Evaluation of Natural Plant Fibers and their Hybrid Composites to Improve Polymer Strength

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Abstract: Natural plant fibers have developed as viable substitutes for synthetic fibers in polymer reinforcement owing to their renewable, biodegradable, lightweight, and environmentally benign characteristics. Nevertheless, natural fibers generally demonstrate inferior mechanical qualities and increased moisture absorption relative to synthetic alternatives, constraining their independent applications. To address these limitations, hybrid composites that integrate natural fibers with either natural or synthetic fibers have been thoroughly investigated. These hybrid composites have superior mechanical, thermal, and moisture resistance characteristics due to better fiber-matrix adhesion and optimized fiber combinations. This article provides an overview of natural plant fibers, their properties, and several hybridization techniques employed to improve polymer composite performance. The text examines current advancements in hybrid composites utilising fibers such as sugar palm, kenaf, oil palm, bamboo, and jute, emphasizing their mechanical properties, manufacturing techniques, and prospective industrial uses. Challenges concerning fiber compatibility, thermal stability, and water absorption are evaluated alongside advancements in fiber treatments and alterations. The review offers insights into the design, processing, and pricing factors of natural fiber-based hybrid composites as sustainable materials for various engineering applications.

Keywords: *Natural Fibers, Polymer Composites, Hybrid Composites, Plant Fibers, Fiber-Matrix Adhesion, Eco-Friendly Materials, Fiber Treatment, Sustainable Composites.*

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I. INTRODUCTION

Natural plant fiber hybrid composites are a novel category of materials that integrate natural fibers with additional natural or synthetic fibers within a polymer matrix to mitigate the constraints associated with the exclusive use of natural fibers. These composites generally demonstrate superior mechanical, thermal, and chemical resilience relative to monolithic natural fiber composites. The hybridisation strategy seeks to enhance deficiencies, including reduced strength, increased moisture absorption, and inadequate fiber-matrix adhesion characteristic of natural fibers. Hybrid composites integrate natural fibers, including kenaf, jute, hemp, flax, sisal, and bamboo, with synthetic fibers such as glass or carbon fibers, or more natural fibers, resulting in enhanced performance through synergistic effects.[1, 2]

The mechanical properties—comprising tensile, flexural, impact, and shear strengths—are markedly enhanced in hybrids relative to composites reinforced exclusively with natural fibers. Alkali treatment, along with fungal and enzyme treatments, enhances interfacial bonding between fibers and the polymer matrix, leading to improved load transfer and durability. Hybrid composites have enhanced moisture resistance, addressing a significant difficulty associated with natural fibers, since hybridisation can decrease water absorption rates and increase dimensional stability in humid environments.[3]

Moreover, these composites include lightweight and biodegradable properties, providing a more sustainable option compared to entirely synthetic fiber composites. They demonstrate potential for utilisation in automotive, construction, packaging, and other sectors necessitating economical, environmentally sustainable, high-performance materials. The advancement of natural plant fiber hybrid composites effectively tackles significant performance deficiencies through fiber combinations, treatments, and optimised fabrication methods, rendering them dependable, sustainable, and versatile materials for various engineering applications.

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II. CLASSIFICATION AND PROPERTIES OF NATURAL PLANT FIBERS

Natural plant fibers constitute a varied collection of fibrous substances obtained from plants, extensively utilised for reinforcement in polymer composites. The primary varieties comprise jute, hemp, flax, and sisal, each exhibiting unique physical, chemical, and mechanical properties that determine their appropriateness for diverse applications. Jute fibers are prevalent natural fibers, distinguished by their gritty texture and substantial tensile strength. Hemp fibers are recognised for their considerable length and resilience, providing superior strength and rigidity in comparison to jute.[4-6]

