42]. Enzymatic treatments selectively degrade non-cellulosic components of natural fibers, improving their surface properties without the use of harsh chemicals. Similarly, microbial treatments utilize microorganisms to modify the fiber structure, enhancing bonding and reducing hydrophilicity.

The impact of these treatments on NFRP composites is significant. By reducing the hydrophilicity of natural fibers, treatments minimize water absorption and its associated negative effects, such as swelling and mechanical degradation [43]. Additionally, improved compatibility between fibers and polymer matrices leads to stronger interfacial bonding, resulting in composites with superior tensile strength, flexural properties, and dimensional stability.

Fiber treatments are thus a crucial step in optimizing the performance of NFRP composites, enabling their use in diverse applications where water resistance and durability are critical [44]. With continued advancements in treatment techniques, particularly eco-friendly and cost-effective methods, the potential of NFRP composites can be fully realized in sustainable engineering solutions. Table 2 summarizes the types of chemical treatments used in treating the natural fibers for use as reinforcing materials in the production of NFRP.

Table 2 Types of chemical treatment on the natural fibers for use as reinforcing materials

Type of treatment	Chemical used	Details
Alkaline treatment	Sodium hydroxide (NaOH)	Hydrophobic nature and water resistance characteristics are increased due to the elimination of alkali-sensitive hydroxyl groups when reacting with water molecule.
Silane treatment	Silane (SiH_4)	A chemical bond is established between the fiber surface and the matrix through a siloxane bridge, with silanol groups forming in the presence of water. Silanol ensures molecular continuity at the composite interface by reacting at one end with the cellulose hydroxyl groups and at the other end with the functional groups of the matrix.
Peroxide treatment	Benzoyl peroxide ($C_{14}H_{10}O_4$) or dicumyl peroxide ($C_{18}H_{22}O_2$)	Peroxide-induced grafting enables polyethylene to bond to the fiber surface. Peroxide-initiated free radicals interact with the fiber's hydroxyl groups as well as the matrix.
Benzoylation treatment	Benzoyl chloride (C_6H_5COCl)	Alkali pretreatment is performed before benzoylation to expose additional reactive hydroxyl groups. The hydrophilic nature of the fiber decreases as the benzoyl group replaces its hydroxyl group.

Isocyanate treatment	Isocyanate	Coupling agent for fiber surface modification. A urethane linkage with strong covalent bonds forms between the isocyanate functional group and the hydroxyl groups of cellulose and lignin. Enhances the bond strength and improves moisture resistance between the fiber and the matrix.
Sodium chlorite treatment	Acidified sodium chlorite ($NaClO_2$)	Chlorine dioxide (ClO2), generated during the oxidation process, reacts with and removes lignin and hemicellulose from the fiber. Moisture was removed, and the hydrophilic nature of the fibers is reduced.
Stearic acid treatment	Stearic acid ($CH_3(CH_2)_{16}COOH$) in ethyl alcohol solution	The carboxyl group of stearic acid reacts with the fiber's hydroxyl group, thereby enhancing water resistance. Noncrystalline compounds, such as pectin and wax oils, are removed, resulting in improved fiber-matrix adhesion.
Triazine treatment	Triazine ($C_3H_3N_3$) derivative	Reactive chlorines undergo esterification with the hydroxyl groups of the fiber. Strong fiber-matrix adhesion is achieved through crosslinking between cellulose and the matrix via hydrogen bonding.
Acetylation treatment	Acetic anhydride ($(CH_3CO)_2O$)	The hydrophilic nature of the fiber is reduced through the reaction between the acetic group and the hydroxyl group. Dimensional stability is improved.
Malleated coupling agents	Maleic anhydride ($C_2H_2(CO)_2O$)	The hydrophilic tendency is reduced by a long-chain polymer coating on the fiber surface, formed through the reaction of maleic anhydride with the hydroxyl groups in the amorphous

