Enhancing Natural Fibre Composites: A Review of Interface Treatment

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***Abstract*— Natural fibre composites are gaining attention due to their sustainability, biodegradability, and favorable mechanical properties. However, weak fibre-matrix interfacial bonding significantly limits their structural performance and long-term durability. This paper presents a comprehensive review of recent advances in interface treatment of natural fibre composites, focusing on chemical, physical, and biological modification techniques. The effects of these treatments on fibre morphology, surface chemistry, and compatibility with polymer matrices are critically examined. Furthermore, the influence of interface modification on mechanical, thermal, and moisture resistance properties of composites is discussed. Emerging trends, including eco-friendly treatments, nanotechnology integration, and hybrid modification approaches, are also highlighted. This review provides insight into optimizing fibre-matrix adhesion for improved composite performance in engineering applications.**

***Index Terms*— Natural fibre composites, interface treatment, fibre-matrix adhesion, chemical modification, biological treatment, sustainability.**

I. INTRODUCTION

The increasing global emphasis on sustainability, environmental conservation, and the reduction of carbon footprints has significantly accelerated the search for eco-friendly and renewable materials in engineering and industrial applications. Conventional synthetic fibre-reinforced composites, such as glass and carbon fibre composites, although possessing excellent mechanical properties, are associated with environmental concerns including non-biodegradability, high energy consumption during production, and disposal challenges [1]– [3]. In response to these challenges, natural fibre reinforced polymer composites (NFRPCs) have emerged as viable alternatives due to their sustainability advantages, including low density, biodegradability, renewability, and relatively low cost [4]– [6].

Natural fibres such as jute, hemp, flax, sisal, kenaf, and bamboo are increasingly being utilized as reinforcements in polymer matrices. These fibres are derived from plant-based sources and are characterized by their lignocellulosic structure, which primarily consists of cellulose, hemicellulose, and lignin [7], [8]. Their abundance and favorable specific mechanical properties make them suitable for various engineering applications. Consequently, NFRPCs have found widespread use in industries such as automotive (interior panels, dashboards), construction (panels, boards), packaging, and consumer goods [9]– [11]. Major automotive manufacturers have already incorporated natural fibre composites into vehicle components to reduce weight and improve sustainability [12].

Despite these advantages, the widespread adoption of natural fibre composites is hindered by several inherent limitations, the most critical of which is the poor interfacial bonding between the fibre and the polymer matrix [13], [14]. The performance of any composite material is largely governed by the efficiency of stress transfer across the fibre-matrix interface. In NFRPCs, this interface is often weak due to the fundamental incompatibility between the hydrophilic nature of natural fibres and the hydrophobic nature of most polymer matrices, such as polypropylene, polyethylene, and epoxy resins [15], [16].

Natural fibres contain a large number of hydroxyl (–OH) groups in their cellulose structure, which readily form hydrogen bonds with water molecules, leading to high moisture absorption [17]. This hydrophilic behavior results in poor wettability by hydrophobic polymers, ultimately leading to inadequate adhesion at the interface [18]. As a consequence, composites exhibit defects such as fibre pull-out, void formation, interfacial debonding, and crack propagation under mechanical loading [19], [20]. These issues significantly reduce the mechanical strength, stiffness, impact resistance, and long-term durability of the composites.

The fibre-matrix interface plays a pivotal role in determining the overall properties of composite materials. A strong interface ensures efficient load transfer from the matrix to the reinforcement, thereby enhancing mechanical performance [21]. Conversely, a interface results in inefficient stress distribution, leading to premature failure of the composite structure [22]. Therefore, improving interfacial adhesion is essential for optimizing the performance of natural fibre composites and expanding their application range.

To address these challenges, extensive research has been conducted on interface modification techniques aimed at enhancing fibre-matrix compatibility. These techniques can be broadly categorized into chemical, physical, and biological treatments [23], [24]. Chemical treatments, such as alkali treatment, silane coupling, acetylation, and peroxide treatment, are widely used to modify fibre surfaces by removing -mpurities and reducing hydrophilicity [25], [26]. While effective, these methods often involve hazardous chemicals and raise environmental and health concerns.

Physical treatments, including plasma treatment, corona discharge, and ultraviolet (UV) irradiation, alter the surface characteristics of fibres without significantly affecting their bulk properties [27]. These methods improve surface roughness and wettability, thereby enhancing mechanical interlocking at the interface. However, their high energy requirements and cost limit large-scale industrial applications.

