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Review of Recent Advancements in Recyclable and Biodegradable Bamboo Fiber Reinforced Composites

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Abstract: The urgent demand for materials that marry high performance with environmental responsibility has catalyzed breakthroughs in natural fiber composites. Bamboo, with its rapid renewability, high strength-to-weight ratio, and biodegradability, has risen as a leading reinforcement for eco-friendly composites. This review synthesizes the latest innovations in recyclable and biodegradable bamboo fiber reinforced composites (BFRCs), emphasizing advances in bio-based polymer matrices (e.g., PLA, PHA, soy-epoxy) and targeted fiber surface modifications (alkali and silane treatments). We analyze how these strategies optimize interfacial bonding, mechanical performance, and end-of-life recyclability or biodegradation. Emerging approaches—such as hybrid fillers and compatibilizers—are also discussed for their role in tailoring density and stiffness while preserving sustainability. The comprehensive evaluation demonstrates BFRCs' strong potential in packaging, consumer products, and lightweight structural panels, offering a clear pathway toward circular-materials design.

Keywords- Bamboo fiber, biodegradable composites, recyclable materials, natural fiber reinforcement composites, sustainable materials.

I. INTRODUCTION

The environmental and health impacts of conventional synthetic composites have spurred intense research into sustainable alternatives. Natural fiber reinforced composites (NFRCs) leverage renewable plant fibers and degradable or recyclable matrices to reduce ecological footprints. Bamboo fibers, in particular, stand out due to their rapid growth cycle, high cellulose content, and mechanical properties comparable to some synthetic reinforcements. However, the hydrophilic nature of bamboo fibers poses a challenge for bonding with hydrophobic polymer matrices. To address this, chemical surface treatments—such as alkali washing to remove lignin and silane coupling to introduce reactive functional groups—have proven effective at enhancing interfacial adhesion, moisture resistance, and composite strength. Additionally, selecting bio-based or recyclable matrices (e.g., PLA, PHA, soy-epoxy, PP) is critical to aligning composite performance with circular-economy goals. This paper systematically reviews recent BFRC developments by examining: (1) eco-friendly matrix formulations, (2) fiber treatment protocols that maximize fiber–matrix compatibility, and (3) composite fabrication techniques that ensure reproducible quality. We place special emphasis on life-cycle considerations, illustrating how material choices and processing methods collectively influence mechanical performance and environmental outcomes. Through this analysis, we aim to guide researchers and practitioners toward designing bamboo composites that deliver both technical excellence and sustainability.

1.1 Bamboo Fiber Characteristics:

Bamboo fiber is a lignocellulosic material composed primarily of cellulose along with significant hemicellulose and lignin. Compared to other plant fibers (e.g. flax, sisal), bamboo typically has higher lignin and hemicellulose content. This gives untreated bamboo fiber a relatively rough surface and high aspect ratio, which can enhance mechanical interlocking with a polymer matrix. However, the lignin also makes the fiber more hydrophilic and susceptible to environmental degradation. Under moisture, heat, or UV exposure, bamboo fibers can degrade without treatment. To realize their full potential, bamboo fibers usually undergo surface treatments (below) to clean and functionalize them. Because bamboo fiber is low-density yet strong, it yields lightweight composites. Its tensile and compressive strengths are very high for a natural fiber. These advantages have driven widespread interest: today bamboo composites are explored for automotive panels, packaging, construction, and consumer goods. Using bamboo in composites can lower the material's carbon footprint and promote green manufacturing.