		region of the cellulose structure.
Permanganate treatment	Potassium permanganate ($KMnO_4$) in acetone solution	Better adhesion between fiber and matrix is obtained due to the enhanced chemical interlocking at the interface by the cellulose manganate formed by the reaction between permanganate (Mn^{3+}) ions and cellulose hydroxyl groups. A reduction in hydrophilic nature is also observed as cellulose permanganate reacts with the hydroxyl groups of lignin, removing it from the fiber cell wall.
Acrylation and acrylonitrile grafting	Acrylic acid	Better interfacial bonding, as higher polymerization degree is achieved by thereaction between $CH_2 = CHCOOH$ with the cellulosic hydroxyl groups. Water resistance characteristics are attained when ester linkages are formed between cellulose hydroxyl groups and carboxylic acids from coupling agents.
Fungal treatment	Fungi	Eliminates noncellulosic materials such as wax. Improves the hydrophobic nature of the fiber by eliminating lignin and enhancing the solubility of hemicellulose.

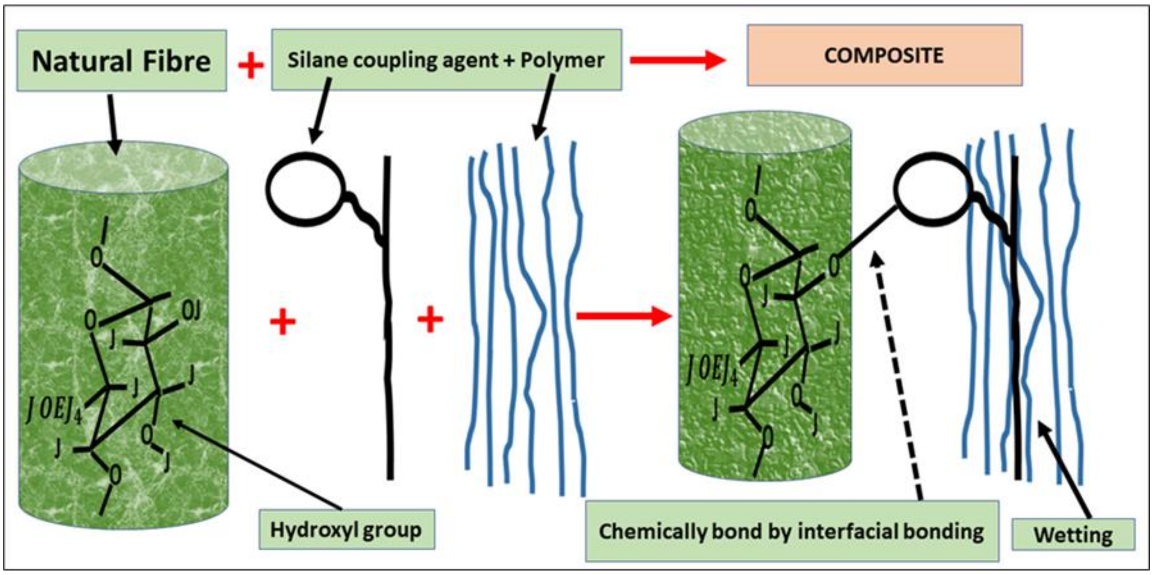

Figure 2: Schematic representation of silane treatment.

