

Natural Fiber Reinforced Polymer Composites: Structural Characteristics, Mechanical Performance, and Emerging Sustainable Applications: A Review

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Abstract: The increasing demand for sustainable and lightweight engineering materials promotes research on natural fiber-reinforced polymer composites as environmentally friendly alternatives to conventional synthetic fiber composites. Natural fibers such as bamboo, curaua, hemp, flax, and *Grewia optiva* have attracted considerable attention due to their renewability, biodegradability, low density, cost-effectiveness, and favorable mechanical performance. Despite extensive research on individual natural fibers, a comprehensive comparative understanding of their structural characteristics, reinforcement potential, and application feasibility in polymer composites remains limited. This review aims to address this gap by critically analyzing the structural features, mechanical behavior, and engineering applications of selected high-performance natural fibers used in composite materials. The study highlights the influence of key structural parameters such as cellulose content, crystallinity, fiber density, and microfibrillar angle on the mechanical performance of natural fiber composites. Although natural fiber composites offer significant environmental and mechanical advantages, challenges such as moisture absorption, interfacial incompatibility, and variability in fiber properties remain critical issues. Recent advancements in fiber surface modification, hybrid composite design, and advanced processing techniques have significantly improved the reliability and performance of these materials. This review paper highlights the growing potential of natural fiber composites as sustainable engineering materials and provides insights for future research aimed at optimizing their structural performance and expanding their applications in automotive, aerospace, and construction industries.

Keywords: Natural fiber composites, Sustainable materials, Polymer composites, Bamboo fiber, Curaua fiber, Hemp fiber, Flax fiber, *Grewia optiva* fiber.

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I. INTRODUCTION

Natural fibers, derived from both plant and animal sources, are fundamental to the composition of a wide range of materials. These organic fibers, which exist as continuous filaments or elongated pieces, play a critical role in the structural integrity of plant and animal tissues, enhancing their strength and cohesion. This diverse and versatile class of materials serves as the foundation for numerous products, from traditional textiles to modern composite materials. Natural fibers can be classified into three primary categories: vegetable fibers, animal fibers, and mineral fibers. The hierarchical structure of plant-based fibers is particularly notable for its excellent performance properties, such as a high strength-to-weight ratio [1]. These fibers can be extracted

from both woody and non-woody plants using a variety of methods, including chemical, mechanical, and biological processes. Plant fibers, such as sisal and hemp, and animal fibers, including wool and silk, are essential components in various applications. Vegetable fibers are further categorized into seed hair fibers (e.g., cotton), bast or stem fibers (e.g., flax, jute, *grewia optiva*), and leaf fibers (e.g., sisal). Animal fibers like wool and silk are known for their unique properties and extensive use in textiles. Mineral fibers, including asbestos, graphite, and glass, are inorganic materials with specialized applications, such as in fireproof fabrics. The distinct properties and wide-ranging uses of these fibers make them indispensable in multiple industries, from traditional clothing to advanced engineering materials. This review paper

encapsulates the potential of natural fiber composites to meet modern engineering demands while promoting sustainability.

The present review is a comprehensive perspective on five significant natural fibers i.e. bamboo, curaua, hemp, flax, and *Grewia optiva*, by examining their structural attributes, mechanical behavior, surface modification techniques, sustainability aspects, and potential engineering applications. There are a number of literature which address natural fiber composites but, a systematic comparison of these fibers within a unified framework is limited. This review aims to bridge that gap by critically evaluating the properties, performance, advantages, and limitations of the natural fibers mentioned based on recent research findings. The specific objectives of this study are to: (i) examine the structural and physicochemical characteristics of the selected fibers; (ii) compare their mechanical performance in polymer composite systems; (iii) assess the influence of fiber treatment and processing techniques on composite properties; (iv) discuss current and emerging application areas; and (v) identify existing challenges and future research opportunities to support the development of sustainable, high-performance natural fiber reinforced composites.

II. REVIEW METHODOLOGY

A structured approach to review the literature was adopted to ensure the comprehensiveness and reliability of the information and data presented in this study. For this the relevant research articles were collected from major scientific databases, including Scopus, Web of Science, Science Direct, Springer Link, and Google Scholar. The keywords such as “natural fiber reinforced polymer composites”, “bamboo fiber composites”, “curaua fiber composites”, “hemp fiber composites”, “flax fiber composites”, “*Grewia optiva* fiber”, “surface treatment” and “sustainable composites” were used to search the research papers. This review mainly considered literature published between 2010 and 2026, while some earlier studies were also included to provide essential background information. The selected literature was systematically categorized according to fiber type, processing methods, structural characteristics, mechanical properties, surface treatment approaches, and application domains. The collected information was critically analyzed to identify performance trends, research gaps, challenges, and future opportunities associated with natural fiber reinforced polymer composites.

III. NATURAL FIBERS

A. Bamboo

Incorporating bamboo fibers as reinforcement in bioepoxy composites notably enhanced impact resistance, achieving maximum impact strength of 8.435 kJ/m² at 50 wt%. The impact of varying fiber loading, from 30 wt% to 60 wt%, on the thermal and mechanical properties of bamboo fiber-reinforced green epoxy composites was studied and it was found that thermal stability improved significantly, with optimal performance observed at 50 wt% fiber loading [2]. A method for transforming natural bamboo into high-performance composite material was presented, highlighting its elevated tensile strength, modulus, and toughness [3]. The

flexural modulus reached its peak at 60 wt% fibers loading, while flexural strength saw significant improvement at 40 wt%, underscoring the advantages of using green epoxy for its sustainability and biodegradability. By removing lignin and infiltrating epoxy in a two-step process, the resulting composite displayed enhanced dimensional stability against moisture. This epoxy-infiltrated bamboo composite demonstrated a remarkable 236 % increase in tensile strength and a 136 % increase in impact strength compared to bulk natural bamboo, making it highly desirable for structural applications due to its simultaneous improvement in strength and toughness. In a similar vein, researchers have extracted bamboo fiber bundles for high-performance composites with phenol resins, examining the influence of density and bamboo species on the physical and mechanical properties of bamboo fiber bundle reinforced composites (BFCs). The findings revealed that BFCs with a density of 1200 kg/m³ exhibited superior water resistance, dimensional stability, and mechanical properties [4]. Microstructural changes in high-density BFCs, attributed to the collapse of bamboo lumens, contributed to the improved performance. Although BFCs from all five bamboo species outperformed commercialized bamboo-based composites, the variations among species highlighted the importance of considering bamboo species in practical production. Vacuum-assisted resin transfer-molding (VARTM)-processed bamboo fiber-reinforced epoxy composites demonstrated considerable enhancement in tensile, flexural, and impact strength relative to neat epoxy with the best performance at 50 vol% fiber content. The composites had tensile strength of 321 MPa, tensile modulus of 25.1 GPa, and flexural strength of 315 MPa, accompanied by improved impact resistance and thermal stability. Enhanced interfacial adhesion and damping properties make bamboo fiber a worthy renewable fiber reinforcement for green applications in the automotive, construction, and aerospace industries [5]. Pressurization and heat densification of bamboo fibers efficiently improved their strength and stability and, thus, their reinforcing performance in epoxy composites. Optimal densification (15 MPa, 120 °C, 60 % MC, 1 h) in the experiment elevated the fiber density by 8-12 % and tensile strength by 29 % (up to 723 MPa), with internode fibers showing better performance compared to node fibers. Stress relaxation tests verified greater residual stress and stiffness in densified fibers, although the influence decreased at high temperatures. In composites manufactured through RTM, densification enhanced tensile strength by 9.3 %, flexural strength by 5.1 %, and flexural modulus by 5.7 %, indicating better load transfer. In general, densification improves bamboo fiber microstructure to produce stronger, more stable composites for aerospace, automotive, and green construction applications [6].

In conclusion, bamboo fiber significantly enhances epoxy composites, with optimal performance at 50 vol% loading and further gains through fiber densification, making it a strong, stable, and sustainable reinforcement for automotive, aerospace, and construction applications. Hence, transformative potential of bamboo fibers in composite materials, demonstrate significant enhancements in thermal stability, impact resistance, and overall mechanical properties. The results suggest that with continued research and

optimization, bamboo fiber-reinforced composites could become a cornerstone in sustainable and high-performance material applications.

