Recycling Bamboo Waste via Additive Manufacturing

A study on the viability and characteristics of 3d printable bamboo plastic composites

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This study explores the feasibility of producing 3D-printed bamboo-plastic composites by incorporating bamboo waste with PLA plastic, aiming to address the underutilization of bamboo residues and promote sustainable material innovation. Through systematic testing of the printability of bamboo-plastic composites with varying proportions, key parameters such as flowability, setting time, workability, and extrudability were assessed, leading to preliminary insights into an optimal formulation suitable for 3D printing. Concurrently, the prepared bamboo waste 3D printing slurry was integrated with a robotic platform and a self-developed extrusion 3D printing toolhead to conduct 3D printing experiments for the designed samples. These experiments validated the stability and operability of bamboo-plastic composites in practical applications. This research not only broadens the utilization scenarios of bamboo waste but also introduces an innovative approach to converting biomass residues into high-value-added products. By combining bamboo waste with advanced 3D printing technology, the study provides a novel pathway for enhancing resource utilization, addressing environmental concerns, and promoting sustainable development in the bamboo industry, offering new opportunities for both industrial application and economic growth.

Keywords: *Bamboo Waste, PLA Plastic, 3D Printing, Bamboo-plastic Composites, Printability, Resource Utilization, Sustainable Development*

INTRODUCTION

Bamboo is renowned for its rapid growth, renewability, and exceptional mechanical properties, making it a versatile material widely used in industries such as construction, furniture, and textiles. However, the processing of bamboo generates substantial waste—like shavings and chips—that is often discarded due to inadequate utilization technologies. This not only leads to resource wastage but also contributes to environmental degradation (Li et al., 2023).

The advent of 3D printing technology offers innovative opportunities to transform biomass waste into high-value-added materials. By integrating biomass residues with polymers, 3D-printed composites can provide sustainable alternatives for industrial applications, enhancing resource efficiency and reducing environmental impacts (Ghazanfari et al., 2022). Polylactic acid (PLA), a biodegradable and renewable polymer, is extensively used in 3D printing due to its ease of processing. Studies have shown that combining PLA with biomass residues like bamboo can yield composites with improved printability and mechanical properties (Singh et al., 2023).

In this study, we utilized our self-developed filament extruder to mix ground bamboo powder with PLA, producing bamboo-plastic filaments. Using 3D printing robot technology, we printed grid structures and conducted performance tests on them. By testing various material formulations, we evaluated critical parameters such as flowability, workability, and extrudability to identify an optimal composition. Practical 3D printing experiments were conducted using a robotic platform equipped with a self-developed extrusion toolhead, validating the material's printability and application potential.

The findings of this study not only provide a sustainable pathway for bamboo waste utilization but also introduce an innovative approach to advancing 3D printing technologies, contributing to the sustainable development of the bamboo industry.

MATERIALS AND METHODS

Before detailing the specific materials and fabrication processes, this section outlines the overall approach taken to prepare bamboo-based composite materials suitable for 3D printing. Emphasis was placed on ensuring material compatibility, printability, and consistency throughout the development workflow.

Bamboo Waste and PLA Plastic

The bamboo waste used in this study was sourced from a processing workshop at the Bartlett School of Architecture, where residues such as bamboo chips and shavings are commonly generated. After collecting, the bamboo residues were dried at 105°C for 24 hours to remove moisture content. This drying step is critical for preventing potential degradation during composite material fabrication (Almeida et al., 2023).

Following the drying process, the bamboo residues were first manually crushed using a crusher to break down larger pieces, making them suitable for further processing, as shown in Figure 1. The crushed bamboo was then ground into fine powder using a mechanical grinder. The resulting powder underwent multiple rounds of filtration and sieving to achieve a particle size range of 50 to 200 micrometers. This particle size range was specifically selected to enhance the homogeneity of the composite material and to ensure smooth extrusion during the 3D printing process (Wong et al., 2024).