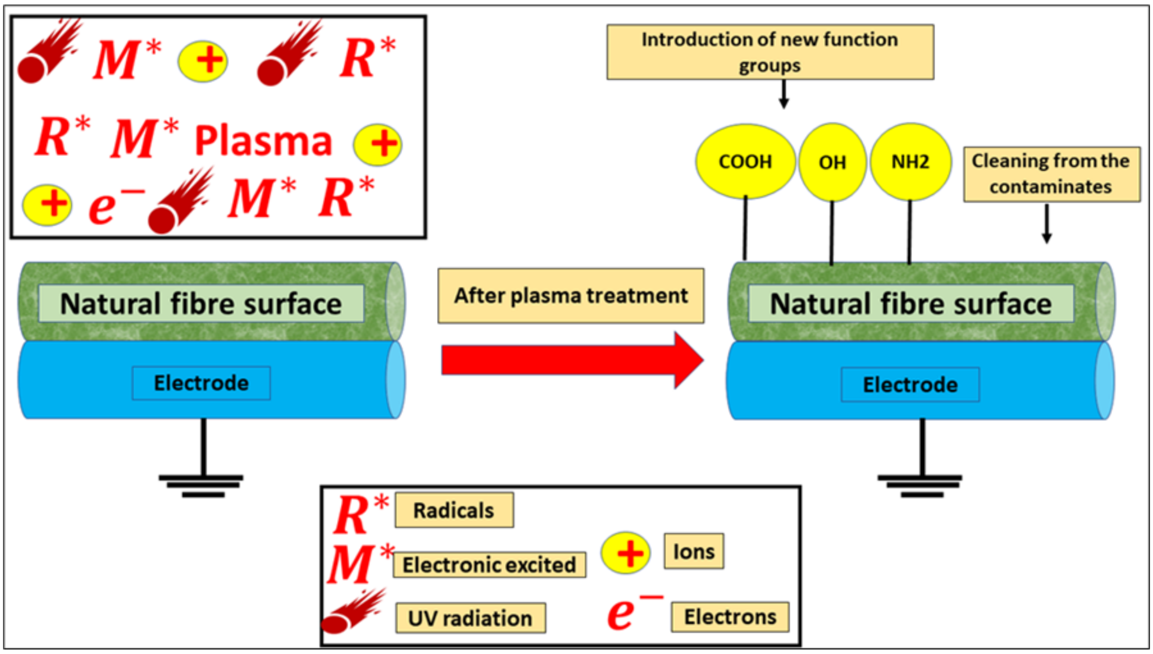

Figure 3: Schematic representation of the plasma surface treatment.

5. Experimental Findings on Water Absorption

Experimental studies on water absorption in Natural Fiber-Reinforced Polymer (NFRP) composites provide valuable insights into the differences between untreated and treated fibers and their impact on composite performance. Comparisons between treated and untreated fibers consistently reveal significant variations in water uptake and saturation levels [45]. Untreated fibers, due to their natural hydrophilicity, exhibit high moisture absorption, which leads to swelling, poor fiber-matrix bonding, and eventual degradation of mechanical properties. In contrast, treated fibers demonstrate reduced water uptake and improved dimensional stability, highlighting the effectiveness of fiber treatments in mitigating these challenges.

Specific treatments, such as alkali, silane, and acetylation, have been extensively studied for their effectiveness in reducing water absorption. Alkali treatment, by removing impurities like lignin and hemicellulose, not only exposes cellulose for better matrix bonding but also reduces hydrophilic sites, thereby lowering moisture absorption [46]. Silane treatment creates chemical linkages between the fiber surface and the polymer matrix, enhancing compatibility and further reducing water ingress. Acetylation, which replaces hydroxyl groups with hydrophobic acetyl groups, is particularly effective in decreasing the moisture absorption capacity of natural fibers [47]. Experimental results consistently show that composites reinforced with treated fibers exhibit significantly lower water absorption rates compared to those with untreated fibers.

The experimental findings on water absorption in fiber-reinforced composites reveal significant differences between treated and untreated fibers, particularly regarding their water uptake and saturation levels. Studies indicate that treated fibers generally exhibit a lower water absorption capacity compared to their untreated counterparts. For instance, Kumar et al. found that treated Borassus fiber reinforced composites had a water absorption capacity of 6.63%, while untreated composites absorbed more water, demonstrating the effectiveness of treatment in reducing hydrophilicity [48]. Similarly, D'Almeida et al. reported that acetylation treatment led to a decrease in water absorption from 8.3% for raw fibers to 7.6% for treated fibers, indicating enhanced hydrophobic behavior, although the difference was small and may suggest limited effectiveness [49]. This trend is consistent across various studies, which collectively suggest that chemical treatments effectively mitigate water absorption in natural fiber composites.

The impact of specific treatments, such as alkali, silane, and acetylation, has been extensively analyzed. Alkali treatment is known to remove hydrophilic components from the fiber surface, thereby reducing water absorption. Chen et al. highlighted that alkali treatment effectively eliminated wax and silica, which contribute to moisture retention, leading to a significant reduction in water uptake [50]. Acetylation modifies the fiber structure by introducing acetyl groups that replace hydroxyl groups, which are responsible for water absorption. This treatment has been shown to improve the mechanical properties of composites while simultaneously reducing water absorption [51,52]. Silane treatment also plays a crucial role; for instance, Maruyama et al. demonstrated that silane-treated bamboo fiber composites exhibited a 72% increase in tensile strength and reduced water absorption, underscoring the treatment's effectiveness in enhancing interfacial adhesion and moisture resistance [53].