II. Literature Survey:

2.1 Surface Treatments for Bamboo Fibers:

Raw bamboo fibers bond poorly to most polymers due to their polar, rough surface and impurities (waxes, lignin). Treatments are therefore essential. Key methods include:

Alkali (Mercerization): Treating fibers in NaOH (5% solution for 30–60 min) removes surface lignin/hemicellulose and wax, increasing roughness and specific surface area. This has been shown to improve tensile strength by up to 45% and reduce water uptake by approximately 60% [1]. (However, excessive alkali can depolymerize the fiber.)
Silane Coupling: Silane agents (e.g. aminopropyltriethoxysilane) bond with the –OH groups on bamboo and with polymer chains, creating a chemical bridge. Silane treatment further increases flexural strength and reduces moisture absorption by introducing reactive organofunctional groups [2].
Compatibilizers and Coupling Additives: For thermoplastics like polypropylene, maleic-anhydride-grafted polymers (MAPP) are commonly added to the matrix. These react with bamboo's hydroxyls and with the polymer, greatly strengthening the interface. In PLA matrices, bio-based compatibilizers (e.g. polydopamine or epoxidized oils) yield similar benefits; for instance, co-treatment of bamboo with 1% dopamine and NaOH led to ~34% higher tensile strength in PLA composites [4].
Other Treatments: Acetylation and benzoylation replace hydroxyls on the fiber with less polar groups, improving compatibility. Permanganate or peroxide oxidation can also modify the surface. Emerging methods like plasma or enzyme treatments offer eco-friendly alternatives. In all cases, the goal is to reduce fiber polarity and increase wetting by the polymer, thereby improving mechanical performance.

2.2 Present Theory and Practices:

Biodegradable polymer matrices, such as polylactic acid (PLA), have gained prominence for their ecological benefits. Kumar et al. demonstrated that PLA-based bamboo composites exhibit significant mechanical and thermal enhancements following alkali and silane treatments, achieving tensile and flexural moduli comparable to petroleum‑derived composites [4]. In parallel, recyclable thermoplastic matrices—most notably polypropylene (PP)—offer a balance of performance and recyclability. Ibrahim et al. reviewed PP‑bamboo composites and reported that coupling agents and compatibilizers can effectively bridge the hydrophilic‑hydrophobic interface, yielding materials suitable for semi‑structural applications [5].Advanced reinforcement strategies now include micro‑ and nano‑scale fillers to further tailor composite properties. Recent work in Composites Part B introduced a micro‑nano reinforcing approach for bamboo/PP composites, achieving over 20% improvements in tensile and flexural performance by dispersing nanosilica alongside treated fibers [6]. Across applications—from automotive panels to consumer packaging—lifecycle assessments indicate that these bamboo composites can achieve 20–30% lower greenhouse‑gas footprints compared to glass‑fiber alternatives, underscoring their role in circular‑economy material design [3, 7].

III. *Materials and Methods:*

3.1 Recyclable and Biodegradable Matrix Materials:

Thermoplastics (e.g. PP, PE): Polypropylene and polyethylene are widely used, are recyclable by remelting, and have low processing cost. High bamboo loadings (30–50%) are common in wood–plastic composites; addition of MAPP significantly increases tensile and flexural strength [5]. Polylactic Acid (PLA): PLA is a biodegradable biopolymer derived from starch. Bamboo/PLA composites are fully compostable under industrial conditions. Bamboo fiber greatly increases PLA's stiffness and strength; combined NaOH and dopamine treatments have been shown to yield +34% tensile and +16% flexural strength [4].

Other Biopolymers (PCL, PHBV, Starch, etc.): Bamboo-PCL composites produced by solvent casting exhibit higher thermal stability and tensile strength with increasing bamboo content. In biodegradation tests, 40 wt% bamboo/PCL samples lost ~20% mass in acid and ~5% in soil over 4 weeks, demonstrating compostable potential. Thermosets (Epoxy, Polyester): Epoxy and unsaturated polyester resins yield strong, stiff composites but are not recyclable. Similar surface treatments are applied for adhesion, though end-of-life options remain limited compared to thermoplastics or biopolymers.

3.2 Composite Fabrication Methods:

Compression Molding / Hot Pressing: Layers of bamboo fabric or particles are laid in a mold with resin, then heat/pressure cures the part.

Extrusion: Mixed bamboo fiber and polymer granules are melted and extruded into profiles or pellets; pre-impregnation with compatibilizer enhances composite strength.

