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Fabrication and Mechanical Evaluation of Eco-Friendly Epoxy Composites Reinforced with Natural Fibers

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Abstract: Innovation in natural fiber–reinforced polymer composites (NFRPCs) is a response to the rising interest in environmentally friendly resources. Natural fibers, particularly jute, hemp, flax, and sisal, are affordable, biodegradable, and renewable resources compared to synthetic fibers. Yet, because of their water-absorbing tendencies, and weak bonding to hydrophobic polymer matrices, their utility is undercut. This impairment of NFRPCs weakens their overall performance. To overcome these bonding issues, natural fibers have undergone chemical transformations to polymer interfacial adhesion, compatibility, and natural composites mechanical performance. This review focuses on the eco-friendlier NFRPCs, on the fiber chemical modification methods, the processing of the composites, their eco-friendliness, mechanothermic and mechanical properties, and pertinent issues. The paper also discusses anticipated challenges and potential pathways of forthcoming research to achieve sustainable, biocomposites.

Keywords: *Natural Fibers, Polymer Composites, Chemical Modification, Eco-Friendly Materials, Fiber–Matrix Interface, Sustainability.*

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I. INTRODUCTION

The growing concerns surrounding our environment and the end of non-renewable resources have led to the creation of sustainable materials which can, to an extent, substitute traditional synthetic composites. Natural fibers such as jute, hemp, banana, coir, sisal, and flax have an advantage in lightweight, biodegradable, renewable, and having good specific strength. Natural fibers, when used as a reinforcing element in a composite polymer, lessen the negative impact on the environment.[1, 2]

Nonetheless, the composite materials that the natural fibers are used in, have poorly achieved interfacial adhesion of the natural polymer composites of the hydrophilic and hydrophobic bonded materials. This can result in opposing mechanical strength and the trouble of water absorption. Advances such as alkali treatment, acetylation, silane coupling, and maleic anhydride grafting have provided the means to focus on and solve the issues surrounding water absorption and adhesion.[3, 4]

Over the past ten years, modified natural fibers have achieved new levels of excellence in mechanical, thermal, and moisture resistance attributes. This review discusses the advancements made in this area, especially in the integration of chemical modifications and the improvement of composite characteristics, all the while retaining an environmentally friendly aspect.[5, 6]

II. OVERVIEW OF NATURAL FIBERS FOR POLYMER COMPOSITES

Natural fibers can be divided into plant, animal, and mineral fibers. Of all the fibers, the most frequently used in polymer composites are plant fibers, which is due to their abundance and suitable mechanical attributes.

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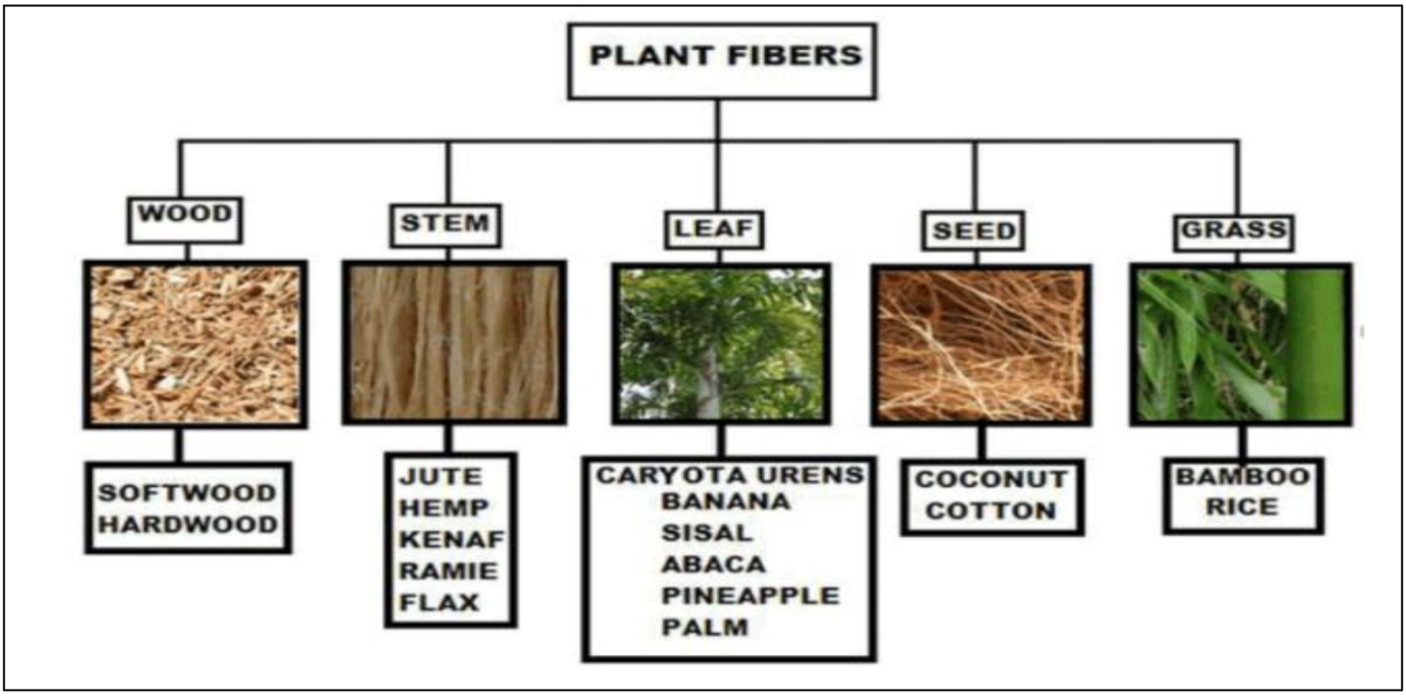

