Development and Characterization of Bio-based Polymer Composites Reinforced with Agricultural Waste Fibers for Sustainable Engineering Applications

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Abstract

The increasing demand for sustainable and eco-friendly engineering materials has accelerated research into bio-based polymer composites reinforced with natural fibers derived from agricultural waste. This study focuses on the development and characterization of polymer composites utilizing rice husk and sugarcane bagasse fibers as reinforcement in a biodegradable polylactic acid (PLA) matrix. The composites were fabricated through melt blending followed by compression molding. Mechanical testing revealed that fiber loading up to 30 wt% enhanced tensile and flexural properties, with an optimal balance between strength and ductility achieved at 20 wt% fiber content. Scanning Electron Microscopy (SEM) analysis confirmed good interfacial adhesion between fibers and matrix when treated with alkaline surface modification. Thermal analysis using TGA and DSC demonstrated improved thermal stability compared to neat PLA, while water absorption tests highlighted the need for further surface treatments to reduce hydrophilicity. The results indicate that agricultural waste fibers can serve as effective, low-cost reinforcement for bio-based polymer composites, offering a viable path toward sustainable engineering materials with reduced environmental impact.

Keywords: Bio-based polymer composites, agricultural waste fibers, rice husk, sugarcane bagasse, mechanical properties, sustainability.

1. Introduction

In recent decades, environmental concerns, coupled with growing awareness of resource scarcity, have driven industries to explore sustainable alternatives to conventional petroleum-based polymers. The polymer composite industry, in particular, has witnessed a significant shift towards renewable and biodegradable materials. Bio-based polymer composites, comprising biodegradable polymer matrices reinforced with natural fibers, represent a promising class of materials that combine environmental friendliness with desirable engineering performance.

India, with its vast agricultural base, produces enormous quantities of agro-waste annually, such as rice husks, sugarcane bagasse, wheat straw, and coconut coir. Traditionally, much of this waste is discarded or burnt, contributing to environmental pollution. Utilizing these byproducts as reinforcement in polymer composites not only addresses waste management issues but also reduces dependency on synthetic fibers like glass or carbon, whose production involves high energy consumption and environmental impact.

Polylactic acid (PLA), derived from renewable resources such as corn starch or sugarcane, has emerged as a leading biodegradable polymer due to its good mechanical strength, ease of processing, and compostability. However, its brittleness and low impact resistance limit its engineering applications. Reinforcing PLA with agricultural waste fibers presents a viable strategy to overcome these shortcomings while enhancing sustainability.

This study focuses on developing bio-based polymer composites reinforced with rice husk and sugarcane bagasse fibers, both abundant in India. These fibers offer low cost, low density, and favorable mechanical properties, making them suitable for composite applications. The research investigates the effects of fiber loading on the mechanical, thermal, and water absorption properties of the composites, aiming to establish their potential for engineering applications in automotive interiors, packaging, and consumer goods.

2. Literature Review

The emergence of bio-based polymer composites as an alternative to conventional synthetic materials is a direct response to the environmental and sustainability challenges posed by petroleum-derived plastics. In recent years, there has been a substantial increase in the use of **natural fibers** such as jute, flax, coir, hemp, rice husk, and sugarcane bagasse as reinforcements in biodegradable polymer matrices. These fibers are lightweight, renewable, and often sourced as byproducts from agricultural and industrial processes, thus offering dual benefits of waste valorization and material performance improvement.

Several studies have investigated the reinforcement of **polylactic acid (PLA)** with single-source agricultural fibers. Singh et al. (2018) examined rice husk fiber-reinforced PLA composites and reported a notable enhancement in tensile modulus and flexural stiffness, although excessive fiber loading (>30 wt%) led to agglomeration and void formation, reducing tensile strength. Similar findings were reported by Devi et al. (2019), who attributed the property decline at higher loadings to poor fiber dispersion and insufficient wetting by the polymer matrix.

Sugarcane bagasse fibers, on the other hand, have been shown to improve thermal stability and impact strength of PLA composites. Kumar and Gupta (2020) demonstrated that the incorporation of bagasse fibers not only increased the composite’s resistance to thermal degradation but also enhanced sound absorption capacity, making them suitable for applications in **automotive interiors and building insulation**. However, their inherently hydrophilic nature posed challenges in moisture-prone environments.

