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Epoxy Based Composite Material using Natural Fibers: A Review

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***Abstract* - The growing demand for sustainable materials has driven significant research into natural fiber-reinforced epoxy composites as alternatives to conventional synthetic composites. This review provides a comprehensive analysis of synthesis methods, mechanical properties, surface treatment strategies, and applications of natural fiber-reinforced epoxy composites. Key natural fibers including jute, flax, hemp, sisal, banana, and pineapple leaf fibers are examined for their reinforcement potential. The synthesis of these composites involves critical steps including fiber selection, surface modification, and epoxy matrix formulation, with processing techniques such as hand lay-up, vacuum infusion, and compression molding playing pivotal roles in determining final properties. The review finds that fiber-matrix compatibility, fiber orientation, and interfacial adhesion significantly influence mechanical performance, including tensile strength, flexural properties, and impact resistance. Surface treatments—particularly alkali, silane, and plasma treatments—effectively enhance interfacial bonding and overall composite performance. Applications span automotive, aerospace, construction, and consumer goods industries, where these composites offer lightweight, durable, and environmentally responsible alternatives. The review concludes with identified challenges and future research directions, including hybrid fiber systems, nanofiller incorporation, and machine learning approaches for property optimization.**

Keywords: *Natural fibers, epoxy composites, surface treatment, mechanical properties, sustainable materials, fiber-matrix interface.*

1. INTRODUCTION

The material sciences have witnessed a notable surge of interest in natural fiber-reinforced polymers over recent decades. This interest stems from growing environmental awareness, depleting petroleum resources, and increasing regulatory pressure to develop sustainable alternatives to conventional synthetic composites. Natural fibers offer compelling advantages: they are renewable, biodegradable, abundant, cost-effective, and possess favorable specific properties [1-2].

Epoxy resins, as thermosetting polymers, serve as excellent matrices for natural fiber reinforcement due to their superior mechanical properties, chemical resistance, thermal stability, and strong adhesion to various substrates. When combined, natural fibers and epoxy matrices create composite materials that balance environmental responsibility with performance requirements [3].

This review aims to provide a comprehensive analysis of natural fiber-reinforced epoxy composites, examining fiber types, synthesis methods, surface treatments, mechanical and physical properties, and applications. Particular emphasis is placed on understanding how fiber characteristics and processing parameters influence composite performance and how surface modification strategies address inherent challenges associated with natural fibers [5].

2. NATURAL FIBERS FOR EPOXY COMPOSITES

2.1 Fiber Types and Characteristics

Natural fibers can be broadly categorized based on their origin: plant-based (cellulosic), animal-based (proteinaceous), and mineral fibers. Plant fibers are most widely used in epoxy composites and include bast fibers (jute, flax, hemp), leaf fibers (sisal, banana, pineapple), seed fibers (cotton), and fruit fibers (coir) [6].

The mechanical properties of natural fibers exhibit considerable variability depending on species, growing conditions, extraction method, and processing. Quantitative data show tensile strengths ranging from 12 MPa (abaca) to 1627 MPa (pineapple), with densities ranging from 295 kg/m³ (kenaf) to 1560 kg/m³ (pineapple). This variability significantly influences composite performance and requires careful material selection for specific applications. Common plant fibers used in epoxy composites include:

- **Jute**: Low cost, moderate strength, widely available.
- **Flax**: High specific strength and stiffness, good fiber-matrix compatibility.
- **Hemp**: Excellent mechanical properties, good thermal stability.

- **Sisal**: High strength, good impact resistance.
- **Banana**: Abundant agricultural waste, moderate properties.
- **Pineapple leaf fiber (PALF)**: High tensile strength, renewable.

2.2 Animal Fibers in Epoxy Composites

Recent research has expanded to include animal-based waste fibers as reinforcements. Studies on chicken feathers, duck feathers, and human hair fibers incorporated into epoxy matrices demonstrate their potential for specific applications. Chicken feather composites, for instance, exhibit low density, enhanced impact resistance, and water-resistant qualities due to their keratinous nature. The hydrophilic amino acids in chicken feathers contribute to higher water absorption, while human hair and duck feather composites show comparatively lower absorption [7].