B. Curaua Fiber

There has been increasing global interest in using natural renewable materials as alternatives to synthetic polymers, particularly in the context of curaua fiber. This fiber, notable for its high strength, low density, and high cellulose content, is becoming significant in composite material development. Curaua fiber's impressive mechanical properties and recyclability make it valuable in various matrices, including polymers and cements. The automotive industry has already recognized its benefits, utilizing curaua fiber to enhance the elastic modulus, tensile strength, and flexural strength of various auto parts. Additionally, the high cellulose content of curaua fiber makes it a promising source for nanocellulose production, contributing to the development of nanocomposites with diverse structural applications. Curaua nanofibers, in particular, show significant potential as reinforcement materials, improving mechanical properties across different matrices and offering transparency for optical applications [7]. A study [8] exploring curaua fiber-reinforced high-density polyethylene (HDPE) composites identified the optimal formulation as 20 wt% milled curaua fibers and 2 wt% poly(ethylene-g-maleic anhydride). These composites demonstrated improved mechanical properties and reduced hygroscopicity compared to uncoupled composites. Overall, curaua fiber-reinforced composites exhibited mechanical performance comparable to commercially produced HDPE composites reinforced with fiberglass. Another study [9] successfully integrated curaua fibers into polyamide-6, enhancing the material's mechanical properties. By depositing polyaniline on the fibers, researchers achieved antistatic properties. Composites with 5 wt% polyaniline-coated curaua fibers exhibited a 56 % increase in tensile strength and suitable conductivity for antistatic applications, making the composite promising for large-scale production using extrusion and injection molding techniques [10]. Assessments of virgin and recycled polystyrene matrices and their composites with 20 wt% curaua fiber showed that recycling expanded polystyrene had a minor impact on mechanical properties but increased thermal stability. The addition of curaua fibers enhanced tensile strength, modulus, rigidity, thermal stability, and melt viscosity. Recycled matrix composites exhibited higher thermal stability and melt viscosity compared to their virgin counterparts. However, poor interfacial adhesion in fractured regions suggested the need for a coupling agent due to curaua fibers pulling out of the matrices [11]. The study addressed the challenge of developing eco-friendly materials that reduce CO₂ emissions, add value to natural fibers, empower rural communities, and enhance income in impoverished regions. Using lignocellulosic fibers as reinforcement, the study aimed to create a fiber-friendly matrix free from calcium hydroxide by replacing a portion of Portland cement with metakaolinite, thus preventing fiber mineralization. Cement composites with varying percentages of short curaua fibers (2 %, 4 %, and 6 %) were compared with those reinforced with sisal fibers through four-point bending tests

to determine their mechanical behavior [12]. Investigations into the impact toughness of polyester composites reinforced with up to 30% alkali-treated curaua fibers revealed that treated fibers enhanced absorbed impact energy, albeit to a lesser extent than non-treated ones. The primary contributing factor was interfacial rupture between the curaua fibers and the polyester matrix, indicating potential for applications in automobile parts requiring impact resistance [13]. Further studies on alkali treatment of 'Curaua' fibers, using various sodium hydroxide concentrations and durations, aimed to enhance their mechanical properties. Tensile tests showed that treated fibers had lower tensile strength but significantly increased fracture strain compared to untreated fibers. Green composites formed with both untreated and alkali-treated curaua fibers subjected to tensile tests revealed that composites using treated fibers exhibited higher tensile strength and fracture strain as compared to that of the untreated fibers [14]. The development of a green composite by reinforcing a cornstarch-based biodegradable resin with high-strength curaua plant fibers was also investigated. Two fabrication methods and concentrated alkali treatment were proposed to enhance mechanical properties. Tensile tests demonstrated that alkali-treated fiber composites significantly increased fracture strain without a substantial decrease in strength, highlighting the importance of appropriate alkali treatment in improving cellulose-based fiber composite properties [15]. A systematic study [16] on continuous and aligned curaua fibers-polyester composites showed that laminates with varying curaua fiber volume fractions exhibited high flexural properties due to microfibril-matrix interaction during crack initiation. Scanning electron microscope analysis supported this mechanism, and impact test results indicated increased notch toughness with higher curaua fiber content. This was attributed to challenging fiber breakdown and preferential de-bonding at the fiber/matrix interface, leading to elevated absorbed energy. Research into the thermal properties and degradation mechanisms of polyurethane composites with varying proportions of curaua fiber (5 %, 10 %, and 15 % w/w) employed thermal analysis techniques including TG, DTG, DTA, and DSC, alongside mechanical property assessments. The polyurethane composites exhibited two degradation stages and three glass transition temperatures due to the presence of flexible and rigid segments. The addition of curaua fiber resulted in an increased Young's modulus and decreased elongation at break in the polyurethane composites [17]. Dynamic mechanical analysis of curaua composites with varying curaua fiber volume fractions (11-38 %) showed increased storage and loss moduli with higher reinforcement content. The activation energy of the relaxation process in the glass-transition region decreased as curaua content increased, supported by elastic chain concentration results. Cole-Cole plots indicated a more homogeneous system with higher curaua content, reflected in decreased $\tan \delta$ peak height and peak width at half-height [18]. Findings of another article [19] indicated that tensile strength (TS) and Young's modulus (YM) decreased with increasing fiber diameter, while the percentage strain at break remained constant. Variations in TS, % strain at break, and YM were observed with changes in test length and strain rate. Density, crystallinity, chemical

groups, and degradation temperatures of fiber constituents were determined, with dynamic mechanical analysis revealing increased modulus after water removal. The potential environmental impacts of substituting glass fibers with curaua fibers in the automobile industry were also examined. Curaua fibers, with physical properties nearly equivalent to glass fibers, offer economic and social advantages. The use of curaua fibers can be 50 % cheaper than fiberglass, and their application can contribute to regional development in the Amazon region. However, for substantial environmental benefits, curaua-based composites would need to be lighter than their glass fiber counterparts [20]. A study proved that chemical treatments (NaOH + hot water, NaClO + NaOH) improved curaua fiber–matrix adhesion via removal of lignin and hemicellulose, improved crystallinity, and strength of the composite. The optimum performance was obtained with PLA composites containing 20 wt% mercerized curaua and PHB composites with hot-water-treated fibers, validating curaua suitability as sustainable biodegradable polymer reinforcement [21]. Another research [22] proved the potential of adding small quantities (3–5 %) of NaOH-treated curaua fibers to bio-based polyethylene (B-HDPE) to enhance significantly the flexural strength, modulus, hardness, fracture toughness, and thermal resistance without affecting the processability and results prove curaua's potential as a lightweight, renewable reinforcement for automotive and packaging industries, supporting its role in developing bio-based polymer composites. Research [23] identified that curaua fiber–reinforced geopolymers exhibited tensile strength of 25.7 ± 7.1 MPa and flexural strength of 18.9 ± 4.7 MPa, with NaOH treatment also improving bonding, ductility, and crack-bridging and outcomes identify curaua suitability as reinforcement in structural and construction materials subjected to tensile and flexural stresses. 2 wt% NaOH-treated curauafiber–reinforced mortars were as durable as traditional mixes with less cement consumption and CO₂ emissions, identifying curaua as a green reinforcement option for construction [24]. In one study [25], hybrid cement composites with 1 % PVA and 1.5 % curaua fiber demonstrated similar strain-hardening and crack control to 2 % PVA composites, minimizing synthetic fiber consumption. The incorporation of curaua enhanced cost-effectiveness, durability, and sustainability with generation of performance for civil engineering uses.

Hence, this critical review of literature suggests that, Curaua fiber, known for its high strength, low density, and recyclability, offers a sustainable alternative to synthetic materials. Its integration into composites enhances mechanical properties, making it valuable for the automotive, construction, and other industries. Research demonstrates its potential in improving tensile strength, thermal stability, and impact resistance, contributing to eco-friendly solutions and regional economic development. Recently, Curaua fiber shifted from studies on cultivation to use in polymeric, cementitious, and hybrid composites with improved adhesion, strength, and durability due to chemical treatments and hybridization. Its application in bio-based polymers, geopolymers, and mortars reflects its potential in being used

as an environmental friendly alternative to synthetic fibers in the automotive, construction, and packaging industries.

C. Hemp Fiber

Hemp fiber is processed from the *Cannabis sativa* L. crop, which has been cultivated for thousands of years as a ubiquitous natural fiber cultivated for industrial use such as fiber, seeds, oil and medicinal purposes, though tight regulations stifled its global cultivation throughout the 20th century. Hemp is a sustainable crop due to its high carbon sequestration rate, rapid growth rate, and climatic and soil tolerance. Hemp fiber, derived from the *Cannabis sativa* L. plant, is a well-known natural fiber cultivated for industrial uses such as fiber, seeds, and oil. Despite its association with marijuana, industrial hemp is distinct and has diverse applications, including textiles and oil extraction [26, 27]. The performance of injection-molded short hemp fiber and hemp/glass fiber hybrid polypropylene composites is also explored, revealing that hybridization with glass fiber enhances strength, stiffness, and thermal resistance, making these composites ideal for structural applications, particularly in automotive interiors [28]. Hemp fibers reinforced in polypropylene and compatibilized with maleic anhydride (MAPP), processed through extrusion and hot compression. The analysis demonstrates that hemp fibers, with their notable crystallinity and molecular orientation, are highly suitable for engineering applications. X-ray diffraction reveals structural changes within the composite, while Fourier-transform infrared spectroscopy indicates strong fiber-matrix interactions. Thermogravimetric analysis shows complete degradation at 5 and 10 wt% MAPP, and differential scanning calorimetry indicates reduced crystallinity. Hardness tests yield varied results based on MAPP content, and impact resistance improves at 3 and 5 wt% MAPP, only to sharply decline at 10 wt%. The study underscores the potential of these composites for sustainable engineering applications [29]. Further investigation into hemp epoxy composites enhanced with nanofillers like graphene shows significant improvements in mechanical properties. The study [30] establishes a strong correlation between experimental and predicted values using artificial neural networks, identifying key parameters like graphene content and size, hemp fiber thickness, and the number of hemp layers as influential factors in flexural strength and interlaminar shear strength. Research [31] examining the interfacial properties of jute and hemp fibers in polypropylene-maleic anhydride copolymer composites reveals that tensile strength analysis favors a bimodal Weibull distribution. Surface energy and acid-base parameters change with alkaline and silane treatments, while microfailure modes differ based on natural fiber tensile strength, as confirmed by acoustic emission analysis. Additional studies focus on enhancing the mechanical properties of hemp fiber-reinforced polypropylene composites for automotive applications. Treatments with NaOH and MAPP improve bonding, with 5 wt% MAPP yielding optimal mechanical performance [32]. Another study [33] analyzes the tensile properties of nonwoven materials using flax, hemp, PP, and MAPP, finding that while hemp fibers have lower tensile properties than flax, their higher lignin content enhances

interfacial shear strength. The enhancement of polypropylene (PP)/hemp fiber (HF) composites for potential use in electric vehicle parts has been also examined. Copolymers like poly[styrene-*b*-(ethylene-co-butylene)-*b*-styrene] (SEBS) and poly(styrene-*b*-butadiene-*b*-styrene) (SBS), along with MAPP to control the interface in multiphase systems, are evaluated. SEBS shows better elongation at break and impact strength, while SBS contributes to higher Young's and storage moduli. SEM analysis reveals superior dispersion and smaller particle size for SEBS-containing composites, indicating its higher affinity for PP [34].