Figure 1
Initial Disassembly of Waste Bamboo Materials

By carefully preparing the bamboo powder, this study ensured optimal compatibility with PLA and consistent performance in 3D printing applications. The meticulous preparation process lays a strong foundation for the development of high-quality bamboo-PLA composites.

Polylactic acid (PLA), a biodegradable thermoplastic derived from renewable resources, was chosen as the polymer matrix for its favorable properties in 3D printing applications. The PLA used in this study had a melting point of approximately 180–200°C and a density of 1.25 g/cm^3, aligning with standard specifications for 3D printing filaments (Almeida et al., 2023). Prior to composite preparation, PLA pellets were dried at 50°C for 12 hours to remove residual moisture, thereby preventing hydrolytic degradation during processing.

Composite Formulation Methods and Printing Experiment

To prepare the bamboo-PLA composites, varying weight ratios of bamboo powder to PLA (10:90, 20:80, 30:70) were formulated. The materials were first manually mixed to ensure preliminary homogenization. Subsequently, the mixtures were compounded using a twin-screw extruder operating at a temperature profile of 180–190°C and a screw speed of 50 rpm. This process facilitated thorough blending and dispersion of bamboo particles within the PLA matrix, which is essential for achieving consistent material properties (Wong et al., 2024). The extrudates were then pelletized and stored in sealed containers to prevent moisture absorption.

Figure 2
Self-Made 3D Printing Filament Extruder

The 3D printing experiments were conducted using a custom-built extrusion platform, as shown in Figure 2. This platform was equipped with a specialized screw extruder and a brass temperature-controlled nozzle head designed to handle composite materials. The nozzle diameter was set to 3 mm, accommodating the particle size and viscosity of the bamboo-PLA composites to ensure smooth extrusion and minimize clogging issues.

Figure 3
Filament Samples Printed with Three Bamboo-PLA Ratios (From Left to Right: 10:90, 20:80, 30:70)

The printing parameters were carefully adjusted for each experiment, with nozzle temperatures ranging from 190°C to 200°C and print speeds set between 30 mm/s and 50 mm/s. These parameters were optimized based on the flowability and stability of the composite material.

For each composite ratio, 3D printing trials were conducted to produce filament samples, as illustrated in Figure 3. The printed samples were evaluated for dimensional accuracy, surface quality, and structural stability to assess the printability of the composite materials. These experiments provided critical insights into the relationship between material formulation and printing performance.

Optimization of Composite Ratio and Printing Parameters

To evaluate the printability and structural performance of bamboo-PLA composites, experiments were conducted on three key ratios: 10:90, 20:80, and 30:70 (bamboo to PLA). The results are summarized in Table 1. While the 10:90 ratio (Experiment A1) exhibited the best overall printability with a high degree of extrudability (rating 5) and minimal extrusion difficulty (rating 1), its low bamboo content limited its contribution to bamboo waste utilization. This result indicates that, within the context of this study, higher printability was associated with lower bamboo content and thus diminished sustainability performance.

The composite with a 20:80 ratio (Experiment A2) demonstrated a strong balance between printability and increased bamboo content. Although its extrudability slightly decreased to a rating of 4, and extrusion difficulty increased to a rating of 2, these changes remained within acceptable limits for efficient printing. The setting time of 30 seconds provided sufficient layer stabilization, and no structural collapse was observed during the experiments. Surface quality was rated at 4, indicating satisfactory smoothness and consistency of printed layers. Importantly, this ratio incorporates 20% bamboo, making it a more sustainable and resource-efficient choice.

