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Thermal, Structural and Chemical Properties of Natural Bark Fibers for Use in Advanced Polymer Composite Reinforcement

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Abstract: The demand for sustainable and high-performance reinforcement materials has led to extensive research on natural fibers derived from plant sources. Among these, bark fibers have emerged as a promising reinforcement for polymer composites due to their unique combination of mechanical strength, low density, renewability, and cost-effectiveness. However, the effective utilization of bark fibers in high-performance applications requires a comprehensive understanding of their thermal, structural, and chemical characteristics. This paper presents an in-depth review of the advanced characterization of natural bark fibers and their suitability for polymer composite reinforcement. It explores various analytical methods such as thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM), which provide insights into the fiber's chemical composition, crystallinity, surface morphology, and thermal degradation behavior. The study also discusses how alkali and silane treatments modify the fiber surface and improve fiber–matrix adhesion in polymer composites. The results of such characterization are crucial in optimizing processing parameters and enhancing the mechanical and thermal performance of bark fiber–reinforced composites for structural, automotive, and aerospace applications.

Keywords: *Natural Fibers, Bark Fiber, Polymer Composites, Thermal Analysis, FTIR, XRD, SEM, Surface Modification, Fiber-Matrix Adhesion, Sustainable Materials.*

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I. INTRODUCTION

The growing emphasis on environmental sustainability and circular materials has accelerated the use of natural fibers as reinforcements in polymer composites. Unlike synthetic fibers such as glass or carbon, natural fibers offer biodegradability, low cost, and reduced environmental impact. Among the wide variety of plant-derived fibers, bark fibers have recently gained attention due to their high cellulose content, inherent strength, and abundance as an agro-industrial by-product. Bark fibers are extracted from the outer layer of trees, which serves as a protective barrier against mechanical and environmental stress. This natural function imparts a complex microstructure rich in lignocellulosic constituents—cellulose, hemicellulose, lignin, and extractives—that directly influence their mechanical and thermal behavior when used as reinforcements in polymer matrices.[1-3].

The aerospace and automotive industries are continuously seeking lightweight yet high-strength materials to enhance energy efficiency. Polymer composites reinforced with natural fibers like bark have the potential to replace synthetic alternatives in semi-structural components, interior panels, and insulation systems. However, the variability of natural fibers in terms of chemical composition, moisture content, and fiber morphology necessitates advanced characterization to ensure performance consistency and predictability. Without understanding the fiber's internal structure and thermal stability, it is difficult to achieve proper interfacial bonding with polymer matrices or to design processing conditions that preserve fiber integrity.[4-12].

Characterization thus forms the foundation of material optimization. By employing sophisticated analytical techniques such as FTIR, TGA, XRD, and SEM, researchers can evaluate the physical, thermal, and chemical attributes of bark fibers. These methods not only reveal the intrinsic composition and crystallinity of the fibers but also provide insights into the effects of surface treatments. The results from such analyses are vital for improving adhesion between fiber and matrix, enhancing load transfer, and achieving superior mechanical properties in the final composite material.[13-17].