Injection Molding: Short bamboo fibers can be injection-molded into complex shapes; a micro-injection approach with graphene-oxide-modified bamboo/PP (with >50% bamboo) improved flexural strength by over 50%.

Hand Lay-Up / Vacuum Infusion: Used for thermosets, where fiber mats are laid and resin is applied under vacuum.

Solvent Casting: Bamboo is mixed into a polymer solution and cast into sheets, allowing fine control of dispersion and enabling degradation studies.

Advanced Techniques: Additive manufacturing with bamboo-filled filaments, pultrusion, and foam processing are emerging; a "micro-nano" strategy dispersing nanosilica alongside treated fibers in PP achieved >20% improvements in tensile and flexural performance [6].

3.3 Design Considerations:

Design for recyclability and durability includes single-polymer systems for homogeneous recycling and selecting matrices that enable mechanical reprocessing or composting. Hybrid and multi-layer assemblies, fastener-free joints, and reversible bonds enhance disassembly and material recovery. Automation (robotic lay-up, precision molding) improves consistency and reduces waste. Lifecycle assessments report bamboo composites can achieve 20–30% lower greenhouse-gas footprints versus glass-fiber alternatives [3, 7].

IV. Testing and Analysis Protocols:

Contemporary bamboo composites are evaluated using standard test methods, ensuring results are comparable with other materials:

Tensile Testing: Specimens (often dog-bone or rectangular) are tested for tensile strength and modulus. In practice, ASTM D3039 (for polymer-matrix composites) is frequently used. (One study noted ASTM D3039-08 was chosen due to the lack of a bamboo-specific standard.) For plastics-like matrices, ISO 527 or ASTM D638 may also be applied.

Flexural Testing: Three-point or four-point bending tests (ASTM D790 / ISO 178) measure flexural strength and modulus. Data from recent studies (Table 3 in Xu et al.) show bamboo/PP or bamboo/PLA flexural strengths ranging tens of MPa.

Impact Testing: Charpy or Izod tests (e.g. ISO 179, ASTM D256) assess toughness. Bamboo composites often show lower impact strength than neat polymer, but adding elastomers or nanofillers can improve this metric.

Thermal Analysis: Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) characterize melting behavior and thermal stability. Bamboo usually increases crystallinity and thermal resistance of a polymer.

Water Absorption: ASTM D570 or ISO 62 are used to measure moisture uptake, since bamboo's hydrophilicity can lead to swelling and property changes. Saturation can significantly reduce mechanical performance if fibers are not well protected.

Microscopy: Scanning electron microscopy (SEM) examines fracture surfaces to check fiber pullout or matrix-fiber adhesion. SEM images in many papers confirm that treated bamboo fibers have fewer voids and better bonding.

Biodegradation/Aging Tests: For biodegradable composites, accelerated soil burial or compost tests are performed. For example, a 40% bamboo/PCL composite showed >20% mass loss in an acidic soil test over 4 weeks. Longer-term weathering (UV/temperature cycling) is also used to simulate service life.

In summary, testing protocols for bamboo composites generally follow established ASTM or ISO standards used in polymer composite engineering. Ensuring standardized testing is critical for comparing new materials with benchmarks.

V. Conclusion:

Overall, recent advances confirm that bamboo fiber composites can meet rigorous mechanical and environmental criteria when properly engineered. State-of-the-art research aligns with standard composite methodologies: surface treatments (alkali, silane, compatibilizers) are used to maximize bonding; fabrication methods (molding, extrusion, injection) are optimized for fiber dispersion; and testing follows ASTM/ISO protocols. By choosing biodegradable matrices like PLA or PCL, fully compostable bamboo composites have been achieved. Alternatively, using recyclable thermoplastics allows mechanical recycling of bamboo composites. The balance of design, materials, and processing ensures that major claims about durability, strength, and sustainability in the literature are supported by empirical results. All key components – from fiber chemistry to testing – now align with contemporary research standards. As a result, bamboo fiber composites are well-positioned to be a technically sound and green alternative to conventional composites, fulfilling both performance and environmental goals.

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