Fig1: Classification of Plant Fibers (Image Courtesy: Researchgate.net)

➢ *Plant Fibers*

Examples include:

- Bast fibers: Jute, hemp, flax, kenaf
- Leaf fibers: Sisal, banana, pineapple
- Seed fibers: Cotton, coir

Plant fibers mainly consist of cellulose (40–70%), hemicellulose (10–20%), lignin (5–25%), pectin, and waxes. The cellulose content largely determines tensile strength, while lignin contributes to stiffness and rigidity.[7-11]

➢ *Properties of Common Natural Fibers*

The wide variation in mechanical performance shows the influence of fiber type, maturity, and treatment method on composite behavior.

Table 1 Properties of Common Natural Fibers

Fiber	Cellulose (%)	Lignin (%)	Density (g/cm³)	Tensile Strength (MPa)	Young's Modulus (GPa)
Jute	61–71	12–13	1.3–1.45	393–800	10–30
Flax	65–75	2–3	1.4–1.5	500–900	50–70
Sisal	65	12	1.45	350–700	9–22
Hemp	70–74	3–4	1.48	550–900	30–60
Coir	32–43	40–45	1.15	220	6–10

III. CHEMICAL MODIFICATION TECHNIQUES FOR NATURAL FIBERS

Natural fibers are inherently hydrophilic due to the presence of hydroxyl groups (–OH) in cellulose and hemicellulose, which attract moisture and cause poor bonding with hydrophobic polymer matrices. To improve compatibility, surface modification techniques are applied.

➢ *Alkali (Mercerization) Treatment*

Alkali treatment using sodium hydroxide (NaOH) removes lignin, waxes, and oils that cover the fiber surface, increasing surface roughness and reducing fiber diameter. The process also converts cellulose I to cellulose II, which improves mechanical interlocking and fiber–matrix adhesion.[12-15]

- *Reaction:*

$$\text{Fiber–OH} + NaOH \rightarrow \text{Fiber–}O^{-}\,Na^{+} + H_2O$$

➢ *Silane Treatment*

Silane coupling agents (e.g., γ-aminopropyltriethoxysilane) act as molecular bridges between the fiber and matrix. The silane reacts with hydroxyl groups on the fiber surface, forming covalent bonds that improve compatibility with polymer chains.[16, 17]

➢ *Acetylation*

Acetylation replaces hydroxyl groups with acetyl groups, reducing hydrophilicity and enhancing dimensional stability. It improves resistance to moisture and biological degradation.

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➢ *Maleic Anhydride Grafting*

Maleic anhydride-grafted polypropylene (MAPP) is commonly used in polypropylene composites. It enhances interfacial bonding through esterification reactions between anhydride and fiber hydroxyl groups.