More recently, biological treatments have gained attention as environmentally friendly alternatives for interface modification. These treatments utilize enzymes, bacteria, or fungi to selectively remove non-cellulosic components such as lignin and hemicellulose from fibre surfaces [28], [29]. Biological methods offer advantages such as low environmental impact, energy efficiency, and minimal fibre damage. They also provide precise control over surface modification, making them promising for next-generation sustainable composites [30].

In addition to traditional treatments, emerging approaches such as nanotechnology-based modifications, hybrid treatments, and the incorporation of nanofillers (e.g., nanocellulose, graphene, and carbon nanotubes) are being explored to further enhance interfacial properties [31], [32]. These innovations aim to improve not only mechanical performance but also thermal stability, moisture resistance, and durability of NFRPCs.

Given the critical role of the interface in determining composite performance, there is a growing need for a comprehensive understanding of various interface treatment methods and their effects on fibre properties and overall composite behavior. This review aims to provide an in-depth analysis of recent advances in interface treatment of natural fibre composites. It focuses on the mechanisms, advantages, and limitations of chemical, physical, and biological treatments, as well as their impact on mechanical, physical, and durability properties of composites.

Furthermore, this review highlights emerging trends and future research directions in the field, including sustainable treatment technologies, hybrid modification techniques, and advanced characterization methods. By synthesizing recent findings from the literature, this work seeks to contribute to the development of high-performance, eco-friendly composite materials suitable for modern engineering applications.

II. OVERVIEW OF NATURAL FIBRE COMPOSITES

A. Composition and Structure

Natural fibre reinforced polymer composites (NFRPCs) are engineered materials composed of two or more distinct phases that work synergistically to achieve enhanced performance. These composites primarily consist of three fundamental components: reinforcement, matrix, and interface. Each of these constituents plays a crucial role in determining the overall behavior and performance of the composite system.

The reinforcement phase typically consists of natural fibres such as jute, flax, hemp, sisal, bamboo, and kenaf. These fibres are lignocellulosic in nature and are composed mainly of cellulose, hemicellulose, and lignin. Cellulose provides strength and stiffness, hemicellulose contributes to moisture absorption, while lignin offers rigidity and resistance to microbial attack [1]. The mechanical properties of the fibres, including tensile strength, modulus, and aspect ratio, significantly influence the load-bearing capacity of the composite.

The matrix phase acts as a binder that holds the fibres together, transfers applied loads, and protects the reinforcement from environmental damage. Matrices used in NFRPCs can be broadly classified into thermoplastics (e.g., polyethylene, polypropylene) and thermosets (e.g., epoxy, polyester). Thermoplastics offer recyclability and ease of processing, whereas thermosets provide superior mechanical strength and thermal stability [2]. The selection of matrix material depends on the intended application and required performance characteristics.

The interface is the region of interaction between the fibre and the matrix and is considered the most critical component in composite design. It governs stress transfer efficiency and directly affects mechanical properties such as tensile strength, flexural strength, and impact resistance. A strong interfacial bond ensures effective load transfer from the matrix to the reinforcement, while a weak interface leads to debonding and failure [3]. However, due to the inherent incompatibility between hydrophilic natural fibres and hydrophobic polymer matrices, achieving optimal interfacial adhesion remains a significant challenge.

Overall, the performance of natural fibre composites is strongly dependent on the interplay between fibre properties, matrix characteristics, and interfacial bonding. Optimizing these three components is essential for achieving high-performance composite materials suitable for engineering applications.

B. Advantages of Natural Fibre Composites

Natural fibre composites have gained considerable attention in recent years due to their numerous advantages over conventional synthetic fibre composites. One of the most notable benefits is their low cost and wide availability, as natural fibres are derived from renewable agricultural resources and are often considered waste by-products of farming activities [14].

Another important advantage is their lightweight nature, which contributes to high specific strength and stiffness. This property is particularly beneficial in applications such as automotive and aerospace industries, where weight reduction leads to improved fuel efficiency and reduced emissions [15]. Additionally, natural fibres exhibit good acoustic and thermal insulation properties, making them suitable for interior components and building materials.