3. FIBER EXTRACTION AND PREPARATION

3.1 Mechanical Extraction

Mechanical extraction relies on physical forces such as shearing, scraping, and ripping to separate fiber bundles from plant stems or leaves. The process typically includes decortication, fiber cleaning, and fiber opening, during which the woody core is mechanically removed and remaining bundles refined into finer strands. While mechanical extraction offers rapid processing and industrial scalability, intense mechanical forces often cause fiber breakage, reduced fiber length, and inconsistent quality. Studies on jute, banana, and *Sansevieria cylindrica* fibers show that mechanically extracted fibers retain higher lignin and wax content than retted fibers, resulting in lower flexibility and variable tensile properties [9,11,13].

3.2 Biological Extraction

Biological extraction uses naturally occurring microorganisms or targeted enzymes to decompose pectin, hemicellulose, and other binding components that hold fiber bundles to plant tissues. This method produces cleaner, more uniform fibers with minimal structural damage [4].

Retting, the most traditional biological extraction method, involves placing stems or leaves in water to allow bacteria and fungi to break down pectin-rich tissues. Water-retted fibers typically exhibit higher cellulose and hemicellulose content and lower lignin content compared to mechanically extracted fibers, resulting in greater flexibility and better tensile performance [14].

Enzymatic extraction applies controlled mixtures of pectinase, cellulase, and hemicellulase to selectively dissolve binding materials. This approach offers more precise control than traditional retting, enhancing fiber surface cleanliness while minimizing damage to cellulose structure. Enzyme-retted fibers show higher stiffness, improved uniformity, and better interfacial bonding in composite applications [9].

3.3 Chemical Extraction

Chemical extraction involves using alkaline, acidic, or oxidative solutions, most commonly sodium hydroxide (NaOH), to dissolve pectin, hemicellulose, waxes, and portions of lignin that bind fibers within plant tissues. This method effectively purifies cellulose but requires careful control to avoid excessive fiber degradation [10].

4. SURFACE TREATMENT OF NATURAL FIBERS

Natural fibers are inherently hydrophilic due to the presence of hydroxyl groups in cellulose and hemicellulose, while epoxy resins are hydrophobic. This fundamental incompatibility leads to poor interfacial adhesion, moisture absorption, and reduced mechanical performance. Surface treatment addresses these challenges by modifying fiber surface chemistry and morphology [3].

4.1 Alkali Treatment (Mercerization)

Alkali treatment, typically using sodium hydroxide (NaOH) solution, is the most common and cost-effective fiber treatment method. The treatment removes hemicellulose, lignin, wax, and oils from the fiber surface, increasing surface roughness and exposing reactive hydroxyl groups. This enhances mechanical interlocking and chemical bonding with the epoxy matrix [7-9]. Research on Walikukun fiber demonstrates that NaOH treatment combined with polyvinyl alcohol (PVA) coating significantly improved composite performance: tensile strength increased from 94.73 MPa to 124.37 MPa, bending strength from 131.73 MPa to 164.37 MPa, and water absorption decreased substantially [5].

4.2 Silane Treatment

Silane coupling agents act as molecular bridges between hydrophilic natural fibers and hydrophobic epoxy matrices. The γ-aminopropyltriethoxysilane (APTES) treatment introduces functional groups that chemically bond to both fiber surfaces and epoxy resin, enhancing interfacial adhesion [6]. Studies on waste mulberry silk fabric/epoxy composites showed that silane treatment produced nearly twofold improvements in tensile strength and modulus, approximately 20% higher flexural strength, 35-45% higher interlaminar shear strength (ILSS), and substantially enhanced impact resistance compared to untreated composites. Scanning electron microscopy (SEM) confirmed that silane modification introduced surface

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roughness and improved interfacial bonding, leading to reduced fiber pull-out and enhanced stress transfer [7-9]. Silane treatment also significantly improves fatigue resistance and drilling quality of composites. Treated ixtle fiber-PET core-biochar epoxy composites exhibited superior fatigue life and lower drilling-induced damage compared to untreated systems, with enhanced interfacial adhesion enabling efficient stress transfer and delaying crack initiation [11].