These studies collectively show the promising potential of hemp fiber-reinforced polypropylene composites for sustainable engineering applications, including bioinspired materials, automotive interiors and electric vehicle components.

Its capacity for weed control and production with low pesticide applications renders it a viable choice for future agriculture and crop rotation [35]. In its structure, hemp is a bast fiber with 60–74 % cellulose, 15–20 % hemicellulose, 3–5 % lignin, and small amounts of pectin and wax. Its fiber bundles beneath the stalk's epidermis require retting and defibration to produce textile-quality fibers. Legislative approval for hemp production in the USA has sped up development in standardized characterization techniques. Fiber length, diameter, tensile strength, linear density, and color are being modified from cotton and flax testing procedures, although hemp's morphological variability presents special challenges [36]. Sophisticated research highlights specific pre-treatment techniques to maximize hemp's performance as a reinforcement material in polymer composites. Chemical and enzymatic retting, alkali treatment, and surface treatments enhance fiber separability, thermal stability, and interfacial adhesion. Such treatments minimize hydrophilicity, increasing mechanical properties like tensile strength, modulus, and toughness in polymer composites. Hemp fibers, with densities of approximately 1.24 g/cm³, tensile strengths of 210–750 MPa, and moduli of 20–41 GPa, provide a cheaper alternative to glass fibers for light-weight composites [37]. The application of hemp fibers has increased to encompass sound absorption applications. Hemp waste fibers have a porous microstructure with cavities, spiral structure, and cracks that allow for damping of sound. Maximum sound absorption coefficients of 0.95 are reported, similar to mineral wool, and hemp fiber waste is hence viable for green building and interior acoustic panels. Additional natural fiber blends (wool, ramie, cotton) are superior in performance. This waste hemp valorization reduces resource loss in the processing of textiles [38]. Concurrent studies into Sunn hemp (*Crotalaria juncea*), another bast fiber, identify its potential as a synthetic fiber replacement. With 66 % cellulose, 19 % hemicellulose, and 15 % lignin, Sunn hemp fibers have 91 % crystallinity indices and stability to 220 °C. SEM and XRD confirm its coarse, strong morphology, and antimicrobial assays show activity towards pathogens such as *Candida albicans*. These findings suggest that Sunn hemp can be used to replace or substitute industrial hemp in reinforcement enhancement of composites and biomedical uses [39]. Besides industrial uses, hemp also finds

applications in the cultural and medicinal sectors. Ayurvedic tradition in India identifies *Cannabis sativa* (fiber type) as having therapeutic use. Hemp seeds, oil, and extracts are referenced for nutritional and medicinal uses, supported by evidence of their use in folk medicine. Their dual industrial–pharmaceutical value enhances the status of hemp as a multi-purpose plant that connects contemporary materials science with traditional medicine [40]. In agronomy, processing, materials engineering, and medicinal applications, hemp fibers prove to be extremely versatile. From cultivation and textile uses to acoustic properties, polymer composites, and medicinal applications, science converges on hemp as a sustainable, environmentally friendly resource. Contemporary problems linger with standardizing the quality of fiber, optimizing pre-treatment for composites, and scaling waste valorization, but the burgeoning literature attests to hemp as a cornerstone of sustainable material innovation. In short, hemp is a multi-purpose, environmentally friendly fiber with superior mechanical, acoustic, and biomedical potential. In spite of remaining concerns regarding quality standardization and processing, its double industrial/medicinal value renders hemp a key material for new ecologically sound innovations.

D. Flax Fiber

Saha et al. [41] studied the impact behavior and reparability of laminated composites made from Elium188 thermoplastic and flax fibers. Utilizing room temperature infusion and deviating from traditional thermoset composites, low-velocity impact studies revealed fiber/matrix debonding as the primary damage mode. Remarkably, successful repairs without fiber breakage highlighted the potential for multiple impact-repair cycles, showcasing enhanced resilience to impact force and stiffness recovery in flax/Elium bio-composites. Another investigation examined the influence of water absorption on flax-hemp-reinforced epoxy composites, fabricated through compression hand layup. Hemp-reinforced composites exhibited higher water absorption, adversely affecting mechanical properties. However, hybrid composites demonstrated superior performance, with enhanced water resistance and thermal conductivity. Despite water affecting the viscoelastic properties, hybrid composites exhibited superior interlocking bonds. Comparative analysis under different moisture conditions, coupled with morphological studies using SEM, confirmed that flax-hemp hybridization was more effective than using hemp alone, offering promising potential for engineering applications [42]. Further research explored enhancing polymeric composites by integrating kenaf, jute, and glass fibers, leading to significantly improved mechanical properties. The study also assessed water absorption's impact on the strength of interwoven cellulosic fibers. Hybrid composites composed of interwoven kenaf/jute and kenaf/hemp yarns embedded in an epoxy matrix were prepared using an infusion process. Water absorption characteristics were evaluated by immersing the composite samples in tap water until saturation. Tensile and flexural tests on both dry and water-immersed composites indicated that hybridization improved mechanical and water-resistant properties. However, prolonged water immersion led to reduced tensile and flexural strength due to water penetration at the fiber/matrix

interface, as observed through field emission scanning electron microscopy (FESEM) [43, 44]. Research on natural hybrid reinforced polymeric (HNRP) composites, specifically aloe vera/flax/barium sulfate, revealed intriguing findings. Barium sulfate, chosen for its inert nature, high density, and high melting point, enhanced flax fiber interlocking and composite plasticity, resulting in the highest tensile strength (34.72 MPa) in HNRP5. Although impact strength decreased with barium sulfate addition, the composite exhibited a 7-9 % weight reduction in the 100–200 °C temperature range. Additionally, the composite's low water absorption capability was highlighted, and its storage modulus showed maximum magnitude in the glassy region and minimum in the rubber region, indicating improved mechanical performance [45]. A historical analysis emphasized the evolution of composite materials, particularly the environmental concerns associated with polymer composites, which have renewed interest in natural composites like aloe vera and jute. The study investigated the mechanical properties (ultimate tensile strength, flexural strength, impact strength), thermal properties (thermal conductivity, heat deflection temperature), water absorption behavior, and weight loss due to temperature for both jute and aloe vera composites. Furthermore, it aimed to compare these properties with hybrid composites combining both jute and aloe vera, seeking to understand the potential of natural composites as eco-friendly alternatives to synthetic counterparts [46]. Another comparative study evaluated the mechanical and damping properties of flax fiber (FF) reinforced thermoset (epoxy) and thermoplastic (polypropylene (PP) and polylactic acid (PLA)) composites with 40 vol% fiber content, juxtaposed against carbon (CF) and glass (GF) fiber reinforced epoxy composites. The specific mechanical properties of unidirectional FF-based composites were found comparable to GF epoxy composites due to FF's relatively low density. Additionally, FF composites exhibited enhanced damping properties compared to synthetic CF and GF composites. Notably, unidirectional FF added to epoxy significantly increased the loss factor, with FF/PP displaying the highest damping at 25 °C and 1 Hz ($\tan \delta$). The best compromise between stiffness and damping was achieved with FF-reinforced semi-crystalline PLA [47]. A review [48] analyzed the recent advancement in flax fiber derived functional composites and their growing use in energy, biomedical, and environmental applications. The review pointed out the inherent advantages of flax such as low weight density, biodegradability, and glass-like mechanical properties. Poor interfacial adhesion between matrix and fiber challenge-fixture issues were resolved using different methods of modification such as alkali, silane coupling, acetylation, and plasma treatments, which enhanced bonding and reduced water absorption. Applications exemplified ranged from antibacterial flax-silver wound dressings and oil/water separation membranes to flexible carbonized flax fiber-based supercapacitors, a characteristic reflecting their multi-functionality. The research concluded that flax, being versatile, can be engineered into high-value composites that meet sustainability and performance requirements. A second study [49] conducted a comprehensive statistical and experimental