The correlation between water absorption and composite performance is critical, particularly concerning tensile strength, flexural modulus, and durability. High water absorption can lead to dimensional instability and reduced mechanical properties due to the weakening of the fiber-matrix interface. For example, Ismail et al. noted that increased water absorption in natural fibers could result in swelling and interfacial breakdown, which adversely affects tensile strength [54]. Conversely, composites with treated fibers generally show improved mechanical performance. For instance, Kumarnitish et al. found that acetylation-treated Borassus fiber composites exhibited enhanced mechanical properties alongside reduced water absorption tendencies [55]. Furthermore, studies have shown that composites treated with silane not only reduce water absorption but also significantly enhance tensile properties, indicating a strong relationship between moisture resistance and overall composite performance [55,56].

The correlation between water absorption and composite performance is evident in various mechanical properties. Reduced water uptake in treated fibers directly contributes to improved tensile strength, as the fibers maintain their structural integrity and bonding within the matrix under moist conditions. Similarly, a lower moisture content in treated composites results in enhanced flexural modulus, reflecting greater resistance to bending and deformation. Durability tests further indicate that treated fibers help maintain long-term stability and mechanical performance, even under prolonged exposure to water or high humidity environments.

Overall, experimental findings underscore the critical role of fiber treatments in enhancing the water resistance and mechanical performance of NFRP composites. By effectively addressing the challenges posed by water absorption, these treatments pave the way for broader applications of NFRP composites in industries where moisture exposure is a significant concern, such as automotive, construction, and marine sectors.

6. Applications and Implications

The development of treated Natural Fiber-Reinforced Polymer (NFRP) composites has opened new avenues for their application in various engineering fields [57,58]. The development of treated Natural Fiber-Reinforced Polymer (NFRP) composites has significantly expanded their applicability across various engineering fields, driven by their unique properties and environmental benefits. NFRPs are increasingly recognized for their potential as sustainable alternatives to traditional synthetic composites, such as glass and carbon fiber-reinforced polymers (CFRPs and GFRPs). This shift is largely due to the favorable mechanical properties, lower density, and cost-effectiveness of natural fibers, which make them suitable for applications in automotive, aerospace, and civil engineering sectors [59].

Natural fibers, such as kenaf, jute, and flax, have been extensively studied for their reinforcement capabilities in polymer matrices. For instance, research indicates that kenaf fibers can effectively replace synthetic fibers in automotive components, enhancing the mechanical properties while reducing environmental impact [60]. The mechanical performance of NFRPs is influenced by several factors, including fiber type, treatment processes, and the nature of the polymer matrix. Studies have shown that chemical treatments, such as alkali treatment, can improve fiber-matrix adhesion, leading to enhanced mechanical properties of the composites [61,62]. Furthermore, the incorporation of nanoclay into flax fiber-reinforced epoxy composites has been found to improve interfacial shear strength and overall mechanical performance, showcasing the versatility of NFRPs in engineering applications [63].

The advantages of NFRPs extend beyond mechanical properties; they also exhibit favorable acoustic and thermal characteristics, making them suitable for applications requiring sound insulation and thermal stability [64]. For example, the acoustic performance of NFRPs can be tailored through various processing methods and reinforcement architectures, allowing for specific applications in sound-dampening materials [65]. Moreover, the lightweight nature of NFRPs contributes to energy efficiency in transportation applications, aligning with the growing demand for sustainable engineering solutions [66].

The enhanced water resistance and mechanical performance achieved through fiber treatments make these composites particularly suitable for industries such as automotive, marine, construction, and packaging. In the automotive sector, treated NFRP composites are used in interior components, dashboards, and door panels, where lightweight materials are crucial for improving fuel efficiency and reducing emissions. In the marine industry, these composites are increasingly employed in boat hulls, decking, and other components exposed to high levels of moisture, as their improved water resistance ensures durability and long-term performance.