Environmental sustainability is a key driver for the adoption of natural fibre composites. These materials are biodegradable and renewable, thereby reducing environmental pollution and dependence on fossil-based resources [6]. Unlike synthetic fibres, natural fibres require significantly less energy for production and generate lower greenhouse gas emissions. This makes them an attractive option for industries seeking to comply with environmental regulations and sustainability goals.

Furthermore, natural fibre composites are non-toxic, non-abrasive, and safer to handle, which improves workplace safety and reduces tool wear during processing. Their versatility allows them to be used in a wide range of applications, including automotive interior panels, packaging materials, construction boards, and consumer products [7].

Due to these advantages, natural fibre composites are widely used in semi-structural and non-structural applications, where moderate strength and environmental performance are prioritized over extreme mechanical requirements.

C. Limitations

Despite their numerous benefits, natural fibre composites face several limitations that restrict their application in high-performance engineering environments. One of the most significant drawbacks is their high moisture absorption, which is primarily due to the presence of hydroxyl groups in cellulose. This leads to swelling, dimensional instability, and degradation of mechanical properties when exposed to humid environments [18].

Another critical limitation is poor dimensional stability. Natural fibres tend to expand and contract with changes in temperature and humidity, resulting in internal stresses and microcracks within the composite structure. This behavior negatively affects long-term durability and reliability, particularly in outdoor or harsh environmental conditions.

The most prominent challenge, however, is the weak interfacial bonding between the fibre and the matrix. The hydrophilic nature of natural fibres and the hydrophobic nature of polymer matrices result in poor wettability and adhesion. This incompatibility leads to inefficient stress transfer, fibre pull-out, and interfacial debonding under mechanical loading [19]. Consequently, the mechanical properties of natural fibre composites are often inferior to those of synthetic fibre composites.

Additionally, natural fibres exhibit variability in properties due to differences in plant species, growth conditions, extraction methods, and processing techniques. This inconsistency makes it difficult to achieve uniform composite performance and poses challenges for large-scale industrial applications [10].

Thermal stability is another concern, as natural fibres degrade at relatively low temperatures (typically between 170°C and 200°C), limiting their compatibility with high-temperature processing techniques and certain thermoplastic matrices [8].

In summary, while natural fibre composites offer significant environmental and economic advantages, their limitations particularly in terms of moisture sensitivity, dimensional instability, and weak interfacial bonding necessitate the use of surface modification and interface treatment techniques. Addressing these challenges is essential for enhancing their performance and expanding their application in advanced engineering fields [12].

III. FIBRE-MATRIX INTERFACE IN COMPOSITES

A. Importance of Interface

In fibr-reinforced composite systems, the fibre-matrix interface represents the transitional region where the reinforcement and matrix interact to transfer applied loads. This interfacial zone is critical because it governs the efficiency with which stress is transmitted from the relatively weak matrix to the stronger reinforcing fibres. A well-bonded interface enables uniform stress distribution and prevents localized stress concentrations, thereby enhancing the structural integrity of the composite [1].

A strong interface contributes significantly to improved mechanical properties such as tensile strength, flexural strength, and impact resistance. It also enhances fatigue performance and long-term durability, especially under cyclic loading and environmental exposure. Conversely, a weak interface leads to inefficient load transfer, resulting in premature failure even when high-strength fibres are used [2]. Therefore, optimizing interfacial adhesion is essential for maximizing the performance of natural fibre composites.

B. Interfacial Challenges

Despite their advantages, natural fibres present several inherent challenges that hinder effective interfacial bonding with polymer matrices. One of the primary issues is their hydrophilic nature, which arises from the presence of hydroxyl (OH) groups in cellulose. These groups readily attract moisture, leading to poor compatibility with hydrophobic polymer matrices such as polypropylene and epoxy resins [3].

In addition, natural fibres contain surface impurities, including lignin, hemicellulose, waxes, and pectin. These non-cellulosic components form a barrier that prevents proper adhesion between the fibre and the matrix. Their presence reduces wettability and limits the formation of strong interfacial bonds [4].

Another significant challenge is the irregular surface morphology of natural fibres. Variations in fibre diameter, roughness, and microstructure create inconsistencies in bonding and stress distribution. These irregularities can lead to void formation and stress concentrations within the composite, further weakening the interface [5].

Collectively, these factors reduce fibre-matrix compatibility, resulting in poor adhesion and suboptimal composite performance. Addressing these challenges requires effective surface modification techniques to improve interfacial characteristics.