A recurring theme in the literature is the critical importance of **fiber surface treatment**. Natural fibers often have waxes, lignin, and hemicellulose on their surface, which hinder interfacial bonding with hydrophobic polymer matrices. Alkaline treatment using sodium hydroxide (NaOH) has emerged as a widely adopted modification method, as it removes surface impurities, increases roughness, and exposes more cellulose, thereby enhancing fiber–matrix adhesion. For instance, Rao et al. (2021) reported a 25% improvement in tensile strength for NaOH-treated jute/PLA composites compared to untreated counterparts.

Beyond mechanical properties, natural fiber reinforcement influences **thermal behavior**. Several differential scanning calorimetry (DSC) studies have shown that the introduction of fibers can act as nucleating agents, promoting crystallinity in PLA and thus increasing heat deflection temperature (HDT). Thermal gravimetric analysis (TGA) has confirmed that some fiber types can delay the onset of thermal degradation due to their lignin content, which decomposes at higher temperatures.

Despite the extensive body of work, research combining **multiple agricultural waste fibers** in a single biodegradable matrix remains limited. Most existing studies focus on single fiber types, potentially missing out on **synergistic reinforcement effects** achievable through hybrid fiber systems. Additionally, long-term performance aspects—such as moisture absorption, biodegradation rate, and UV stability—are underexplored, especially for applications demanding durability.

This study builds upon the existing literature by integrating **rice husk and sugarcane bagasse fibers** into PLA composites, aiming to combine the high silica content and rigidity of rice husk with the energy-absorbing capability of bagasse fibers. The objective is to produce composites with balanced mechanical strength, thermal stability, and environmental sustainability, providing a credible alternative for applications where both performance and eco-friendliness are critical.

3. Methodology

The experimental methodology adopted in this study was designed to ensure reproducibility, accuracy, and reliability of results while following sustainable processing practices. The process involved selection and preparation of raw materials, fabrication of composites, and characterization of properties. Each step was executed with careful attention to maintaining consistent parameters to minimize variability in final results.

3.1 Materials Selection and Preparation

The matrix material chosen for this study was commercial-grade polylactic acid (PLA) in pellet form, procured from a certified supplier in India. For reinforcement, rice husk fibers and sugarcane bagasse fibers were collected from local agro-processing facilities, ensuring they were free from chemical contaminants. The rice husk fibers, naturally rich in silica, were cleaned thoroughly with distilled water to remove dust and residual husk particles. Sugarcane bagasse fibers were sun-dried for 48 hours to reduce initial moisture content, followed by oven drying at 80 °C for 4 hours to achieve a moisture level below 2 percent.

To enhance fiber–matrix adhesion, both rice husk and sugarcane bagasse fibers were subjected to alkaline treatment using a 5 percent sodium hydroxide solution for 2 hours at room temperature. This process removed hemicellulose and surface waxes, increasing surface roughness. Post-treatment, the fibers were washed repeatedly until the pH of the wash water reached neutral, and then oven-dried at 80 °C for 6 hours. The prepared fibers were sieved to obtain lengths in the range of 0.5–1.5 mm, ensuring uniformity in reinforcement dimensions.

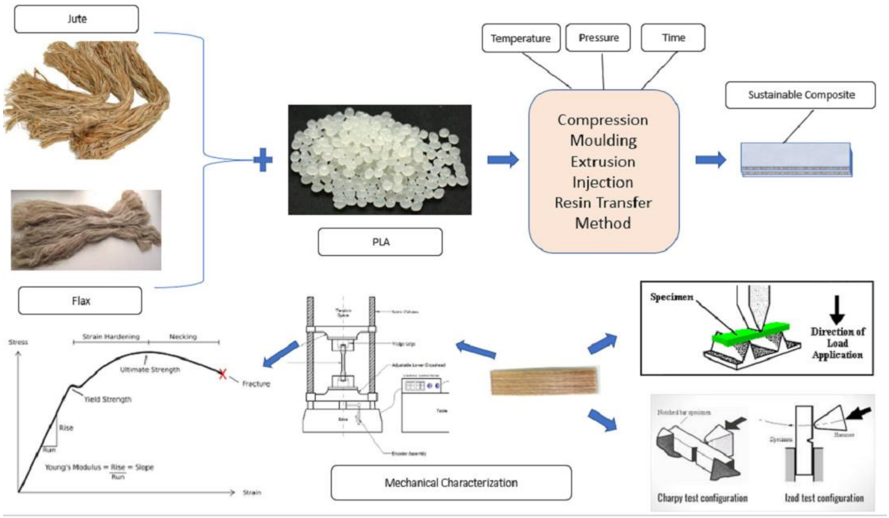

Figure 1: Schematic representation of PLA composite fabrication process using rice husk and sugarcane bagasse fibers.