In construction, treated NFRP composites are utilized in applications such as cladding, roofing, and insulation panels. Their lightweight nature, coupled with enhanced resistance to environmental degradation, makes them an attractive alternative to conventional materials in building designs that prioritize sustainability and energy efficiency. In civil engineering, NFRPs have been utilized for the rehabilitation of concrete structures, demonstrating comparable performance to traditional FRPs while offering lower costs and reduced environmental impact [67]. Their application in structural components is further supported by advancements in manufacturing techniques, which enhance the mechanical properties and durability of NFRPs . The integration of natural fibers into polymer matrices not only promotes sustainability but also addresses the challenges associated with waste management in the agricultural sector, as these fibers can be sourced from renewable resources [68]. The packaging industry also benefits from treated NFRP composites, where their biodegradability and reduced moisture absorption are key factors in developing eco-friendly and durable packaging solutions for various products.

Beyond their engineering applications, the implications of treated NFRP composites extend to environmental sustainability. By addressing the challenges of water absorption, fiber treatments significantly improve the lifespan and reliability of NFRP composites, reducing the need for frequent replacements and the associated environmental costs. The use of renewable natural fibers as reinforcement materials further contributes to the reduction of carbon footprints, promoting sustainable practices across industries [69]. Additionally, many fiber treatment methods are evolving to become more environmentally friendly, such as the adoption of enzymatic and green chemical treatments, aligning with the global push for sustainable material development.

The applications and implications of treated NFRP composites highlight their potential to bridge the gap between performance and sustainability. By leveraging advancements in fiber treatments, industries can adopt these composites as reliable and eco-friendly alternatives, contributing to a more sustainable future across engineering and manufacturing sectors [70].

The development of treated NFRP composites presents a promising avenue for innovation in various engineering fields. Their mechanical, acoustic, and thermal properties, combined with environmental benefits, position them as viable alternatives to conventional materials. As research continues to explore the optimization of fiber treatments and composite manufacturing processes, the potential applications of NFRPs are expected to expand further, contributing to a more sustainable future in engineering.

7. Challenges and Limitations

Despite the significant advancements in fiber treatments for Natural Fiber-Reinforced Polymer (NFRP) composites, several challenges and limitations remain, hindering their widespread adoption and performance optimization. One of the primary limitations lies in the cost and scalability of current treatment methods. Many chemical treatments, such as silane or acetylation, involve expensive reagents and processes that can increase the overall production cost of NFRP composites [71]. This cost factor poses a barrier to their adoption in cost-sensitive industries, particularly in developing regions. Additionally, scaling these treatment processes for large-scale manufacturing often requires specialized equipment and facilities, further complicating their implementation [72].

Environmental concerns also persist with certain fiber treatment methods. Many chemical treatments rely on non-renewable resources or generate hazardous byproducts that can negatively impact the environment [73]. While efforts are being made to develop more eco-friendly treatments, such as enzymatic or green chemical methods, their effectiveness and scalability still require further refinement. Balancing the trade-off between performance enhancement and environmental impact remains a critical challenge for the development of sustainable NFRP composites.

Research gaps further exacerbate the challenges in optimizing fiber treatments for NFRP composites. Limited studies have been conducted on the long-term behavior of treated composites under real-world conditions, such as prolonged exposure to varying environmental factors, mechanical loads, and chemical interactions. Understanding the durability and aging behavior of treated composites is essential to ensure their reliability and suitability for applications with demanding performance requirements [74]. Additionally, the biodegradability of treated composites remains an area with insufficient exploration. While natural fibers are inherently biodegradable, certain treatments can alter this property, potentially affecting the environmental benefits of NFRP composites. Comprehensive studies on the lifecycle and end-of-life behavior of treated composites are needed to address these uncertainties [75].

Overcoming these challenges and addressing research gaps is critical for advancing the potential of treated NFRP composites. Developing cost-effective, scalable, and environmentally friendly treatments while expanding the knowledge of their long-term behavior and biodegradability will enable these materials to fulfill their promise as sustainable alternatives in various engineering applications. Continued research and innovation are essential to achieving these goals and unlocking the full potential of NFRP composites in the global market.