C. Failure Mechanisms

The integrity of the fibre-matrix interface directly influences the failure behavior of composite materials. In natural fibre composites, several interfacial failure modes are commonly observed. One of the most prevalent is fibre pull-out, which occurs when fibres are detached from the matrix due to weak adhesion. This indicates that the applied stress is not effectively transferred across the interface [6].

Another common failure mode is interfacial debonding, where separation occurs at the fibre-matrix boundary under mechanical loading. This often initiates crack propagation and leads to a reduction in load-bearing capacity. Additionally, delamination may occur in layered composite structures, where adjacent layers separate due to inadequate interfacial bonding [7].

These failure mechanisms significantly reduce the reliability, strength, and service life of composite materials. Understanding and mitigating these interfacial failures is therefore crucial for improving composite performance.

IV. CHEMICAL INTERFACE TREATMENT METHODS

Chemical surface treatments are among the most widely adopted approaches for enhancing fibre-matrix adhesion in natural fibre composites. These treatments modify the chemical composition and surface characteristics of fibres, thereby improving compatibility with polymer matrices and strengthening interfacial bonding [8].

A. Alkali Treatment (Mercerization)

Alkali treatment, commonly referred to as mercerization, is one of the simplest and most effective chemical modification methods. It involves treating natural fibres with sodium hydroxide (NaOH) solution to remove surface impurities such as lignin, hemicellulose, oils, and waxes [20].

This treatment increases surface roughness and exposes more cellulose fibrils, thereby enhancing mechanical interlocking between the fibre and matrix. Additionally, alkali treatment improves fibre wettability and reduces fibre diameter, leading to better dispersion within the matrix [19]. As a result, composites exhibit improved tensile strength, stiffness, and overall mechanical performance.

B. Silane Treatment

Silane coupling agents are widely used to improve chemical bonding at the fibre-matrix interface. These agents contain functional groups that can react with both the hydroxyl groups of the fibre and the polymer matrix, forming a stable chemical bridge.

Silane treatment enhances interfacial adhesion by creating covalent bonds, which significantly improve load transfer efficiency. It also reduces moisture absorption by modifying the fibre surface, thereby improving dimensional stability and durability. Furthermore, silane-treated composites often exhibit enhanced thermal stability and resistance to environmental degradation [10].

C. Acetylation

Acetylation is a chemical modification process that involves replacing the hydroxyl groups in natural fibres with acetyl groups. This reduces the hydrophilic nature of the fibres and improves their compatibility with hydrophobic matrices [24].

The primary advantage of acetylation is the significant reduction in moisture absorption, which enhances dimensional stability and resistance to swelling. This treatment also improves fibre dispersion within the matrix and contributes to better interfacial bonding, resulting in improved mechanical properties [25].

D. Other Chemical Treatments

In addition to alkali, silane, and acetylation methods, several other chemical treatments have been explored to enhance interfacial properties. Benzoylation introduces hydrophobic benzoyl groups to reduce water affinity, while maleated coupling agents (e.g., maleic anhydride-grafted polymers) improve compatibility between fibres and thermoplastic matrices [30].

Permanganate treatment is another technique that modifies fibre surface chemistry through oxidation, leading to improved adhesion and mechanical performance. These treatments, although effective, must be carefully controlled to avoid fibre degradation [31].

Overall, chemical treatments play a vital role in improving the mechanical and thermal properties of natural fibre composites by strengthening the fibre matrix interface. However, concerns related to environmental impact and chemical usage have encouraged the exploration of more sustainable alternatives [32].

V. PHYSICAL INTERFACE TREATMENT METHODS

Physical interface treatment methods are widely employed in composite engineering to improve fibre-matrix adhesion without significantly altering the chemical composition of the reinforcement. These methods primarily act by modifying the surface topography, energy, and wettability of fibres, thereby enhancing mechanical interlocking and interfacial bonding efficiency [34].

A. Plasma Treatment
Plasma treatment is an advanced surface modification technique that utilizes ionized gases to activate the fibre surface. During the process, energetic species such as ions, electrons, and radicals interact with the fibre surface, introducing functional groups and increasing surface energy. This leads to improved wettability and stronger interfacial adhesion between the fibre and matrix. Additionally, plasma treatment enhances surface roughness at the microscopic level, promoting better stress transfer across the interface [1], [2].