work on the tensile performance of more than 400 flax fibers with varied gauge lengths (10–500 mm). Quasi-static tensile tests yielded high dispersions in ultimate tensile strength (UTS), Young's modulus, and failure strain, which were significantly dependent on fiber diameter and length. By using Weibull statistical distributions (two- and three-parameter) and maximum likelihood and least-squares estimations, the researchers quantified flax fiber variability and reliability. Analysis of variance (ANOVA) confirmed that mechanical properties decreased with increasing fiber diameter due to the lumen effect by which larger lumens result in thinner effective load-carrying walls. This book created a predictive reliability model for flax fibers, providing valuable information for their application in composite reinforcement with high durability and consistency demands. A research [50] Investigated experimentally the dynamic compressive behavior of recycled aggregate concrete (RAC) reinforced with flax fibers for enhancing the structural performance of recycled coarse aggregate concrete. The influence of strain rate, fiber volume ratio (0–1 %), and replacement of RCA (0–100 %) on failure modes, strength, and toughness was investigated in accordance with a Split Hopkinson Pressure Bar (SHPB). Results showed compressive strength, toughness, and critical strain were all enhanced by higher strain rates. Flax fibers, however, significantly improved ductility and reduced brittleness, especially at over 200 s⁻¹ strain rates. Higher RCA content reduced strength, but the addition of flax fibers countered such deficiency and raised energy absorption capacity, thus rendering RAC's dynamic performance equivalent to natural aggregate concrete. Empirical relations were also developed to predict compressive strength and toughness at various strain rates, demonstrating the prospects of flax fibers in impact-absorbing structures such as bridge piers and defense fortifications. One study [51] compared the manufacturing defects of flax fiber-reinforced polypropylene (flax-PP) composites as an eco-friendly alternative to glass fiber-based composites in the automotive and semi-structural sectors. The current study cited significant benefits such as recyclability, improved damping, impact damage tolerance, and weight savings (40–60 % less than glass fibers). Issues such as poor fiber-matrix adhesion, high melt viscosity of polypropylene, and flax degradation around about 200 °C were identified as significant barriers. New processing methods like compression resin transfer molding (CRTM), sequential pressure cycles, and hot press molding were explored to attain maximum impregnation and minimum void content. It was concluded that the tuning of process conditions (temperature, dwell time, and pressure) is important to compensate for thermal sensitivity of flax and flow behavior of polypropylene to realize the potential of sustainable, high-performance composites at a commercial level. Research [52] investigated the effect of fiber length, loading, and surface treatment on natural rubber (NR) green composites reinforced with flax fibers. Optimum studies in the initial phases showed that 1.25 cm length and 40 % loading provided optimum tensile properties. Interfacial bonding was also improved through surface treatment of flax fibers using NaOH alkali and laccase enzyme. FTIR and XRD analysis showed diminished hydrophilicity and

increased crystallinity in treated fibers, while SEM micrographs indicated better roughness and adhesion with the rubber matrix. Mechanical test showed high improvements, such as 9 % tensile strength and 27.4 % tear strength improvements in NaOH-treated composites over untreated composites. Results highlighted that surface modification improved the mechanical performance as well as favored the sustainability of flax-based NR composites as viable candidates for eco-friendly industrial rubber products such as hoses, belts, and seals. Flax fiber was demonstrated to be a universal renewable reinforcement, and its appraisals included its potential for energy, biomedical, and environmental applications. Studies indicate it can prevent brittleness in concrete, enhance the strength of thermoplastic composites for automotive use, and create durability in elastomers with surface treatment. Overall, optimal flax fiber offers balanced mechanical, environmental, and functional advantages and is a green alternative to man-made reinforcements.

These studies collectively highlight the immense potential of natural fiber-reinforced composites, particularly those incorporating hemp, flax, and hybrid combinations. Through various treatments and enhancements, such composites exhibit improved mechanical, thermal, and water-resistant properties, positioning them as sustainable and effective alternatives to traditional synthetic materials in engineering and automotive applications. In summary, flax fiber is a sustainable, multifunctional reinforcement that, with optimized treatments and processing, enhances strength, durability, and functionality across construction, automotive, biomedical, and environmental applications, making it a strong alternative to synthetic fibers.

E. *Grewia optiva* Fiber

Grewia optiva, commonly referred to as ‘bhimal’ or the ‘wonder tree of Uttarakhand, is a tree of significant cultural and economic importance found in the sub-Himalayan region. The traditional method of extracting *Grewia optiva* fiber is water retting. Chemical composition of *Grewia optiva* fibers varies based on geographical and climatic conditions, soil type, and extraction method. Typically, the fibers consist of 58-75 % cellulose, 10-25 % hemicelluloses, and 7-22 % lignin [53]. *Grewia optiva* (G.O.) fibers have emerged as promising reinforcements in polymer composites, offering significant enhancements in mechanical and thermal properties. Studies have consistently demonstrated improved tensile, flexural, compressive, and impact strengths in G.O. fiber reinforced composites across various polymer matrices. For instance, composites reinforced with G.O. fibers have shown an impressive tensile strength of up to 200 MPa in epoxy polymer matrices, highlighting their potential in structural applications where high strength is crucial [54]. Flexural strength is also notably enhanced, with mercerized G.O. fibers demonstrating robust load-bearing capabilities in bending applications [54, 55]. Compressive strength reaches peak performance with 30 % benzoylated G.O. fibers, indicating resistance to compressive forces. Impact strength, crucial for toughness in dynamic applications, shows significant improvement in G.O. fiber reinforced polypropylene composites, emphasizing their durability

under sudden loading conditions [54]. The fracture properties have been also investigated in an article which claims the dependence of fracture toughness on the fiber weight%, fiber length and orientation [56] with optimum mode I fracture toughness as 2.122 MPa $\sqrt{m}$. The mechanical improvements are not solely attributed to the inherent properties of G.O. fibers but also to effective surface modification techniques. Surface treatments such as benzoylation and graft copolymerization have been particularly effective in enhancing interfacial bonding between fibers and matrices, thereby improving overall mechanical performance [57]. Hybridization studies combining G.O. fibers with other natural fibers have also demonstrated synergistic benefits, achieving higher tensile strengths than single fiber composites, suggesting versatility in composite design and application-specific tailoring [58]. In addition to mechanical properties, the thermal characteristics of G.O. fiber reinforced composites have been thoroughly investigated. Enhanced thermal stability is observed in G.O. fibers treated with aminopropyltriethoxy silane (APS), which forms strong covalent bonds with cellulose, thereby improving resistance to thermal decomposition [57]. Thermogravimetric analysis (TGA) reveals multi-stage decomposition processes in these composites, with surface modification techniques influencing decomposition temperatures and patterns. Mercerization [53] and silane [57] treatments contribute to delaying thermal degradation onset, while benzoylation, though slightly reducing thermal stability, underscores the nuanced effects of different treatments on thermal behaviors. Comparative studies among various polymer matrices (e.g., PLA, PP, epoxy) reinforced with G.O. fibers consistently show improved thermal stability and modified decomposition characteristics compared to unreinforced matrices [57]. Traditionally retted by extracting its fibers through water retting, a microbial process that prevents serious harm to cellulose but preserves strength and elasticity [58]. Fibers typically consist of 58–75 % cellulose, 10–25 % hemicellulose, and 7–22 % lignin, based on climate, soil, and the process of extraction [59]. Preliminary studies indicated the potential of *Grewia optiva* fiber in bio-composites. Micro-cellulose fibers were successfully separated through chemo-mechanical and steam explosion processing and gave rise to 10 μ m diameter fibers with enhanced crystallinity and thermal stability. Tensile, impact, and hardness values of composites having 40 wt% of these fibers as filler in epoxy matrices were astounding, qualifying the material for lightweight and durable structural applications [60]. Parallel studies demonstrated that 5 % NaOH mercerization greatly improved tensile fiber strength to 315 MPa, elongation to 4.9 %, and work-to-failure, though higher alkali levels decreased performance due to excessive lignin removal [61]. Surface treatments played a crucial role in promoting fiber–matrix bonding [62]. Progressing towards value-added engineering applications, *Grewia optiva* fibers were combined as hybrid composites. When combined with basalt fibers in polyester matrices, the hybrids showed better vibrational damping and natural frequency response, and they were also shown to be useful in automotive and aerospace structures subject to dynamic loading [59]. Similarly, the brake friction composites at 7.5 wt% *Grewia optiva* fibers proved to be the

best with stable coefficient of friction (0.41–0.44), reduced wear rates, and improved fade-recovery characteristics. The research also pointed towards their environmental advantage compared to synthetic reinforcements [58]. To multifunctional features, the fibers were found to possess antimicrobial activity against *Aeromonas*, natural UV resistance, and heat stability up to 470 °C. Such features along with tensile strengths of 11.8 MPa and modulus of 5.4 GPa made their place in green, flame-resistant composites more solid [58]. In addition, hybrid jute-*Grewia optiva*-Tasar silk waste laminates in epoxy matrices showed synergistic improvement. Tensile strength increased from 54 to 79 MPa, and doubled flexural strength with the addition of 14 wt% Tasar silk [63]. This proves the versatility of *Grewia optiva* when it is compounded with both industrial and natural waste reinforcements.

Grewia optiva studies have evolved from initial extraction and composition studies to high-end applications in hybrid and functional composites. Surface modifications, inorganic and natural fiber hybridization, and composite tailoring have extended its application in engineering, ranging from brakes and aerospace components to hybrid laminates. In general, *Grewia optiva* manifests potential for replacing synthetic fibers with multifunctional advantages, which categorizes it as a scalable, sustainable material for applications across various industries. Its versatility categorizes G.O. fiber composites for high-temperature-resistant applications such as automotive components, aerospace components, and electronic enclosures. Synergy of higher mechanical strengths and higher thermal stability positions G.O. fibers as potential alternatives to man-made reinforcement in composite materials, to sustainable and high-performance engineering applications. Through the virtues of effective surface modification and hybridization technologies, these fibers offer optimized solutions for various industry-based applications, driving sustainable and high-performance material evolution.

Figure 1 illustrates the water retting process of *Grewia optiva*, where plant stems are immersed in water. Microbial activity and periodic agitation break down non-cellulosic materials, enabling fiber separation. The fibers are then washed, dried, and bundled for later use. These properties make G.O. fiber composites suitable for applications requiring resistance to high temperatures, such as automotive components, aerospace materials, and electronic housings. The combination of enhanced mechanical strengths and improved thermal stability positions G.O. fibers as promising alternatives to synthetic reinforcements in composite materials, contributing to sustainable and high-performance engineering solutions. Through effective surface modification and hybridization techniques, these fibers offer tailored solutions across diverse industrial applications, advancing the development of sustainable and high-performance materials.