8. Future Directions

The future of fiber treatments for Natural Fiber-Reinforced Polymer (NFRP) composites lies in the development of advanced techniques that address current limitations while enhancing performance and sustainability. A key area of focus is the creation of eco-friendly and cost-effective treatment methods. Researchers are exploring green chemical treatments and enzymatic processes that minimize environmental impact without compromising effectiveness. These methods aim to replace hazardous chemicals with renewable or biodegradable alternatives, aligning with global sustainability goals. Developing treatments that are both affordable and scalable will be crucial for widespread adoption, particularly in industries where cost constraints are a significant barrier.

Another promising avenue is the use of hybrid approaches that combine chemical and physical treatments. For instance, coupling alkali treatment with plasma or UV irradiation can synergistically enhance fiber surface properties, improving both water resistance and interfacial bonding. These hybrid methods leverage the strengths of multiple techniques, offering enhanced performance compared to single-treatment methods. By tailoring the combination of treatments to specific application requirements, these approaches can achieve superior composite properties while maintaining efficiency and scalability.

The integration of nanotechnology presents another exciting frontier for advancing NFRP composites. The application of nanomaterials, such as nano-silica, carbon nanotubes, and graphene, can significantly enhance water resistance, mechanical strength, and thermal stability. Nanomaterials can be incorporated into fiber treatments to create surface coatings or embedded directly within the matrix, improving the overall composite structure. These nano-enhancements open new possibilities for high-performance composites in demanding applications, such as automotive and aerospace industries.

Standardization and scalability are critical factors for translating these advanced treatments into practical applications. Establishing standardized protocols for fiber treatments will ensure consistency and reliability across manufacturing processes, enabling industries to adopt these methods with confidence. Additionally, scalable treatment technologies that are compatible with industrial production lines will facilitate the large-scale adoption of treated NFRP composites, particularly in markets where volume production is essential.

Future advancements in fiber treatments for NFRP composites promise to overcome current challenges and unlock the full potential of these sustainable materials. By focusing on eco-friendly innovations, hybrid methods, nano-enhancements, and standardized practices, the next generation of NFRP composites can deliver exceptional performance while contributing to a more sustainable and environmentally conscious future. Continued research and collaboration among academia, industry, and policymakers will be vital in realizing these advancements.

9. Conclusion

Fiber treatments play a pivotal role in enhancing the performance of Natural Fiber-Reinforced Polymer (NFRP) composites by significantly reducing water absorption and improving mechanical properties. By addressing the inherent hydrophilicity of natural fibers, treatments such as chemical, physical, and biological methods modify the fiber surface to enhance hydrophobicity and strengthen fiber-matrix bonding. Experimental findings consistently demonstrate that treated composites exhibit lower water uptake, better dimensional stability, and improved tensile and flexural properties compared to untreated counterparts. These advancements are crucial for extending the applicability of NFRP composites across diverse industries, particularly in environments where moisture resistance is critical.

This review highlights the importance of fiber treatments in optimizing the properties of NFRP composites, offering valuable insights into their mechanisms, effectiveness, and implications. By providing a comprehensive analysis of the different treatment methods and their impacts, this review contributes to a deeper understanding of how these treatments address the challenges associated with water absorption and durability. Furthermore, it underscores the potential of treated NFRP composites to serve as sustainable and high-performance alternatives to conventional materials in engineering applications.

To fully realize the potential of NFRP composites, continued research and innovation in fiber treatments are essential. Future efforts should focus on developing eco-friendly, cost-effective, and scalable methods that align with global sustainability goals. Hybrid approaches and nano-enhancements offer promising avenues for achieving superior performance, while standardized protocols can facilitate the widespread adoption of treated composites. By prioritizing sustainability and innovation, researchers, industry professionals, and policymakers can collaboratively advance the field, ensuring that NFRP composites remain at the forefront of sustainable material development. This commitment will pave the way for environmentally conscious engineering solutions that meet the demands of a rapidly evolving world.

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