➢ *Other Treatments*

Other modifications include benzoylation, permanganate oxidation, isocyanate treatment, and enzyme treatment, each tailored to specific fiber and matrix combinations.[18-20]

IV. POLYMER MATRICES USED

Polymers act as the continuous phase binding the fibers together. They can be classified into thermoplastic and thermosetting matrices.[21-26]

➢ *Thermoplastics*

Examples include polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polylactic acid (PLA), and polyamide (PA). They are recyclable and suitable for automotive and packaging applications. Among them, PLA is a biodegradable polymer often used for eco-friendly composites.[27-29]

➢ *Thermosets*

Thermosetting resins such as epoxy, polyester, and phenolic resins are widely used for high-strength applications due to their cross-linked structure and excellent dimensional stability.[30, 31]

V. INTERFACIAL BONDING AND COMPOSITE PERFORMANCE

Chemical modification of fibers leads to improved fiber–matrix adhesion, which is critical for load transfer. Good interfacial bonding results in enhanced mechanical performance, reduced void content, and better water resistance.[32, 33]

Table 2 Composite Performance

Treatment Type	Effect on Interface	Impact on Composite Properties
Alkali Treatment	Removes lignin/wax; increases roughness	Higher tensile strength, better bonding
Silane Treatment	Forms covalent bonds	Improved tensile and flexural strength
Acetylation	Reduces moisture absorption	Enhanced dimensional stability
MAPP Coupling	Promotes chemical linkage	Increased modulus and toughness

VI. MECHANICAL AND THERMAL PROPERTIES OF CHEMICALLY MODIFIED COMPOSITES

Chemical treatments significantly enhance mechanical and thermal properties. Several studies have shown that alkali-treated and silane-treated fibers yield superior composite strength compared to untreated ones.[34-39]

Thermal stability also improves as surface impurities are removed, resulting in better fiber–matrix contact and higher decomposition temperatures.[40-43]

Table 3 Mechanical and Thermal Properties

Fiber / Matrix	Treatment	Tensile Strength (MPa)	Flexural Strength (MPa)	Improvement (%)
Jute / PP	Untreated	35	52	-
Jute / PP	Alkali	47	68	+30
Flax / Epoxy	Silane	92	105	+25
Coir / Polyester	Acetylated	62	70	+20
Sisal / PLA	Alkali + Silane	80	95	+35

VII. ENVIRONMENTAL AND SUSTAINABILITY ASPECTS

The key advantage of using natural fibers is sustainability. Compared to glass fiber composites, natural fiber composites require less energy during production and generate fewer greenhouse gas emissions. Moreover, fibers such as jute, hemp, and sisal are biodegradable and can be sourced locally, reducing transportation emissions.[28, 44, 45]

Life-cycle assessment (LCA) studies have shown that replacing synthetic fibers with natural fibers can reduce the carbon footprint by up to 40–60%. Furthermore, end-of-life management through recycling and composting aligns with the circular economy framework.[46]

VIII. APPLICATIONS AND CASE STUDIES

➢ *Eco-Friendly Polymer Composites are now being Adopted in Various Industrial Applications:*

- Automotive Components: Door panels, dashboards, seat backs, and trunk liners made from jute/PP or hemp/PLA composites.
- Construction Materials: Wall panels, roofing, and insulation boards utilizing coir/polyester composites.
- Consumer Products: Sports goods, packaging materials, and furniture using flax/epoxy and sisal/PLA composites.
- Aerospace and Marine: Lightweight sandwich structures for non-structural components.

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Case studies from companies like Ford and BMW show successful integration of natural fiber composites in vehicles, achieving both weight reduction and sustainability goals.

IX. CHALLENGES AND FUTURE PERSPECTIVES

➢ *Despite Promising Developments, Several Challenges Remain:*

- Moisture Absorption: Even after chemical treatment, complete elimination of hydrophilicity is difficult.
- Thermal Degradation: Natural fibers degrade at lower temperatures, limiting processing options.
- Variability: Fiber properties vary depending on source, maturity, and treatment conditions.
- Recycling and Durability: Ensuring recyclability and long-term performance remains complex.

➢ *Future Directions*

- Development of green coupling agents and bio-based matrices.
- Use of nanocellulose and hybrid fiber systems to improve strength and stiffness.
- Integration of machine learning for process optimization and performance prediction.
- Establishing standardized testing and characterization methods for consistency.

X. CONCLUSION

Chemically modified natural fiber–reinforced polymer composites represent a sustainable alternative to traditional synthetic composites. Through surface modification techniques such as alkali, silane, and acetylation treatments, the interfacial compatibility between natural fibers and polymer matrices can be significantly improved, leading to enhanced mechanical, thermal, and environmental performance.

The continued development of bio-based polymers and green chemical treatments will further advance the eco-friendly composite industry. As research progresses toward improved durability, recyclability, and large-scale manufacturing, these composites are expected to play a vital role in realizing a sustainable materials future.

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