Experiment Group	PLA Ratio (%)	Bamboo Powder Ratio (%)	Flowability (Manual Extrusion Difficulty 1-5)	Degree of Extrudability (Rating 1-5)	Surface Quality (Rating 1-5)	Remarks
A1	90	10	1	5	5	Highly printable, smooth layers
A2	80	20	2	4	4	Moderate printability, slight flow issues
A3	70	30	3	3	3	Poor layer adhesion, reduced stability

Table 1
Experiment Results for Selected Composite Ratios

In contrast, the 30:70 ratio (Experiment A3) exhibited significant challenges in printability. The extrudability was rated at 3, and the flowability showed increased difficulty (rating 3). Poor layer adhesion and reduced structural stability were observed, with some samples collapsing during testing. The setting time of 45 seconds and a surface quality rating of 3 further highlighted its limitations for reliable and efficient 3D printing.

From the experiments, the 30:70 bamboo-PLA formulation demonstrates poor print fidelity and significant deformation, consistent with its low extrudability and high failure rate. In contrast, the 20:80 ratio produced more stable and defined forms, with acceptable surface quality and no collapse, reinforcing its position as the optimal balance between sustainability and printability. The 10:90 formulation exhibited the most precise geometric output and minimal print defects, attributed to the higher PLA content (Figure 4).

Given the goal of maximizing bamboo utilization while maintaining acceptable printability, the 20:80 ratio was identified as the most suitable composite formulation for achieving a balance between sustainability and performance.

Figure 4
Printing Performance of the 30:70, 20:80, and 10:90 Bamboo-PLA Formulations (From left to right)

The optimized composite (20:80) was further tested under varying printing conditions to determine the best parameters. Nozzle temperatures of 190°C, 195°C, and 200°C were compared alongside print speeds of 30 mm/s, 40 mm/s, and 50 mm/s. The results indicated that a nozzle temperature of 195°C provided the best extrusion consistency and layer adhesion. Meanwhile, a print speed of 40 mm/s achieved optimal dimensional accuracy and surface smoothness. This parameter combination minimized defects such as uneven extrusion and layer misalignment, ensuring stable and high-quality prints.

By adopting the 20:80 bamboo-PLA composite ratio and printing at a nozzle temperature of 195°C and a speed of 40 mm/s, this study aligns with the objective of utilizing more bamboo waste while maintaining effective 3D printing performance.

3D PRINTING EXPERIMENTS AND PERFORMANCE VALIDATION

Before diving into the specifics of prototype design, it is essential to contextualize how the optimized bamboo-PLA composite informs structural applications. With the 20:80 formulation demonstrating both strong printability and sustainability, this section explores its real-world potential through experimental printing and mechanical validation.

Prototype Design and Printing Setup

The prototype for this experiment was a triangular bamboo-PLA grid structure designed to showcase the material's performance potential. The design process was conducted using Grasshopper, where a 3D printing path for the bamboo-PLA grid was generated. To simulate and analyze the grid's mechanical behavior under different load conditions, the K2Engineering plugin was utilized, as shown in Figure 5. The simulation predicted the deformation of the grid when subjected to varying uniform loads, helping refine the grid's structural layout.

Following a series of iterative parametric simulations, a large-scale triangular grid structure was finalized, yielding a total cumulative printing path length of 10,820 mm. The design was strategically developed to optimize material efficiency while ensuring the mechanical robustness required for structural applications. Triangular geometries were selected due to their well-established performance in load distribution and deformation resistance. Through finite element analysis using the K2Engineering plugin, the structural behavior of the grid under uniform loading conditions was thoroughly evaluated. The simulation results indicated that the structure could sustain a maximum uniformly distributed load of 120 kg without exceeding predefined deformation thresholds. This suggests that the bamboo-PLA composite, in combination with the proposed geometric configuration, offers considerable promise as a lightweight yet mechanically resilient construction material, suitable for applications requiring both material efficiency and structural integrity.