B. Corona Treatment
Corona treatment involves exposing fibres to a high-voltage electrical discharge in air, which generates reactive oxygen species. These species introduce polar functional groups such as hydroxyl and carbonyl groups onto the fibre surface. As a result, the surface polarity increases, improving compatibility with polymer matrices. This method is particularly effective for thermoplastic composites where interfacial bonding is often limited [3].

C. Heat Treatment
Heat or thermal treatment modifies fibres by exposing them to controlled temperatures, leading to structural rearrangement and removal of volatile components. This process enhances dimensional stability and reduces moisture sensitivity. However, excessive heat can degrade cellulose structure in natural fibres, leading to a reduction in tensile strength. Therefore, temperature control is critical to achieving optimal performance [4].

D. Mechanical Treatment
Mechanical treatments such as abrasion, grinding, and fibrillation physically alter the fibre surface. These processes increase surface roughness and create micro-scale irregularities that improve mechanical interlocking between fibre and matrix. Mechanical fibrillation, in particular, splits fibres into finer fibrils, increasing the effective surface area available for bonding. The result is improved load transfer efficiency and enhanced composite strength [5].

VI. BIOLOGICAL INTERFACE TREATMENT METHODS

Biological treatments have emerged as sustainable and environmentally friendly alternatives to conventional chemical methods. These approaches utilize natural biological agents such as enzymes, fungi, and bacteria to modify fibre surfaces while minimizing environmental impact.

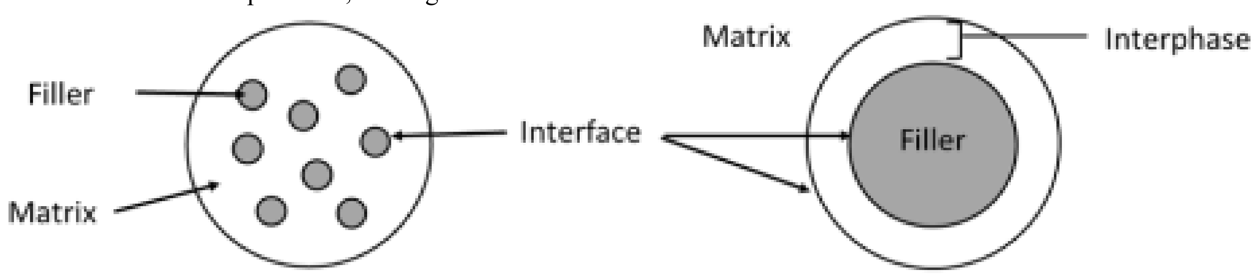

Figure 1: Schematic of filler-matrix interface; (b) interphase region between the filler and matrix [5].

A. Enzymatic Treatment
Enzymatic treatment involves the use of specific enzymes such as cellulase, hemicellulase, and pectinase to selectively remove non-cellulosic materials like lignin, waxes, and pectin from fibre surfaces. This results in cleaner, more reactive surfaces with improved roughness and wettability. Enzymatic treatment enhances fibre-matrix adhesion and reduces environmental pollution associated with chemical processing [6].

B. Fungal Treatment
Fungal treatment employs microorganisms capable of degrading lignin and hemicellulose components of natural fibres. Fungi such as white-rot species selectively break down amorphous components,

exposing the crystalline cellulose structure. This improves fibre surface characteristics and promotes better interfacial bonding. However, process control is essential to prevent excessive degradation of the fibre [7].

C. Bacterial Treatment

Bacterial treatment, particularly involving bacterial nanocellulose, enhances fibre surface properties by depositing nanoscale cellulose structures. These nanostructures improve surface roughness and increase bonding sites, leading to stronger fibre-matrix interactions. Additionally, bacterial treatments contribute to reduced moisture absorption and improved durability of composites [8].

Overall, biological treatments offer eco-friendly solutions that not only improve interfacial adhesion but also align with sustainable material development goals.