Flax fibers possess a delicate texture and superior mechanical qualities, such as elevated tensile strength and modulus, rendering them appropriate for high-performance composites. Sisal fibers exhibit superior toughness and coarseness, possessing commendable impact resistance and moderate strength, frequently employed in applications where longevity is paramount. These natural fibers are mostly composed of cellulose, hemicellulose, lignin, pectin, and waxes, with differing amounts across species. Cellulose is the principal component that provides mechanical strength, but hemicellulose and lignin affect fiber rigidity and moisture retention.[7, 8]

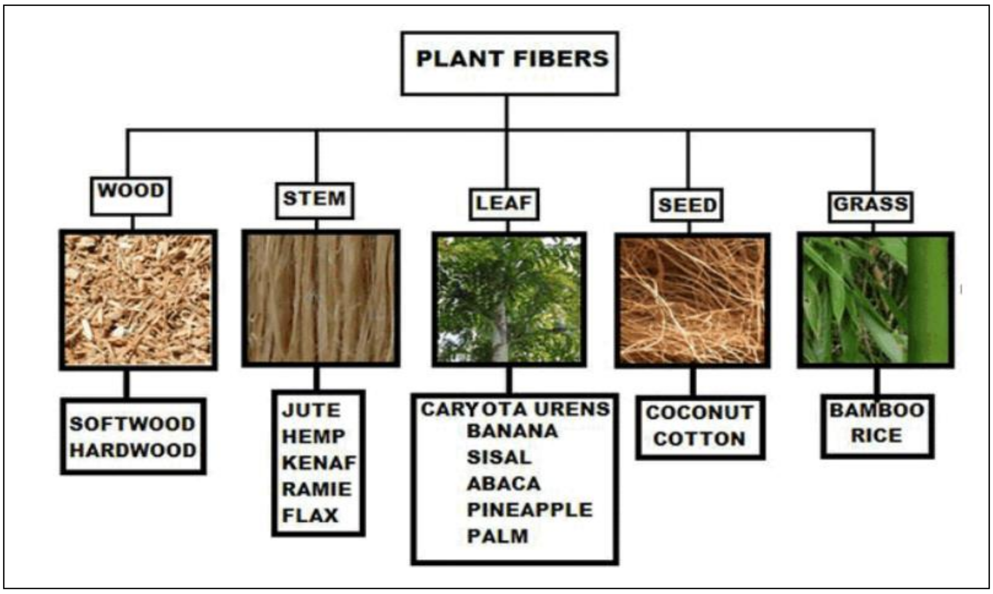

Fig 1: Classification of Plant Fibers (Image Courtesy: Researchgate.net)

Flax fibers comprise approximately 70–80% cellulose, hemp around 70%, jute roughly 61–71%, and sisal about 56–63%. The lignin level is elevated in jute and sisal, enhancing stiffness and biodegradability. The chemical composition influences fiber compatibility with polymer matrices and their overall durability in composites. These fibers exhibit variations in tensile strength, Young's modulus, and elongation at break. Flax and hemp often possess greater tensile strength (up to 900–1100 MPa) and modulus values than jute and sisal, which commonly demonstrate tensile strengths of approximately 300–600 MPa.[9, 10]

The variety in attributes is contingent upon growth circumstances, extraction techniques, and treatments. Although natural fibers exhibit inferior mechanical qualities compared to synthetic fibers such as glass or carbon, they offer adequate reinforcement for several applications, particularly when hybridised or chemically treated to enhance their bonding and moisture resistance. The benefits of natural plant fibers compared to synthetic fibers are their sustainability, renewability, low density, and biodegradability. They provide ecological advantages by diminishing reliance on fossil fuel-derived materials and decreasing composite weight, hence improving energy efficiency in applications like automotive components.[3, 5, 11]

Moreover, natural fibers are economically advantageous, readily accessible, and safer to manipulate owing to their non-abrasive characteristics in contrast to synthetic options. These characteristics render natural plant fibers progressively appealing for sustainable, lightweight, and cost-effective composite materials.