IV. PHYSICAL PROPERTIES OF NATURAL PLANT FIBERS

The potential of natural fiber-reinforced composites, examining their ultrastructure, geometric features,

microfibrillar angle, cellulose content, density, and water repellent treatments have been also reviewed.

A. Ultrastructure

At the macroscopic scale, typically ranging from 0.1 to 1 meter, wood fibers are predominantly located within the xylem layer. The cell wall structure of bagasse is analyzed using a top-down approach, covering both macrostructure and ultrastructure. Natural fibers inherently function as composite materials, with cellulose fibrils embedded within a hemicellulose/lignin matrix. Hemicellulose molecules are hydrogen-bonded to cellulose, forming a cementing matrix between cellulose microfibrils. This interaction creates the cellulose/hemicellulose network, which serves as the primary structural component of the fiber cell. The mechanical properties of fibers depend on their composition, the amount of cellulose, its crystallinity, the degree of polymerization (DP) of cellulose, and the microfibrillar orientation [64]. The microfibril angle (MFA) significantly influences the axial strength properties of fibers, with plant fibers exhibiting high anisotropy due to their low MFA. This anisotropy results in relatively low transverse mechanical properties, with the cell wall structure dictating the physical properties of natural plant fibers [65].

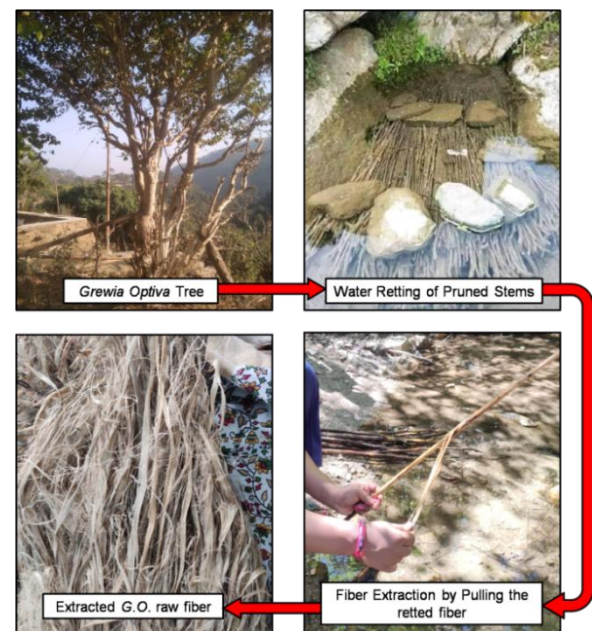


Fig. 1. Water retting process of *Grewia optiva* fiber extraction

B. Geometric Features of Natural Fibers

Plant fibers generally have mechanical properties that are significantly lower than those of commonly used reinforcing glass fibers [64]. Despite their lower mechanical properties, plant fibers exhibit comparable specific properties, strength, and stiffness to glass fibers due to their lower density. Low aspect ratios limit reinforcing ability, achieving an aspect ratio above the critical value is essential for optimal reinforcement and maximum stress transfer in composite systems. A fiber aspect ratio below the critical value leads to inadequate stress transfer to the fiber, resulting in improper reinforcement. In certain cases, the fiber merely functions as filler [66]. Conversely, an excessively high fiber aspect ratio can result in fiber entanglement during processing, leading to suboptimal mechanical properties due to poor dispersion. Flexible cellulosic fibers are less prone to breakage during processing, maintaining the original fiber length distribution. Therefore, understanding fiber length or distribution is crucial for assessing the efficacy of the reinforcement material. A high aspect ratio implies that only a small portion of the fiber ends bears lower stress. High aspect ratio seed fibers are ideal for spinning technologies, while natural plant fibers with short aspect ratios not fully utilize their strength under stress. In composite failure, intact fibers are pulled out of the matrix, highlighting the significance of a minimum fiber length [67]. The critical fiber length is the shortest length enabling maximal loading, initiating fiber failure [68]. Increased tensile, flexural strength, and impact performance can be achieved by enhancing both the aspect ratio and fiber volume fraction, allowing for more interaction with the matrix [69,70]. However, partial fibrillation of short natural fibers is a crucial method to enhance the aspect ratio and surface area per unit volume of fiber bundles. This process ensures that fibers act as reinforcement rather than mere fillers when they surpass a critical aspect ratio [48].

C. Microfibrillar Angle

The microfibrillar angle (MFA) is defined as the angle microfibrils make with respect to the fiber axis. It is concluded that the MFA is the primary parameter influencing the inherent strength properties of the fiber. High cellulosic content and a lower MFA are essential for achieving high fiber strength. Fibers with higher cellulosic content and lower MFA exhibit higher ultimate tensile strength and initial modulus with intracellular fracture [71]. In contrast, fibers with higher MFA and lower cellulose content demonstrate greater ductility, as seen in coir fibers. A larger MFA results in a higher failure strain, as the fibrils can twist when stretched [72, 73]. The relationship between MFA and failure strain varies among different natural plant fibers. For instance, fibers like cotton and bamboo may exhibit several MFAs, with smaller angles playing a role in determining the overall anisotropic properties of these fibers. The Young's modulus of the cell wall is influenced by the volume fraction of cellulose and the average MFA concerning the loading direction. This model helps elucidate the impact of MFA on the modulus of wood. Data from sisal fiber specimens and variations among different bast fibers show the influence of MFA on modulus. Typically, the MFA in wood fibers ranges from 3 to 45 degrees, varying based on fiber type and location

in the wood (e.g., early and late wood). In contrast, MFA in plant fibers is more consistent, typically falling within the range of 6 to 10 degrees [74]. In terms of strength, MFA is a crucial property, inversely proportional to fiber stiffness [75]. There is a well-correlated relationship between the stiffness of wood fibers and MFA. At small angles (<5 degrees), stiffness ranges from 50 to 80 GPa, while at larger angles (40-50 degrees), stiffness reduces to approximately 20 GPa. Non-wood fibers generally exhibit higher stiffness compared to wood fibers. A smaller MFA contributes to higher stiffness and strength in fibers, while a higher MFA leads to increased ductility. The orientation of microfibrils also influences the ductility of plant fibers. If microfibrils are spirally oriented to the fiber axis, greater ductility is observed. Conversely, if microfibrils are parallel to the fiber axis, the fiber tends to be rigid with high tensile strength. A lower MFA is associated with a smaller failure strain. The MFA also governs the nonlinear stress-strain behavior of plant fibers, with a smaller elastic range but an increased plastic range as MFA rises [76].

D. Cellulose Content and Its Crystallinity Index

Cellulose content and cellulose crystallinity are crucial microstructural factors influencing the mechanical properties of natural plant fibers. Crystalline cellulose exhibits superior stiffness compared to other constituents. Therefore, in choosing plant fibers for structural reinforcement, a preference is given to those with high cellulose content and high cellulose crystallinity. Wood fibers typically have lower cellulose crystallinity (55-70 %) compared to natural plant fibers (60-70 %). The crystallinity of natural plant fibers increases with partial delignification and alkaline peroxide bleaching. Physical and chemical treatments of plant fibers are recognized to alter both the cellulose content and the degree of crystallinity. The rigidity of cellulose fibers tends to increase, and their flexibility decreases as the ratio of crystalline to amorphous regions rises. Higher crystallinity is associated with greater strength, while lower crystallinity results in increased elongation, higher water absorption, and more sites available for chemical reactions. Corn husk fibers exhibit a crystallinity degree of 48-50% and a crystal size of 3.2 nm [77]. In comparison, flax and jute fibers have higher crystallinity degrees of 65-70% and smaller crystal sizes of 2.8 nm. The degree of crystallinity also influences the moisture absorption of fibers, as amorphous regions have a greater capacity to absorb water. The thermal decomposition of natural fibers shifts to higher temperatures with an increase in cellulose crystallinity and crystallite size. These findings suggest that the cellulose crystallite size plays a role in influencing the thermal degradation temperature of natural fibers [78]. Physical characteristics of the curauafibers also make them more promising for composite applications. The fibers exhibit a high cellulose content (77.2 %), and low lignin (6-9 %) and extractives (3.81 %), all of which result in low density, better adhesion to the polymer matrices, and higher stability. Low ash content (0.36 %) minimizes inorganic impurities that have the potential to act as stress concentrators. In addition, the high crystallinity index (73.53 %) accounts for enhanced dimensional stability, restricts moisture uptake, and confers protection against degradation by ambient conditions. These characteristics not only

increase the inherent stability of the fibers but also the durability of fiber-reinforced composites over long periods. The favorable combination of high crystallinity and low amorphous content gets transferred to the composites with greater thermal stability, minimized water absorption, and improved interaction with both thermoset and thermoplastic resins [79]. Curauafibers, 65 % cellulose, 15 % hemicellulose, and 7.3 % lignin content, are rigid (elastic modulus 26 GPa) and potentially good candidates to be reinforced composites biodegradable. Physical morphology is smooth when untreated, but chemical treatments such as hot water treatment, mercerization, and sodium hypochlorite modification effectively remove waxes, pectins, hemicellulose, and lignin. These treatments increase the surface roughness, fibrillation, and crystallinity and therefore enhance adhesion between the fiber and matrix. X-ray diffraction confirmed that the most crystalline NaClO-treated and mercerized fibers are, and thermal analysis proved that untreated fibers are stable at 250 °C, but treated fibers degrade with slightly lower onset temperatures due to lignin removal [80]. Curauafibers yielded from *Ananas comosus* var. *erectifolius* leaves are natural high-performance fibers. They possess a tensile strength of over 600 MPa, Young's modulus of over 38 GPa, and failure strain of 2.5%. The density is 1.29 g/cm³ with a mean diameter of the fiber being 90 µm. After alkali treatment, curauafibers used in the study possessed a tensile strength of 697 MPa, modulus of 39 GPa, fiber length of 20 mm, and diameter of 77 µm. The fibers were subjected to hot water washing treatments, combing, cutting, and ultimately alkali treatment in Ca(OH)₂ solution. The treatments removed hemicellulose and lignin, increased surface roughness, and improved the fiber–matrix bonding [25].