Table 1: Advantages and Disadvantages of Various Natural Fibre Pre-Treatment Methods

Pre-Treatment Method	Description	Advantages	Disadvantages	Typical Applications	References
Alkali Treatment (NaOH Treatment)	Fibres are treated with sodium hydroxide solution to remove lignin, hemicellulose, waxes, and impurities.	Improves surface roughness and fibre–matrix adhesion; enhances mechanical interlocking; increases tensile strength.	Excessive treatment may damage cellulose structure and reduce fibre strength.	Widely used for jute, hemp, sisal, corn stalk, and kenaf fibres in thermoplastic composites.	[44][50][51]
Silane Treatment	Silane coupling agents form chemical bridges between fibre surfaces and polymer matrices.	Improves compatibility between hydrophilic fibres and hydrophobic matrices; reduces moisture absorption; enhances durability.	Relatively expensive and requires controlled processing conditions.	Automotive interior panels and structural bio-composites.	[47][49]
Acetylation	Hydroxyl groups in fibres are replaced with acetyl groups to reduce hydrophilicity.	Improves dimensional stability and moisture resistance; enhances weather durability.	Chemical cost is high and treatment may reduce biodegradability.	Outdoor wood plastic composites and construction materials.	[48][45]
Maleic Anhydride Compatibilization (MAPP/MAPE)	Maleic anhydride grafted polymers are added to improve fibre–matrix bonding.	Enhances interfacial adhesion; improves tensile and flexural properties; promotes stress transfer.	Additional processing step increases production cost.	Polypropylene and polyethylene-based composites.	[41][50]
Steam Explosion Treatment	Fibres are exposed to high-pressure steam	Removes hemicellulose effectively;	Equipment cost is high; fibres may become brittle	Bio-refinery applications and advanced	[42][49]

Pre-Treatment Method	Description	Advantages	Disadvantages	Typical Applications	References
	followed by rapid decompression.	increases fibrillation and surface area.	under severe conditions.	lignocellulosic composites.	
Plasma Treatment	Fibre surfaces are modified using ionized gas under controlled conditions.	Environmentally friendly; improves surface activation without chemical waste; enhances wettability.	Requires sophisticated equipment and skilled operation.	High-performance polymer composites and aerospace applications.	[46][47]
Enzymatic Treatment	Natural enzymes are used to remove lignin and non-cellulosic components from fibres.	Eco-friendly process; preserves fibre structure; improves flexibility and surface cleanliness.	Slow treatment rate and relatively high enzyme cost.	Sustainable and biodegradable composite production.	[43][45]
Heat Treatment	Fibres are thermally treated at moderate temperatures to reduce moisture sensitivity.	Improves dimensional stability and fungal resistance; reduces water absorption.	High temperatures may reduce fibre strength and toughness.	Wood plastic composites and building materials.	[51][48]

VII. EFFECTS OF INTERFACE TREATMENT ON COMPOSITE PROPERTIES

Interface treatments play a critical role in determining the overall performance of composite materials by improving the interaction between fibre and matrix.

A. Mechanical Properties

Surface treatments significantly enhance mechanical properties such as tensile strength, flexural strength, and impact resistance. Improved adhesion ensures efficient stress transfer from the matrix to the reinforcement, reducing the likelihood of fibre pull-out and interfacial failure [9].

B. Thermal Properties

Enhanced interfacial bonding contributes to improved thermal stability by restricting polymer chain mobility at the interface. This leads to higher resistance to thermal degradation and better performance at elevated temperatures [10].

C. Moisture Resistance

Untreated natural fibres are highly hydrophilic, which leads to increased moisture absorption and reduced durability. Interface treatments reduce hydrophilicity and improve resistance to water ingress, thereby enhancing long-term performance [12].

D. Morphological Changes

Surface treatments alter fibre morphology by increasing roughness, removing impurities, and introducing micro- and nano-scale features. These changes improve compatibility with the matrix and result in stronger interfacial bonding, as observed through scanning electron microscopy (SEM) analyses [10].

VIII. EMERGING TRENDS IN INTERFACE TREATMENT

Recent advancements in composite technology have led to the development of innovative interface treatment methods aimed at improving performance and sustainability.

A. Nanotechnology Integration

The incorporation of nanoparticles such as graphene, carbon nanotubes, and nanocellulose has revolutionized interface engineering. These nanomaterials enhance interfacial strength, electrical conductivity, and mechanical performance by bridging the gap between fibre and matrix at the nanoscale [14].

B. Hybrid Treatments
Hybrid treatments combine physical, chemical, and biological methods to achieve synergistic effects. For example, combining enzymatic treatment with plasma treatment can significantly improve both surface chemistry and roughness, resulting in superior composite performance [15].

C. Green Processing Techniques
There is a growing emphasis on environmentally friendly processing methods that reduce energy consumption and eliminate hazardous chemicals. Techniques such as enzymatic modification and low-temperature plasma treatment are gaining popularity in sustainable composite manufacturing [37].