III. POLYMER MATRICES USED IN COMPOSITE FABRICATION

Polymer matrices function as the continuous phase of composite materials, uniting the reinforcing fibers and facilitating load transfer among them. They are chiefly classified into two categories: thermoplastics and thermosets. Thermoplastics are polymers that may be repeatedly softened by heating and solidified by cooling without substantial chemical alteration. They have advantages like recyclability, impact resistance, and processing simplicity. Prevalent thermoplastics encompass polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyamide (PA). Conversely, thermosets are cross-linked polymers that undergo irreversible curing during processing, resulting in enhanced mechanical strength, thermal stability, and chemical resistance.

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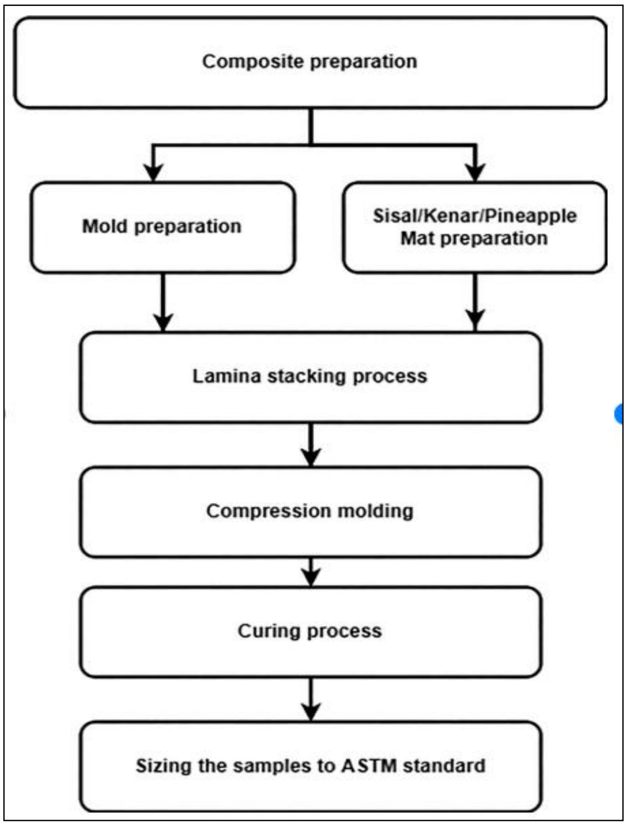

Fig2: Process Flow Chart of Composite Fabrication
(Image Courtesy: Researchgate.net)

Epoxy, polyester, and vinyl ester resins are common thermosetting materials utilized in composites. The compatibility of natural fibers with polymer matrices is a crucial determinant of composite performance. Natural fibers possess hydrophilic surfaces attributed to hydroxyl groups in cellulose, resulting in inadequate interfacial adhesion with the predominantly hydrophobic polymer matrix. This incompatibility may lead to inadequate fiber-matrix adhesion, compromising mechanical characteristics and moisture resistance.[12-14]

To resolve this issue, fiber surface treatments including alkali treatment, silane coupling, and compatibilizer additives are utilized to augment interfacial bonding and promote compatibility with both thermoplastics and thermosets. Thermoplastics such as polypropylene and polyethylene are predominantly preferred in natural fiber hybrid composites because to their affordability, processing simplicity, and recyclability. Polypropylene is widely utilized because to its good mechanical properties and compatibility with treated fibers.[15, 16]

Thermoset matrices, including epoxy and polyester resins, are prevalent in hybrid composites that necessitate enhanced mechanical strength and heat stability. The choice of polymer matrix is contingent upon the specific application, processing technique, and the requisite equilibrium of performance, cost, and environmental consequences.[17-19]