4.3 Plasma Treatment

Plasma treatment offers a dry, environmentally friendly surface modification method. Glow discharge air plasma treatment of banana and pineapple leaf fibers for varying time periods effectively modifies fiber surfaces, improving wettability and interfacial adhesion with epoxy matrices. The treatment introduces polar functional groups and increases surface roughness without using chemicals or generating waste [3].

4.4 Other Surface Treatments

Additional treatment methods include acetylation, benzoylation, permanganate treatment, and peroxide treatment. Each method aims to reduce fiber hydrophilicity, improve surface characteristics, and enhance interfacial bonding. Hybrid approaches combining multiple treatments (e.g., alkali followed by silane or plasma) often show synergistic effects [5].

5. COMPOSITE FABRICATION METHODS

5.1 Hand Lay-Up

Hand lay-up is the simplest and most widely used technique for natural fiber-epoxy composites, particularly for large or custom components. Layers of fiber reinforcement are manually placed in a mold and impregnated with epoxy resin, followed by roller compaction to remove entrapped air and ensure uniform wetting. While labor-intensive, this method offers flexibility and low capital investment [11].

5.2 Vacuum-Assisted Resin Transfer Molding (VARTM)

VARTM involves placing dry fiber preforms in a mold, sealing with a vacuum bag, and infusing liquid epoxy resin under vacuum pressure. This technique ensures uniform resin infusion, low void content, and controlled fiber alignment . VARTM produces higher quality composites with improved mechanical properties compared to hand lay-up [12].

Studies using VARTM for flax/epoxy composites achieved tensile strength of 68-72 MPa, flexural strength of 105-110 MPa, Young's modulus of 17-18.2 GPa, and impact strength of 4-4.1 kJ/m² . Analysis of variance identified fiber volume fraction and resin viscosity as the most critical factors influencing mechanical performance [13].

5.3 Compression Molding

Compression molding involves placing fiber-resin preforms between heated platens under pressure. This method produces consistent, high-quality composites with controlled fiber volume fraction and dimensional accuracy. It is particularly suitable for high-volume production of automotive and consumer components [4].

5.4 Vacuum Infusion

Vacuum infusion combines elements of hand lay-up and VARTM, using vacuum pressure to draw resin into dry fiber preforms. This method offers good fiber-to-resin ratio control and reduced void content while maintaining equipment simplicity [2].

6. MECHANICAL PROPERTIES

6.1 Tensile Properties

Tensile properties of natural fiber-epoxy composites depend on fiber type, content, orientation, surface treatment, and matrix properties. The fiber-matrix interface critically influences stress transfer efficiency; poor interfacial adhesion leads to fiber pull-out and premature failure, while strong interfacial bonding enables effective load transfer from matrix to fibers. Research on waste animal fiber composites demonstrates significant property improvements over pure epoxy resin. The addition of fibers substantially impacts mechanical properties, with chicken feather, duck feather, and human hair composites showing marked performance differences [9].

6.2 Flexural Properties

Flexural strength and modulus depend on the same factors as tensile properties, with fiber alignment and distribution playing particularly important roles. Well-aligned fibers oriented along the loading direction maximize flexural performance. NaOH and PVA treatments significantly improve flexural properties by enhancing interfacial bonding [10].

6.3 Impact Properties

Impact resistance is critical for automotive, aerospace, and consumer applications. Natural fiber composites generally show moderate impact strength compared to synthetic fiber composites, although specific fiber types and surface treatments can significantly enhance performance [11].

Studies on *Grewia optiva* natural fiber-reinforced epoxy composites demonstrate that fiber treatment, humidity conditions, and fiber content significantly influence fracture toughness and dynamic properties. The interlaminar and

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intralaminar fracture toughness of natural fiber composites shows sensitivity to temperature and hygrothermal conditions, similar to conventional composites [12].