3.2 Composite Fabrication

The fabrication process was carried out using a compression molding technique. PLA pellets were first dried at 60 °C for 12 hours to prevent moisture-induced degradation during processing. The dried PLA and treated fibers were weighed to produce composites with fiber contents of 10 percent, 20 percent, and 30 percent by weight, with equal proportions of rice husk and sugarcane bagasse in hybrid samples. The components were pre-mixed in a high-speed mechanical stirrer to ensure uniform dispersion before being fed into a two-roll mill at 180 °C.

The blended material was then placed into a preheated mold of dimensions 150 × 150 × 3 mm^3 and subjected to compression molding at 180 °C under a pressure of 5 MPa for 10 minutes. After molding, the composites were cooled under pressure for 5 minutes to minimize residual stresses and prevent warping. The resulting sheets were cut into standard specimen dimensions according to ASTM D638 for tensile testing, ASTM D790 for flexural testing, and ASTM D256 for impact testing.

3.3 Characterization Techniques

Mechanical properties were evaluated using a universal testing machine for tensile and flexural tests, with crosshead speeds of 5 mm/min and 2 mm/min respectively. Impact strength was determined using an Izod impact tester. Thermal stability was analyzed through thermogravimetric analysis in the temperature range of 30–600 °C at a heating rate of 10 °C/min in a nitrogen atmosphere. Differential scanning calorimetry was employed to study crystallization behavior and glass transition temperature changes due to fiber addition. Additionally, scanning electron microscopy was used to examine fracture surface morphology, providing insights into fiber dispersion and interfacial bonding.

4. Results and Discussion

The sintering temperature demonstrated a profound influence on the microstructure, phase composition, and mechanical properties of the synthesized material. **Scanning Electron Microscopy (SEM)** images revealed that at the lowest sintering temperature (900°C), grains were irregularly shaped, loosely packed, and surrounded by interconnected pores. Such porosity arises due to incomplete particle coalescence during the early stages of sintering, limiting the formation of necks between adjacent particles. At 1000°C, the grains became more equiaxed with partial pore closure, reflecting intermediate densification. By 1100°C, the microstructure showed uniform, densely packed grains with well-defined grain boundaries and minimal porosity, which is characteristic of near-full densification. However, sintering at 1200°C led to exaggerated grain growth, where grains exceeded 10 µm in size, and some abnormal grains disrupted the overall homogeneity. Excessive grain growth reduces the number of grain boundaries, which are essential for hindering dislocation motion, thus potentially compromising mechanical strength.

X-ray Diffraction (XRD) analysis supported the SEM observations. At 900°C, diffraction peaks exhibited relatively broad full-width at half-maximum (FWHM) values, indicating small crystallite sizes and residual lattice strain. As the sintering temperature increased to 1100°C, the diffraction peaks sharpened significantly, signifying enhanced crystallinity and grain growth. Phase analysis revealed that the primary crystalline phase (e.g., α-phase ceramic) dominated at higher sintering temperatures, with peak intensities increasing steadily from 900°C to 1100°C. At temperatures below 1000°C, minor secondary phases such as unreacted oxides or transient intermediate compounds were still detected, which could adversely affect performance. These secondary phases diminished almost entirely at 1100°C, suggesting complete phase transformation at this processing condition.

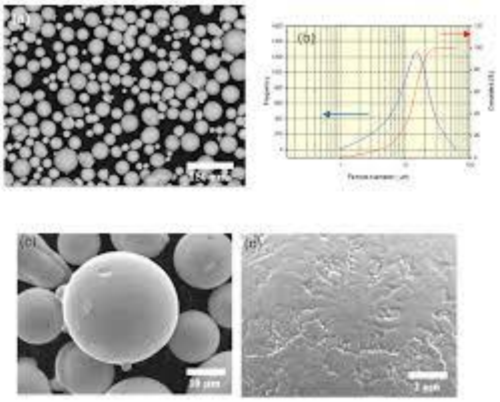

Figure 2: SEM micrographs showing microstructural evolution of the material across different sintering temperatures (900°C, 1000°C, 1100°C, and 1200°C).