IV. FABRICATION TECHNIQUES FOR NATURAL FIBER HYBRID COMPOSITES

Hybrid composites made from natural fibers demonstrate superior mechanical and physical properties when compared to composites made solely from natural fibers. They provide an optimal combination of strength, stiffness, and impact resistance, along with enhanced thermal and moisture resistance. These hybrid composites utilize the advantageous properties of multiple fiber types integrated within a single matrix, resulting in enhanced tensile, flexural, and impact strengths. The combination with synthetic fibers or alternative reinforcements frequently leads to improved stiffness and toughness. For instance, incorporating basalt fibers into natural fibers such as coconut sheath markedly enhances tensile, flexural, and impact strengths, attributable to the superior stiffness and load-bearing capacity of basalt fibers.[20]

The arrangement and sequence of fibers play a crucial role in performance, as strategic layering can significantly improve resistance to crack propagation and mechanical stresses. Natural fiber hybrid composites demonstrate superior thermal stability and moisture resistance compared to pure natural fiber composites, which are naturally prone to moisture sensitivity due to their hydrophilic characteristics. Hybrid composites that include synthetic fibers or treated natural fibers exhibit enhanced thermal degradation temperatures, elevated glass transition temperatures, and decreased water absorption, rendering them more appropriate for challenging applications. Nonetheless, pure synthetic fiber composites typically exhibit enhanced mechanical and thermal characteristics, whereas hybrid composites present a more sustainable and economical option without significantly compromising performance. The improvement in properties is affected by various factors such as the type of fiber, the treatment of the fiber surface (whether chemical or physical), the content and orientation of the fiber, the type of matrix used, and the methods of fabrication.[21, 22]

The hybridization method—integrating natural fibers with other natural fibers or with synthetic fibers—enables the customization of mechanical and thermal properties to meet particular requirements. For example, investigations indicate that optimal mechanical properties are achieved at particular fiber loadings (such as approximately 30 wt%), and specific stacking sequences of fibers result in the highest tensile modulus and impact resistance. In comparison to pure natural fiber composites, hybrid composites exhibit markedly enhanced mechanical strength, stiffness, and impact resistance, attributed to the synergistic interaction between the fibers. These materials demonstrate superior performance compared to pure natural fiber composites in terms of thermal stability and moisture resistance. In contrast to entirely synthetic composites, hybrids typically exhibit lower absolute mechanical properties; however, they provide benefits in terms of environmental sustainability, cost-effectiveness, and weight reduction.[23-25]

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Therefore, hybrid composites present a compelling intermediate solution that merges the advantages of synthetic fibers with the sustainability offered by natural fibers, making them suitable for various sectors, including automotive, construction, and packaging industries, among others. [26-28]

In conclusion, natural fiber hybrid composites exhibit enhanced mechanical and physical properties due to the careful selection of fiber combinations, surface modifications, and advanced fabrication methods. The advancements position them as a viable option against both purely natural and synthetic fiber composites, striking a balance between performance, environmental sustainability, and cost-effectiveness for various industrial uses.[29, 30]

V. CONCLUSION

The review of natural fiber hybrid composites underscores their promise as sustainable, high-performance materials that effectively connect purely natural and fully synthetic fiber composites. The findings reveal that integrating natural fibers with synthetic or additional natural fibers in a hybrid configuration can markedly improve mechanical properties, including strength, stiffness, and impact resistance, alongside enhancements in thermal stability and moisture resistance.

Recent developments in fabrication methods, surface treatments, and material compositions have overcome various challenges, resulting in enhanced fiber–matrix adhesion, decreased moisture sensitivity, and increased durability. Furthermore, the environmental advantages—arising from renewable sourcing, biodegradability, and reduced energy demands during production—position them as a compelling option for sustainable materials engineering.

The overall importance of natural fiber hybrid composites in the polymer reinforcement domain is rooted in their capacity to offer a practical balance between performance and sustainability. The lightweight, cost-effective, and renewable qualities of natural fibers are utilized, while addressing their inherent limitations through hybridization, thus expanding their use in automotive, construction, packaging, and aerospace interior components.

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