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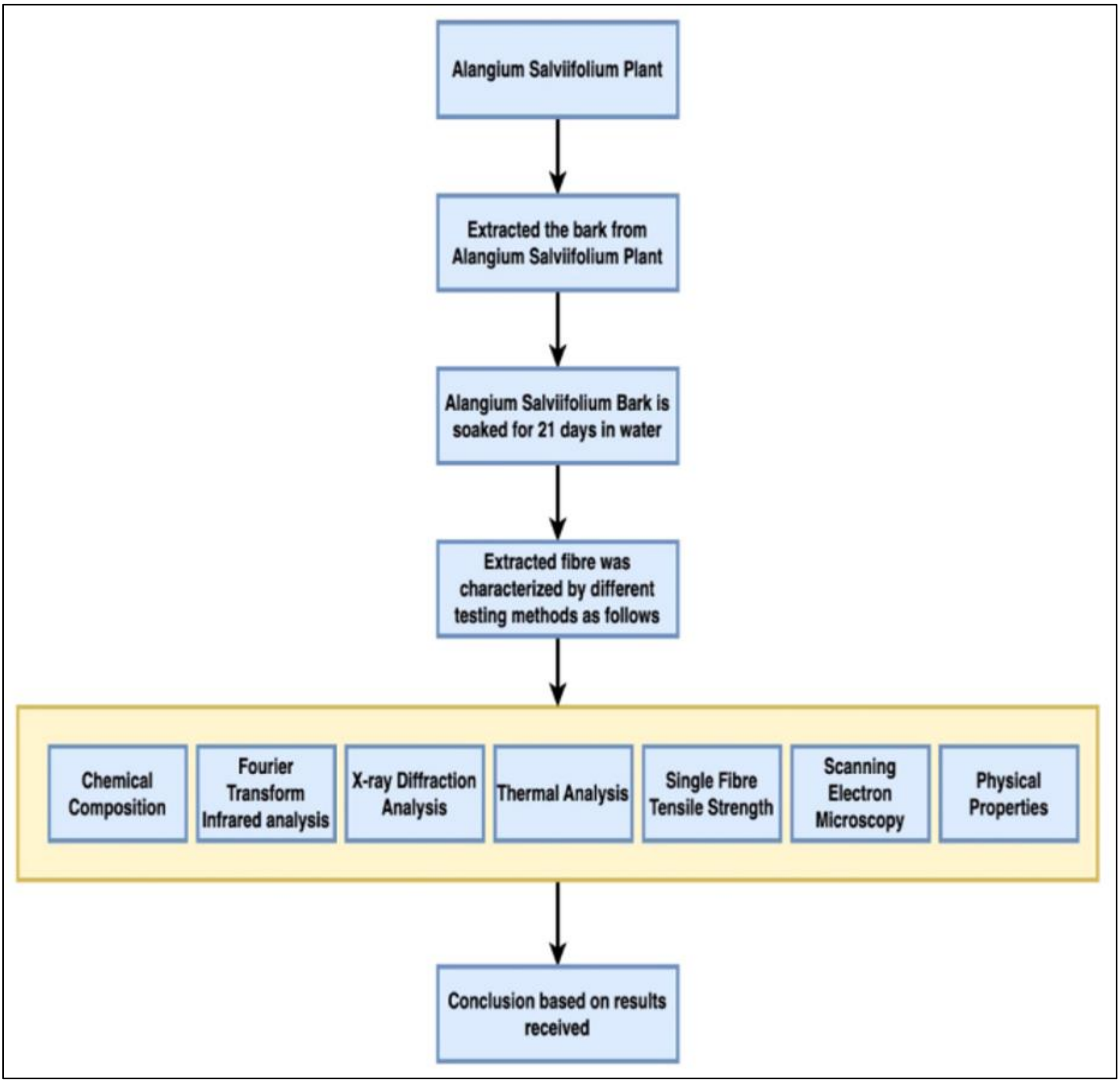

Fig 1 Flow Chart of Alangium Salviifolium Fibre Extraction Characterization Process.

II. COMPOSITION AND STRUCTURAL FEATURES OF BARK FIBERS

Bark fibers are composed primarily of cellulose, hemicellulose, and lignin, along with minor quantities of waxes, pectins, and extractives. Cellulose provides the fundamental structural framework, conferring stiffness and tensile strength through its semi-crystalline arrangement of β-D-glucose chains. Hemicellulose, an amorphous polysaccharide, contributes to flexibility but also influences moisture absorption. Lignin acts as a natural adhesive, providing rigidity and resistance against biological degradation. The relative proportion of these components varies depending on the botanical source, age of the plant, and extraction method.

The microstructure of bark fibers reveals a hierarchical organization, with microfibrils embedded in a lignin–hemicellulose matrix. The degree of crystallinity, often quantified using X-ray diffraction (XRD), determines the mechanical stiffness and thermal resistance of the fiber. Higher crystallinity correlates with improved strength and dimensional stability, whereas higher amorphous content enhances flexibility but increases moisture sensitivity.

The fiber surface morphology, typically examined using scanning electron microscopy (SEM), shows longitudinal ridges, microvoids, and surface impurities. These irregularities can either facilitate or hinder bonding with the polymer matrix depending on the degree of cleanliness and roughness. To improve adhesion, chemical surface treatments

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such as alkali (NaOH) or silane modification are commonly employed. Alkali treatment removes waxes and lignin, exposing the cellulose fibrils and increasing surface roughness, while silane treatment introduces functional groups that chemically bond with polymer chains.[18-21]

Such structural and surface characterizations are essential for tailoring the fiber–matrix interface. In polymer composites, weak interfacial adhesion leads to poor stress transfer and premature failure. Understanding the structure-property relationship at the fiber level enables the engineering of composite systems with optimized strength, durability, and environmental resistance.[22-26]

III. THERMAL CHARACTERIZATION OF BARK FIBERS

Thermal analysis plays a critical role in determining the suitability of natural fibers for high-temperature processing and end-use applications. The two most widely used techniques—thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC)—provide quantitative information on the fiber's degradation profile and thermal transitions.[27-31].