D. Smart Interfaces
Emerging research focuses on developing smart interfaces capable of sensing damage, stress, or environmental changes. These multifunctional composites integrate sensors or responsive materials within the interface, enabling real-time monitoring and improved reliability in advanced engineering applications [38].

IX. APPLICATIONS OF TREATED NATURAL FIBRE COMPOSITES

Treated natural fibre composites have gained significant attention across multiple engineering sectors due to their improved interfacial bonding, enhanced durability, and reduced environmental impact. Surface treatment techniques enhance compatibility between fibres and matrices, thereby expanding the range of practical applications [39].

In the automotive industry, these composites are widely used for manufacturing interior and semi-structural components such as door panels, dashboards, seat backs, and trunk liners. The improved fibre-matrix adhesion achieved through treatment methods ensures better mechanical strength, reduced vibration, and improved impact resistance, while also contributing to overall vehicle weight reduction and fuel efficiency [40].

In construction, treated natural fibre composites are increasingly utilized in panels, roofing sheets, insulation materials, and partition boards. Their enhanced to moisture and improved dimensional stability make them suitable for both indoor and outdoor applications. Additionally, their biodegradability and low carbon footprint align with the growing demand for sustainable building materials [40].

The packaging industry also benefits from treated natural fibre composites, particularly in the production of biodegradable containers, cushioning materials, and protective packaging. Improved interfacial properties ensure adequate strength and durability during handling and transportation, while maintaining environmental sustainability [36].

In aerospace applications, these materials are primarily used in interior components such as cabin panels, overhead compartments, and decorative structures. Although natural fibre composites are not yet widely used in primary load-bearing aerospace structures, ongoing improvements in interface treatment are gradually enhancing their mechanical performance and fire resistance, making them viable for more demanding applications [37].

Overall, improved interface bonding significantly broadens the usability of natural fibre composites, allowing them to compete with conventional synthetic materials in both performance and sustainability.

X. CHALLENGES AND FUTURE DIRECTIONS

Despite the numerous advantages of treated natural fibre composites, several challenges continue to limit their widespread industrial adoption.

A. Challenges
One of the major limitations is the high cost associated with advanced treatment methods, particularly those involving sophisticated equipment such as plasma systems or nanotechnology-based processes. These costs can make large-scale production economically challenging, especially in developing regions.

Another critical issue is scalability. Many treatment techniques that perform well at laboratory scale are difficult to implement consistently in industrial settings. Achieving uniform treatment across large volumes of fibres remains a technical challenge that affects product quality and reliability.

Environmental concerns also persist, particularly with chemical treatment methods that involve hazardous reagents and generate waste. Improper handling and disposal of these chemicals can negate the environmental benefits of using natural fibres, making sustainability a key consideration in process selection.

B. Future Research Areas

Future research is expected to focus on the development of bio-based coupling agents derived from renewable resources. These agents can improve fibre-matrix compatibility without the environmental drawbacks associated with synthetic chemicals.

Another promising direction is the advancement of nano-engineered interfaces, where nanoparticles are used to enhance bonding at the microscopic level. This approach has the potential to significantly improve mechanical, thermal, and barrier properties of composites.

Additionally, there is increasing interest in industrial-scale biological treatments, such as enzymatic and microbial processes. These methods offer environmentally friendly alternatives that can be scaled up with proper process optimization, making them suitable for commercial applications.

Continued innovation in these areas will be essential for overcoming current limitations and unlocking the full potential of natural fibre composites.

XI. CONCLUSION

Interface treatment remains a fundamental aspect in the development of high-performance natural fibre composites. By improving the interaction between fibres and matrix materials, various treatment methods chemical, physical, and biological have demonstrated substantial enhancements in mechanical strength, thermal stability, and resistance to environmental degradation.

The evolution of treatment technologies has made it possible to tailor composite properties to meet specific engineering requirements, thereby increasing their applicability across diverse industries. In particular, the shift toward eco-friendly and hybrid treatment approaches reflects the growing emphasis on sustainability and environmental responsibility in material engineering.

Looking ahead, the future of natural fibre composites will depend largely on the ability to develop cost-effective, scalable, and environmentally benign treatment methods. Achieving this balance will enable wider industrial adoption and position natural fibre composites as a viable alternative to conventional synthetic materials in modern engineering applications.

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