Crystallinity was determined by X-Ray Diffraction (XRD) according to the Segal method. The natural fibers under no treatment had high cellulose crystallinity, which has a direct relation to stiffness and strength. Surface morphology with Scanning Electron Microscopy (SEM) had rough textures and fibrillation, which present good mechanical interlocking with polymer matrices [58]. Following mercerization with 5 % NaOH, SEM photographs indicated increased surface roughness and fibril separation, improved matrix adhesion, while XRD attested to increased cellulose crystallinity corresponding to enhanced mechanical performance [61].

E. Density

Biodegradable plant-based "lignocellulosic" fibers are non-abrasive and hence do not cause much damage. They have a hollow and cellular nature, making them effective acoustic and thermal insulators. The hollow tubular structure also reduces their bulk density and makes them lighter in weight. Natural plant fibers have an advantage over E-glass fibers for reinforcement due to their 40-50 % lower density. Different natural plant fibers have varying density values. Most natural fibers have a maximum density of about 1600 kg/m³ and are heavier than water. Though some natural fibers, such as wood, are hollow and have low densities in their native state, they are often densified during processing. Nevertheless, even the maximum density of these fibers is

considerably less than that of inorganic fibers such as glass fibers. Their low density makes them attractive as reinforcements in applications where weight is a consideration. Natural fibers are incorporated into plastics to enhance mechanical performance, specifically improving stiffness and strength, while minimizing the increase in density [81]. The limited impact performance of natural fiber composites is a common challenge, and ongoing research is focused on addressing this issue. However, the low density of natural fibers provides increased flexibility in the design of composite structures [82, 83]. The low density of lignocellulosic fibers contributes to the competitiveness of specific mechanical properties in cellulose fiber composites, especially when compared to glass fiber composites. This underscores the role of density in achieving weight reduction in biocomposites [84]. Incorporating 10% short sisal fibers into low-density polyethylene increases the storage and loss moduli of the composites, stabilizing at a higher volume fraction. Natural plant fibers offer an advantage over glass fibers in reinforcement due to their 40-50 % lower density, making them particularly valuable for weight reduction in structures. Specific properties, especially specific tensile modulus and tensile strength, are of interest in such composites. Notably, with a natural fiber density of approximately 1500 kg/m³, higher fiber content at the same structural weight can be achieved in biocomposites, leading to enhanced reinforcement. Due to their outstanding mechanical properties and low density, natural plant fibers and their derived composites have gained popularity in various industries, including aerospace, marine, automotive, and construction. The density and moisture-related properties of *Grewia optiva* fibers and composites were examined to evaluate their suitability for lightweight applications. Raw fibers showed a low density in the range of 1.2–1.4 g/cm³, which directly contributes to producing lightweight composites [58]. Moisture absorption capacity was tested using water immersion methods, and fibers exhibited 8–10 % water uptake, comparable to other bast fibers. In hybrid epoxy laminates reinforced with jute/*Grewia optiva* and Tasar silk waste (0–14 wt%), water absorption increased with fiber loading and became saturated after 216 hours of immersion, with void fraction rising from 1.8 % to 3.4 % [63]. These results indicate that while *Grewia optiva* fibers maintain lightweight characteristics, proper hybridization and optimized fiber content are required to minimize water uptake.

F. Water Repellent Treatment

A significant drawback of natural plant fibers as a matrix is their susceptibility to water absorption and swelling. When these fibers absorb water, they expand, and during drying, they lose water and revert to their original size, potentially compromising their bonding with filler materials. Typically, the water absorption of natural fiber composites tends to rise with an increase in natural fiber content. The water absorption process in natural fiber composites is considered Fickian diffusion when the water absorption curve aligns with the linear Fickian diffusion curve. In a linear Fickian diffusion curve, the water absorption of natural fiber composites increases linearly during the early period of immersion,

reaches a plateau region, and eventually becomes constant. Incorporating a coupling agent at the fiber-matrix interface can help reduce water absorption in natural fiber composites. Additionally, the coupling agent is distributed on the surface of the fiber and acts to block water permeation into the fiber. Maleated Polyethylene (MAPE) is commonly incorporated into composite formulations to enhance water repellency. However, in certain cases, the inclusion of MAPE in the formulation led to elevated levels of water absorption compared to composites without MAPE. Various researchers have documented that the inclusion of maleate olefins in the composite blend significantly diminishes water absorption, especially when employing biofillers such as Paulownia wood, loblolly wood, pine wood, sisal fiber, and wheat straw [83, 85, 86]. Treating oil palm empty fruit bunches (EFB) with Maleic Anhydride (MAH) leads to the conversion of OH groups into a more hydrophobic ester group. Consequently, composites incorporating MAH-treated EFB exhibited lower water absorption and thickness swelling compared to those without treated EFB [87]. Treating sisal epoxy composites with pure silane significantly reduces water absorption. The effects of various chemical modifications, such as dewaxing, alkali treatment, cyanoethylation, and Acrylonitrile (AN) grafting, on the mechanical properties and water absorption of Pineapple Leaf Fiber (PALF) have been studied. These chemical modifications enhance the mechanical strength of the resulting composites and reduce the percentage of water absorption [88]. Incorporating polyvinyl alcohol and fast curing agents in cement enhances bending strength and dimensional stability, while significantly reducing water absorption and swelling thickness [89]. Linoleic acid has demonstrated greater effectiveness than oleic acid in reducing the water absorption of sheets, potentially due to the filling of pores and gaps in the structure, thereby preventing swelling. Hybridization significantly influences the water absorption properties of composites. A study explored the moisture uptake characteristics of hybrid systems using sisal/glass and pineapple/glass fiber-reinforced polyester composites with varying concentrations of glass fiber and different chemical treatments applied to the biofibers. The findings of another study [66] indicated that hybrid composites exhibited lower water uptake compared to their unhybridized counterparts. A comparative analysis of water absorption between glass fiber (7 wt%) and natural biofiber (13 wt%) hybrid composites and non-hybrid composites reveals lower water absorption in the hybrid system.

Hence, by delving into the ultrastructure, geometric features, microfibrillar angle, cellulose content, density, and water repellent treatments of natural fibers, it becomes evident that these materials offer significant advantages for various applications. Enhancements in mechanical, thermal, and water-resistant properties through specific treatments and modifications position natural fiber composites as sustainable and effective alternatives to traditional synthetic materials. These findings pave the way for their increased use in industries such as automotive, aerospace, marine, and construction, where their unique properties can be fully leveraged.

V. MECHANICAL PROPERTIES OF NATURAL FIBER COMPOSITES

Natural fibers offer a compelling alternative to fossil-based materials due to their high impact strength and

moderate tensile and flexural properties. This study explores their reuse potential for waste disposal, emphasizing economic and environmental benefits in regions abundant with these fibers [91]. For instance, composite materials using coir and abaca fibers reinforced with linear low-density polyethylene (LLDPE) have been developed. These fibers underwent treatment with methyl methacrylate (MMA) under UV radiation, optimizing mechanical properties. Coir fiber composites, especially those treated with a 3 % starch solution, demonstrated superior performance, supported by evaluations of water uptake and soil degradation [92].

Additionally, the stress-strain behavior of sisal fibers was investigated, revealing variations in mechanical properties such as ultimate tensile strength (UTS) and modulus influenced by test length and speed. SEM studies underscored the internal structure's role, particularly the uncoiling of microfibrils, in fiber failure [93]. Furthermore, research focused on the impact of stacking sequence variations on tensile, flexural, and interlaminar shear properties in composites fabricated using the hand lay-up technique. Hybrid composites, notably those incorporating jute fibers, exhibited favorable mechanical properties compared to neat epoxy [94].

In recent decades, the integration of various natural fibers like flax, hemp, jute, straw, and wood into plastics has expanded across diverse applications. These fibers offer cost savings and reduced density compared to glass fibers, making them appealing as environmentally friendly reinforcements in polymeric materials [95]. Moreover, biocomposites of polylactic acid (PLA) with abaca and man-made cellulose fibers were produced via a two-step extrusion coating process and injection molding. Significant enhancements in Charpy impact strength, tensile strength, and stiffness were achieved with the addition of 30 wt% man-made cellulose or abaca fibers. SEM and optical microscopy studies provided insights into fiber orientation and length distribution, validating improved mechanical properties in PLA biocomposites [96].

The tensile properties of natural fiber reinforced polymers (NFRP) depend crucially on factors like adhesion and fiber content, both of which are enhanced through chemical modifications. Optimal tensile behavior is typically observed at specific fiber contents, leading to improvements in strength and modulus, as evidenced in studies involving hemp and other fibers [97]. Practical composite fabrication often favors higher fiber weight percentages to maximize mechanical properties such as tensile strength and modulus [98, 99]. For instance, the role of fiber length and surface characteristics in NFRP's tensile properties has been extensively studied, highlighting the importance of achieving optimal adhesion between the matrix and reinforcement for enhanced composite strength [100-102]. These studies prove the versatility and potential of natural fibers in enhancing the mechanical performance of composites while reducing environmental impact. By exploring various treatments and composite formulations, researchers aim to optimize the integration of these sustainable materials into industrial applications across sectors such as automotive, aerospace, marine, and construction.