TGA measures the weight loss of the fiber as a function of temperature, revealing distinct stages of thermal decomposition. Typically, an initial weight loss below 120°C corresponds to moisture evaporation, followed by major decomposition between 200°C and 400°C due to the breakdown of hemicellulose and cellulose. Lignin decomposition occurs over a broader range (250°C–500°C) because of its complex aromatic structure. The residual char content after 600°C provides insight into the fiber's thermal stability and potential for fire retardancy. Bark fibers often exhibit high residual mass due to the presence of lignin, indicating better resistance to thermal degradation compared to purely cellulose-based fibers.[32-37].

DSC analysis identifies endothermic and exothermic transitions, such as moisture desorption, softening, or crystallization. The glass transition temperature (Tg) provides an estimate of the fiber's dimensional stability under varying thermal conditions. These parameters are critical when integrating bark fibers into thermoplastic matrices, as the processing temperature must remain below the degradation onset temperature of the fiber to prevent structural damage.[38-44].

The effect of chemical treatments on thermal properties is also significant. Alkali treatment generally increases the thermal stability of bark fibers by removing low molecular weight impurities and improving crystalline order. Silane-treated fibers exhibit enhanced interfacial compatibility, resulting in improved heat transfer across the fiber–matrix interface. Such improvements make bark fibers suitable for applications requiring elevated thermal resistance, such as automotive under-hood components and aerospace interior panels.[45-47].

IV. CHEMICAL AND SPECTROSCOPIC ANALYSIS

Chemical characterization of bark fibers provides insights into their molecular composition and functional groups, which govern their bonding potential with polymer matrices. The most widely used analytical tool is Fourier-transform infrared spectroscopy (FTIR). FTIR spectra reveal characteristic absorption bands associated with cellulose, hemicellulose, and lignin components. Peaks near 3400 cm^{-1} indicate hydroxyl (–OH) stretching vibrations, representing hydrogen bonding in cellulose. Absorptions at 1730 cm^{-1} correspond to carbonyl (C=O) groups in hemicellulose and esterified lignin, while aromatic skeletal vibrations near 1500 cm^{-1} are signatures of lignin. The relative intensity of these bands provides information about the chemical composition and purity of the fiber.[48].

After chemical modification, FTIR spectra show noticeable changes. For instance, alkali treatment reduces the intensity of peaks associated with lignin and hemicellulose, confirming their partial removal. Silane treatment introduces new peaks corresponding to Si–O–Si and Si–O–C bonds, indicating the successful formation of chemical bridges between the fiber surface and the silane coupling agent. These modifications enhance fiber hydrophobicity and improve compatibility with hydrophobic polymer matrices like polypropylene or epoxy.

Complementary techniques such as X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDS) provide additional information. XRD determines the crystallinity index (CI) of bark fibers, a measure of the ordered cellulose regions relative to amorphous components. Higher CI values correlate with increased stiffness and lower moisture uptake. EDS, performed alongside SEM imaging, reveals elemental composition—useful for detecting residual alkali or silane content after surface treatment. Together, these methods form a comprehensive picture of the chemical state and structural organization of bark fibers.

Such detailed chemical insights are crucial for designing fiber–matrix interfaces that enable efficient stress transfer. For high-performance composites, the interfacial bond strength often dictates the overall mechanical performance more than the intrinsic strength of the fiber itself. Hence, chemical characterization not only confirms composition but also guides the optimization of surface treatments for targeted applications.

V. APPLICATION POTENTIAL AND CONCLUSIONS

The successful integration of natural bark fibers into polymer composites has opened new pathways for sustainable high-performance materials. Detailed characterization enables engineers to select optimal fibers, treatments, and processing methods tailored to specific requirements. The enhanced mechanical and thermal properties achieved through controlled chemical modification make bark fiber–reinforced composites suitable for a range of applications including

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automotive interiors, aircraft cabin panels, building materials, and consumer products.

From a sustainability standpoint, bark fibers offer significant advantages: they are biodegradable, renewable, and often derived from waste streams of the timber and agro-industries. Utilizing these fibers not only reduces environmental impact but also adds economic value to underutilized biomass resources. With advancements in hybrid composite technology, bark fibers can be combined with synthetic reinforcements or nanoparticles to achieve properties comparable to traditional glass or carbon fiber composites while maintaining ecological benefits.

In conclusion, the advanced characterization of natural bark fibers is fundamental to unlocking their full potential in high-performance polymer composites. Thermal, structural, and chemical analyses provide critical insights into their behavior during processing and service. The combination of improved surface chemistry, enhanced crystallinity, and stable thermal response ensures that bark fiber–reinforced composites can meet the demanding requirements of modern engineering applications. As research progresses, these materials are poised to become key contributors to the next generation of eco-efficient, lightweight, and durable structural composites.

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