6.4 Tribological Properties

The tribological performance of plant fiber-reinforced epoxy composites depends on fiber type, treatment, and testing conditions. Chemical treatments such as hydrogen peroxide or sodium carbonate modify fiber surface structure, improving the fiber-matrix interface and overall wear performance. A better fiber-matrix link promotes formation of a protective layer during sliding, enhancing tribological properties [13].

7. ENVIRONMENTAL DURABILITY

7.1 Moisture Absorption

Natural fibers' hydrophilicity leads to moisture absorption in humid environments, causing swelling, plasticization, and interfacial degradation. This negatively impacts mechanical properties and dimensional stability. Surface treatments that reduce hydrophilicity, such as silane and alkali treatments, significantly improve moisture resistance [8].

Water absorption varies significantly among fiber types. Chicken feather composites exhibit the highest water absorption due to hydrophilic amino acids in keratin, while human hair and duck feather composites absorb less water [7].

7.2 Thermal Stability

Natural fibers begin thermal degradation at temperatures around 200-250°C, limiting processing temperatures. Epoxy matrices typically cure at moderate temperatures, compatible with natural fiber thermal stability. Fiber treatment can improve thermal stability by removing hemicellulose and other heat-sensitive components [6].

7.3 Aging Effects

Prolonged service temperature exposure causes progressive degradation in natural fiber composites. Studies on silane-treated ixtle fiber composites show that even after 90 days of thermal exposure at 50°C, treated composites retain higher property values and exhibit lower drilling-induced damage than untreated systems . The decline in properties with aging is attributed to matrix softening, micro-crack formation, and gradual fiber-matrix debonding [5].

8. APPLICATIONS

8.1 Automotive Industry

Natural fiber-epoxy composites have found significant application in automotive interiors and exteriors, contributing to sustainability efforts while offering lightweight and durable alternatives. Applications include door panels, dashboard components, seat backs, and trunk liners. The lightweight nature of these composites improves fuel efficiency without compromising performance.

8.2 Aerospace Interiors

Aerospace applications are primarily in non-structural interior components where weight reduction is critical. Natural fiber composites offer fire resistance (when appropriately formulated), acoustic damping, and lightweight properties suitable for cabin interiors. However, strict certification requirements limit structural applications.

8.3 Construction and Furniture

Construction applications include non-load-bearing components, paneling, insulation, and decorative elements. The aesthetic appeal of natural fibers combined with epoxy's durability makes these composites attractive for furniture applications. Natural fiber composites also offer thermal and acoustic insulation properties valuable in building construction.

8.4 Consumer Goods and Sports Equipment

Consumer products benefit from the lightweight, sustainable image of natural fibers. Applications include sporting goods, luggage, electronics housings, and packaging. The combination of natural fiber aesthetics with epoxy durability appeals to environmentally conscious consumers.

9. CONCLUSIONS

Natural fiber-reinforced epoxy composites represent a promising class of sustainable materials that balance environmental responsibility with performance requirements. This review demonstrates that:

- **Fiber selection** and preparation critically influence composite properties, with fibers like flax, hemp, jute, and sisal offering favorable mechanical properties and sustainability credentials.
- **Surface treatment** is essential for achieving optimal performance. Alkali, silane, and plasma treatments effectively enhance fiber-matrix interfacial adhesion, with silane treatment showing particular effectiveness for moisture resistance and long-term durability.
- **Processing methods** including hand lay-up, VARTM, and compression molding enable diverse applications, with VARTM providing superior fiber alignment and void control.
- **Mechanical properties** show strong dependence on fiber type, content, orientation, treatment, and interface quality. Quantitative data demonstrate significant improvements through optimized treatment and processing.

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- **Applications** span automotive, aerospace, construction, furniture, and consumer goods, with increasing adoption driven by sustainability requirements and technological advances.
- **Emerging approaches** including machine learning optimization, hybrid systems, and novel fiber sources offer pathways for continued improvement and expanded applications.

Natural fiber-epoxy composites offer a viable sustainable solution for reducing environmental impact while maintaining material performance in diverse structural applications. Continued research on surface treatments, processing optimization, novel fibers, and predictive modeling will further enhance performance and expand applications.

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