The densification of bamboo fibers was studied under varying widths, node presence, temperatures, pressures, compression times, and moisture contents. Fiber width had

little effect, while nodes slightly lowered density. Dry fibers at high temperature, however, sometimes developed microcracks. Overall, the optimal condition was 15 MPa, 120 °C, and 60 % moisture content, producing the greatest density improvement with minimal damage [6]. Tensile testing showed that densification improves the mechanical strength of bamboo fibers, with tensile strength increasing by about 29 % after 1 h at 8 MPa, while fibers with nodes exhibited a smaller gain of ~12 %. Fiber width had little effect, though smaller widths showed slightly higher strength. Increasing pressure to 15 MPa raised strength from 670 to 700 MPa, and both higher temperature and moisture further enhanced performance, with temperature exerting the stronger influence. The highest tensile strength was achieved at 15 MPa, 120 °C, and 60 % moisture content for 1 h, confirming this as the optimal condition for mechanical reinforcement [6]. The mechanical behavior of curaua fibers is exceptional, with tensile strength ranging from 514–2113 MPa and Young's modulus between 27–151 GPa. These values are significantly higher than those typically reported for conventional curaua fibers (326–872 MPa tensile strength; 5.8–16.5 GPa modulus) and outperform many widely used natural fibers such as sisal, jute, and coir. The improvement is attributed to the fibers' high cellulose content and crystallinity, which strengthen the microfibril structure and enhance stress transfer within composites [79].

The cellulose fibril exposure enhances the mechanical reinforcement while embedded in polymer matrices. The addition of curaua fibers to polylactic acid (PLA) considerably enhanced mechanical performance. Tensile strength of neat PLA was 58.2 MPa, Young's modulus was 5.6 GPa, flexural strength was 93.5 MPa, and flexural modulus was 3.0 GPa. When 20 wt% hot water and mercerization-treated curaua fibers (CWM) were added, the tensile strength increased to 75.7 MPa, modulus to 8.8 GPa, flexural strength to 103.6 MPa, and flexural modulus to 4.5 GPa. The improvement shows better adhesion and stress transfer than when no treatment or NaClO treatment was applied. PHB composites also improved with fiber reinforcement, albeit less spectacular. Pure PHB exhibited tensile strength of 18.5 MPa and Young's modulus of 2.5 GPa, which increased to 22.6 MPa and 4.0 GPa, respectively, in CWM 20 wt% composites, and flexural strength increased from 26.3 to 33.4 MPa and flexural modulus from 1.3 to 2.2 GPa. In contrast to PLA, the PHB matrix became flexible and manifested moderate stiffness gains, but interfacial adhesion was poor. Total, chemical treatment boosted reinforcing efficiency of curauafibers, with the most significant mechanical improvement found in PLA matrix, but PHB composites had moderate strength increases but enhanced ductility [80]. Hemp fibers retted, alkali-treated, and formed into polymer composites by using common molding techniques at 10–30 wt% fiber loadings in recent studies.

Tensile testing revealed strengths of 250–450 MPa in untreated fibers and 750 MPa with the alkali treatment, and modulus rose from 20–25 GPa to 40 GPa. Composites of 20 wt% treated hemp registered tensile strength of 30–40 % and 50% higher flexural modulus than neat polymers, proving strong reinforcement potential [36]. A Study analyzed untreated and treated hemp in polymers through compression molding and hand lay-up with 5–30 wt% loadings. Neat resin tensile strength (40 MPa) was increased to 70 MPa at 20 wt%

hemp, and modulus was raised from 2.5 GPa to 5 GPa. Treated fibers performed better than untreated ones, providing 15–20 % enhanced tensile strength and improved impact energy absorption. Fiber loadings greater than 25 wt% caused performance decrease owing to agglomeration [37]. Untreated raw Sunn hemp fibers recorded tensile strength of 400–700 MPa and modulus of 20–38 GPa. Composites with 20 wt% reinforcement yielded tensile strength 35–40 % and flexural strength 30 % greater than neat polymers. Higher crystallinity (91 %) was seen in sunn hemp compared to industrial hemp and natural antimicrobial properties, improving durability [39]. Researchers have explored the mechanical properties of flax fibers and their composites in a wide range of applications. Comparisons with other natural and man-made fibers are reported to have demonstrated that flax fibers have a tensile strength of 345–1500 MPa, a tensile modulus of 10–80 GPa, and an elongation at break of approximately 1.4–3 %, which is comparable with glass fibers but lighter and more environmentally friendly [48]. To gain a clearer insight into variability at the fiber level, quasi-static tensile tests were conducted on 400 flax fibers with gauge lengths ranging from 10 to 500 mm, and then subjected to statistical analysis using Weibull distribution and ANOVA. Their research indicated that tensile strength was greatest in the shorter fibers and reduced with longer gauge length, and Young's modulus decreased with greater diameters because of the effect of the lumen. Failure strains typically remained less than 3 %, indicating that flax exhibits substantial property variability depending on size and structure [49]. The fibers were effective in minimizing brittleness, changing the failure mode, and enhancing toughness and therefore proved to be appropriate for impact-absorbing and protective concrete structures [50].

In polymer systems, study investigated flax–polypropylene (PP) composites produced predominantly by hot press molding. Their review emphasized that flax–PP composites reach tensile strengths of 0.5–1.5 GPa, moduli of 50–70 GPa, and elongations of 2–3 % and exhibit better impact damage tolerance than glass fiber composites at 40–60 % less density. Weak adhesion between fiber and matrix as well as degradation when the processing temperature exceeds 200 °C are nevertheless major problems that require favorable molding conditions to be able to exploit the full reinforcing potential of flax [51]. Subsequent studies on elastomer matrices involved flax–natural rubber (NR) green composites. Flax fibers of different lengths (1–1.5 cm) and percentages (20–50 %) were compared, and optimum condition was 1.25 cm length with 40% percentage. Chemical treatment by sodium hydroxide and enzymatic modification using laccase improved fiber–matrix adhesion by degumming non-cellulosic impurities and enhancing surface roughness. Therefore, tensile strength increased by 9 % and tear strength by 27.4 %, as microscopy and spectroscopic analyses ensured better interfacial bonding and enhanced crystallinity. These results confirm that surface treatments have a significant enhancing effect on the mechanical performance of flax–NR composites [51].

In general, these studies uniformly show that flax fibers offer high specific stiffness and strength and, with suitable treatment and processing, substantially augment tensile strength, toughness, and ductility of composites. In concrete, thermoplastic polymers, or elastomers, they enhance

mechanical performance while providing benefits of low density, renewability, and sustainability, for which they are a potentially valuable substitute for traditional synthetic fibers. In the latest research, the mechanical properties of *Grewia optiva* fibers and their composites were investigated comprehensively with varying reinforcement levels and processing methods. First, the water retting method was used to extract the untreated *Grewia optiva* fibers, and their tensile strength and Young's modulus were 11.8 MPa and 5.4 GPa, respectively, as per ASTM tests [58]. For the improvement of such properties, chemical treatment through mercerization was performed where fibers were immersed in 5 %, 10 %, and 15 % concentrations of NaOH [62]. Tensile tests indicated 5 % NaOH as a preferred concentration with tensile strength of 315.4 MPa, elongation of 4.94 %, and work-to-failure of 132.04 N-cm, whereas greater concentrations of NaOH drew strength through over removal of lignin [61].

In another research, hybrid polymer composites were prepared by reinforcing *Grewia optiva* fibers (0–12 wt%) with chopped basalt fibers (6–12 mm length, up to 12 wt%) in a polyester matrix through the hand lay-up technique. Mechanical testing identified that for 12 wt% basalt and 0 wt% *Grewia optiva*, the composite had a tensile strength of 44.71 MPa and enhanced vibrational stability, whereas varying *Grewia optiva* proportion altered damping properties [59]. Jute/*Grewia optiva* fibers and Tasar silk waste hybrid epoxy laminates (0–14 wt%) were fabricated using hand lay-up molding. Outcomes indicated substantial enhancements, in which the tensile strength reached from 54.44 MPa to 79.16 MPa and flexural strength from 21.91 MPa to 51.22 MPa when incorporating 14 wt% of Tasar silk waste with an increase in impact and hardness at 12 wt% reinforcement [63].

Natural fibers such as bamboo, hemp, flax, curaua, and *Grewia optiva* demonstrate strong potential as renewable reinforcements, offering high specific strength, stiffness, and damping while reducing environmental impact. Through chemical treatments, densification, hybridization, and optimized fiber loadings, their mechanical, thermal, and tribological performances are significantly enhanced, enabling applications in automotive, aerospace, construction, biomedical, and environmental sectors. Despite challenges in fiber variability and matrix compatibility, ongoing advances in processing and surface modification position these fibers as sustainable alternatives to synthetic reinforcements for high-performance composites.