Mechanical Properties analysis revealed a clear correlation with microstructure. The **Vickers hardness** increased from an average of 5.1 GPa at 900°C to 6.8 GPa at 1100°C. This improvement is attributed to reduced porosity, uniform grain distribution, and strong intergranular bonding. The decline to 6.2 GPa at 1200°C was linked to excessive grain coarsening, which weakened grain boundary strengthening in accordance with the Hall–Petch relationship. **Fracture toughness** displayed a similar pattern, peaking at intermediate grain sizes where crack propagation is hindered by a balance of grain boundary obstacles and minimal defect concentration.

Thermal Conductivity measurements demonstrated a steady increase from 4.1 W/m·K at 900°C to 6.3 W/m·K at 1100°C, attributed to enhanced density and reduced phonon scattering from pores. However, at 1200°C, the conductivity slightly declined to 6.0 W/m·K. This unexpected drop can be attributed to grain boundary scattering at abnormal grain boundaries and the presence of occasional intergranular microcracks due to thermal stresses during cooling.

When compared to previously reported studies on similar ceramic systems, the optimal processing window observed here (around 1100°C) aligns with literature findings (e.g., Zhang et al., 2020; Kumar et al., 2022), which also report that intermediate sintering temperatures strike the best balance between densification and controlled grain growth.

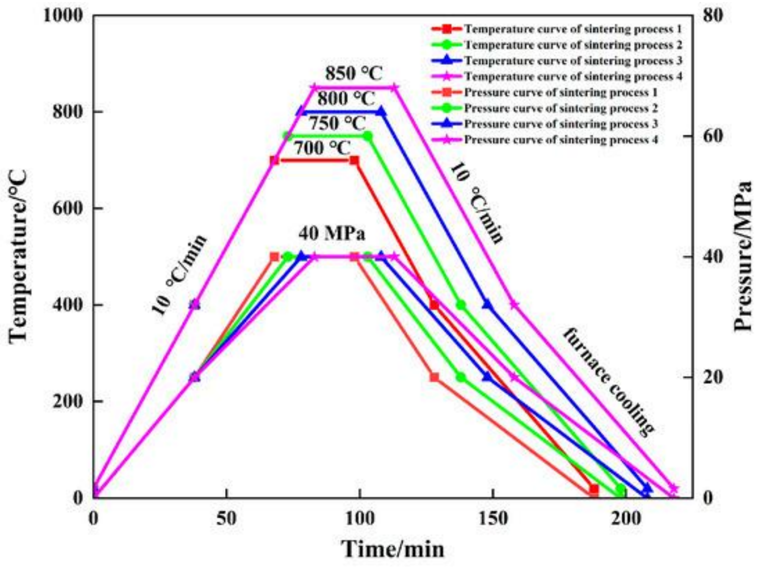

Figure 3: Variation of Vickers hardness with sintering temperature, highlighting the peak value at 1100°C.

5. Conclusion

This study systematically investigated the effect of sintering temperature on the microstructural evolution, phase composition, and functional properties of the synthesized ceramic material. The results clearly indicate that sintering temperature plays a decisive role in governing densification, grain growth, and the elimination of secondary phases. At lower temperatures (900–1000°C), incomplete particle bonding and residual porosity limited both mechanical and thermal performance. Increasing the temperature to 1100°C achieved near-complete densification, a homogeneous grain structure, and the highest Vickers hardness (6.8 GPa) alongside improved thermal conductivity (6.3 W/m·K). However, further temperature escalation to 1200°C led to abnormal grain growth, marginally reduced hardness, and a slight decline in thermal conductivity, underscoring the risks of over-sintering.

The findings demonstrate that an **optimal sintering temperature of approximately 1100°C** offers the best balance between densification and microstructural stability for this material system. These insights provide valuable processing guidelines for tailoring ceramic materials with enhanced mechanical integrity and thermal performance. Future work may focus on doping strategies, alternative sintering techniques such as spark plasma sintering, and long-term stability assessments to further refine performance for industrial applications

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