VI. COMPARATIVE DISCUSSION OF NATURAL FIBERS FOR COMPOSITE APPLICATIONS

The natural fibers studied in this paper vary significantly structural characteristics, mechanical behavior, processing compatibility, and engineering applicability. In this study it is found that, curaua and flax fibers show highest tensile performance due to their high cellulose content and crystallinity index. High tensile strength of Curaua makes them highly suitable for lightweight structural composites. Moreover, curaua-reinforced composites show good stress transfer capability which is attributed to their highly aligned microfibrillar structure and enhanced fiber-matrix adhesion after chemical treatment. Similarly, Flax fibers also possess high specific stiffness and excellent damping behavior,

making them suitable reinforcements for automotive and semi-structural applications. On the other hand, Bamboo fibers, show superior flexural stiffness and structural load-bearing capability because of their dense vascular bundle structure and relatively low microfibrillar angle. Bamboo composites demonstrate better dimensional stability and compressive resistance than hemp and flax fibers, especially after densification treatments. However, bamboo fibers possess relatively higher moisture sensitivity which affects their long-term durability under humid atmospheric conditions. Therefore, it is desired to do surface treatments and moisture-resistant coatings for structural bamboo composites. Hemp fibers possess excellent mechanical, acoustic and thermal insulation properties which makes the hemp composites suitable for electric vehicle interiors, insulation panels, and sustainable building materials. Studies indicate that mercerized *Grewia optiva* fibers can achieve significant improvements in tensile and thermal performance through optimized alkali treatment. Unlike many conventional natural fibers, *Grewia optiva* also exhibits antimicrobial activity and thermal resistance, indicating potential for multifunctional engineering applications.

The comparative study reveals that chemical treatments play a decisive role in improving composite performance across all natural fibers. Alkali treatment is the most commonly used surface modification method. It effectively removes lignin, waxes, and hemicellulose, and hence increases surface roughness and interfacial bonding. Silane and benzoylation treatments additionally improve thermal stability and moisture resistance. Nevertheless, excessive chemical treatment may damage cellulose chains and reduce mechanical performance, indicating the need for optimized treatment parameters.

A comparative table of chemical composition and physical properties shown in Table 1 indicates that, Curaua fiber exhibits the highest tensile strength and modulus among all the reviewed fibers. Flax fiber offers excellent specific stiffness and damping properties suitable for automotive applications. Hemp fiber provides balanced structural and acoustic properties. Bamboo demonstrates superior stiffness and load-bearing capability for structural composites. *Grewia optiva* is comparatively less explored but shows promising multifunctional behavior and sustainability potential. Table 2 shows that, Bamboo and flax composites exhibit superior stiffness and structural performance. Curaua composites demonstrate exceptional tensile reinforcement efficiency. Hemp composites provide an effective balance between mechanical performance and sustainability. *Grewia optiva* composites show promising tribological and multifunctional characteristics but require further industrial validation. Effect of different surface treatments on natural fibers is listed in Table 3. Alkali treatment is the most widely used modification method due to its effectiveness and simplicity. Surface modifications generally improve fiber roughness, crystallinity, and stress transfer. Silane and benzoylation treatments significantly improve moisture resistance and thermal stability. Excessive chemical treatment may damage cellulose structure and reduce strength.

Despite substantial progress, there are several challenges which restrict the large-scale industrial implementation of natural fiber composites. Table 4 lists the applications, advantages, sustainability benefits and limitations of the natural fibers studies in this review paper. Future research should focus on developing advanced surface modification techniques to enhance the fiber-matrix compatibility, so that the moisture resistance and

environmental durability could be improved. Additionally, investigations on life-cycle assessment, recyclability, bio-based matrix systems and scalable manufacturing processes should be done to accelerate the adoption of natural fiber reinforced polymer composites in various sectors like automotive, construction, aerospace, packaging, and other sustainable engineering applications.

Table 1. Chemical Composition and Physical Properties of Selected Natural Fibers

Fiber	Cellulose Content (%)	Hemicellulose (%)	Lignin (%)	Density (g/cm ³)	Tensile Strength (MPa)	Young's Modulus (GPa)	Key Characteristics	References
Bamboo	40–60	15–25	20–30	0.9–1.3	140–800	11–46	High stiffness, excellent structural capability, rapid renewability	[5,6]
Curaua	65–77	15	6–9	1.29	514–2113	27–151	High crystallinity, excellent tensile performance, lightweight	[19,25,79,80]
Hemp	60–74	15–20	3–5	1.24	250–750	20–41	Good acoustic behavior, balanced mechanical properties	[36,37]
Flax	60–70	16–20	2–5	1.4–1.5	345–1500	10–80	High specific strength, good damping behavior	[48,49]
<i>Grewia optiva</i>	58–75	10–25	7–22	1.2–1.4	118–315	5.4–15	Sustainable Himalayan bast fiber with multifunctional properties	[53,58,61]

Table 2. Mechanical Performance and Processing Methods of Natural Fiber Reinforced Composites

Fiber	Matrix Material	Processing Method	Optimum Fiber Loading	Major Mechanical Improvements	Major Limitations	Potential Applications	References
Bamboo	Epoxy, Green epoxy	VARTM, RTM, Compression molding	50 wt%	Improved tensile, flexural & impact strength; enhanced thermal stability	Moisture absorption, interfacial incompatibility	Aerospace, automotive, construction	[5,6]
Curaua	PLA, PHB, HDPE, Polyester	Extrusion, Injection molding, Hand lay-up	20 wt%	High tensile strength, improved stiffness & toughness	Poor adhesion without treatment	Automotive parts, packaging, geopolymers	[19,25,79,80]
Hemp	Polypropylene, Epoxy	Compression molding, Hot pressing	20 wt%	Enhanced tensile and flexural properties,	Fiber agglomeration at higher loading	Automotive interiors, EV components	[36,37]

				improved impact resistance			
Flax	PP, PLA, Epoxy, NR	Hot press molding, Infusion	40 wt%	Improved damping, toughness and water resistance	Thermal degradation above 200 °C	Biomedical, construction, impact-resistant structures	[48,49]
<i>Grewia optiva</i>	Epoxy, Polyester, PP	Hand lay-up, Hybrid reinforcement	30 wt%	Improved tensile, flexural, tribological and damping properties	Limited industrial-scale validation	Brake pads, hybrid laminates, structural composites	[53,58,61]

Table 3. Surface Treatments and Their Effects on Natural Fiber Composites

Fiber	Surface Treatment	Purpose of Treatment	Major Effects on Fiber/Composite Properties	Key Outcome	References
Bamboo	Densification, Heat treatment	Improve fiber packing and strength	Increased tensile strength and stiffness	Enhanced structural performance	[5,6]
Curaua	NaOH treatment, Hot water treatment, NaClO treatment	Remove lignin/hemicellulose and improve adhesion	Increased crystallinity and surface roughness	Improved tensile and flexural strength	[19,25,79,80]
Hemp	Alkali treatment, Silane treatment, MAPP compatibilizer	Improve fiber–matrix bonding	Reduced hydrophilicity and enhanced modulus	Better mechanical stability	[36,37]
Flax	Alkali treatment, Enzymatic treatment, Plasma treatment	Improve interfacial adhesion and reduce moisture absorption	Enhanced crystallinity and tear resistance	Improved durability and toughness	[48,49]
<i>Grewia optiva</i>	Mercerization, Benzoylation, Silane treatment	Enhance thermal stability and interfacial bonding	Increased tensile strength and thermal resistance	Better tribological and structural behavior	[53,58,61]

Table 4. Advantages, Limitations, and Engineering Applications of Natural Fibers

Fiber	Major Advantages	Major Limitations	Sustainability Benefits	Major Engineering Applications	References
Bamboo	High stiffness, fast growth, low density	Moisture sensitivity, variability	Renewable and biodegradable	Structural panels, aerospace interiors	[5,6]
Curaua	Exceptional tensile strength, lightweight	Limited commercial availability	Reduced carbon footprint	Automotive composites, biodegradable plastics	[19,25,79,80]
Hemp	Good acoustic and thermal insulation	Processing variability	Low pesticide requirement	EV components, insulation panels	[36,37]
Flax	High specific modulus, excellent damping	Thermal sensitivity	Recyclable and biodegradable	Biomedical products, sporting goods	[48,49]
<i>Grewia optiva</i>	Multifunctional behavior, local availability	Limited research and commercialization	Eco-friendly Himalayan resource	Brake pads, hybrid composites	[53,58,61]

VII. CONCLUSIONS

Natural fiber reinforced polymer composites have become a strong sustainable alternatives to conventional synthetic fiber composites due to their low density, biodegradability, renewability, and favorable mechanical properties. This review paper discusses about the structural characteristics, mechanical properties, processing methodologies, surface modification techniques and engineering applications of bamboo, curaua, hemp, flax and *Grewia optiva* fibers. Flax and hemp natural fibers possess superior tensile properties and dimensional stability which make them suitable for load-bearing and structural applications. The combination of strength, stiffness, availability and cost-effectiveness in bamboo fiber makes it a good option for making light weight composites. Excellent specific mechanical properties of Curaua fiber also make it suitable for lightweight composite applications. An underexplored natural fiber *Grewia optiva* has emerged as a promising reinforcement material with significant scope for further investigation.

The comparative study of the above natural fiber composites reveals that the properties of natural fiber composites are strongly influenced by fiber morphology, chemical composition, interfacial adhesion, processing techniques and environmental exposure conditions. There are number of literature which discuss about improving composite performance by chemical treatments and hybridization strategies. But there are still many challenges like moisture absorption, long-term durability, variability in fiber properties, and large-scale industrial implementation which limits the broader commercialization of natural fiber composites.

To minimize these challenges, the future research should focus on developing advanced surface modification techniques to enhance the fiber-matrix compatibility, so that the moisture resistance and environmental durability could be improved. Moreover, investigations on life-cycle assessment, recyclability, bio-based matrix systems and scalable manufacturing processes should be done to accelerate the adoption of natural fiber reinforced polymer composites in various sectors like automotive, construction, aerospace, packaging, and other sustainable engineering applications.

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