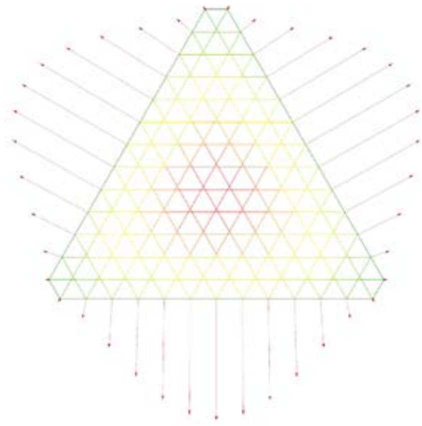

Figure 5
Performance Simulation of 3D Printing Paths Using K2Engineer

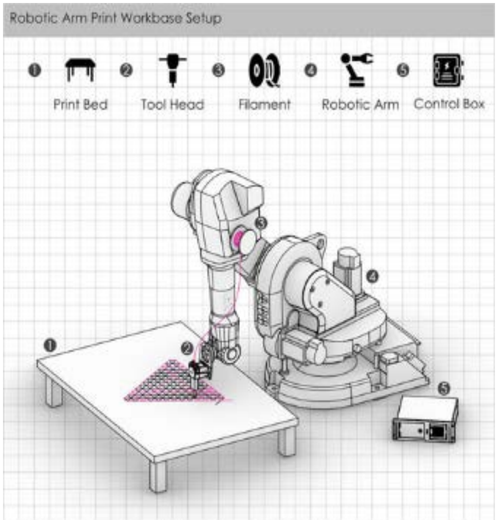

Figure 6
Experimental Equipment and Platform Setup

To validate the digital simulations through physical prototyping, 3D printing experiments were carried out utilizing an ABB IRB1400 industrial robotic arm. This robotic platform provided six-axis movement with high precision and repeatability, which was critical for accurately executing the complex print paths derived from the digital model. A custom-developed, temperature-controlled extrusion toolhead was mounted on the robotic arm, specifically engineered to accommodate the rheological behavior of the 20:80 bamboo-PLA composite. The toolhead incorporated a 3.0 mm brass nozzle (Figure 6), selected based on extensive preliminary tests to ensure optimal compatibility with the composite's particle size and flow characteristics.

The experimental setup was calibrated to match the thermal and flow properties of the composite material, with nozzle temperatures maintained between 190°C and 200°C to ensure consistent melt viscosity and extrusion behavior. Print speed and pressure parameters were also optimized to achieve uniform layer deposition and minimize defects such as under-extrusion or warping. The integration of robotic control with material-specific toolhead design facilitated the precise deposition of filament along the designated path, enabling the successful fabrication of the large-scale triangular grid with minimal process interruptions or geometric inaccuracies. This outcome underscores the viability of using robotic additive manufacturing in conjunction with bamboo-PLA composites for producing high-performance structural prototypes in a sustainable manner.

Printing Procedure and Performance Validation

The triangular grid was successfully printed over a total duration of 42 minutes. During the process, the 20:80 bamboo-PLA composite filament exhibited stable extrusion without any issues such as material breakage or nozzle clogging, as shown in Figure 7.

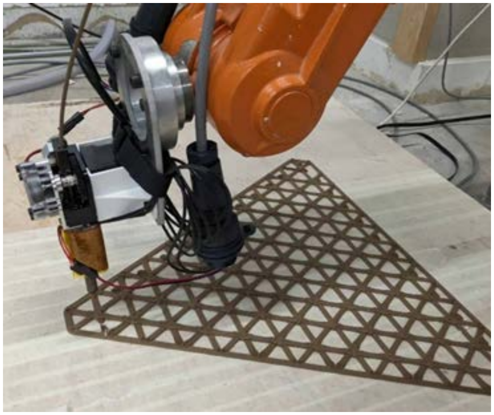

Figure 7
Photos of the Printing Process Using 20:80 Composite

Figure 8
Physical Performance Validation Experiments of 3D-Printed Grids

The printed structure retained its intended dimensions and geometric precision, demonstrating the high printability and process compatibility of the 20:80 bamboo-PLA composite. The success of this experiment validated the ability of the composite to support large-scale and complex 3D printing projects.

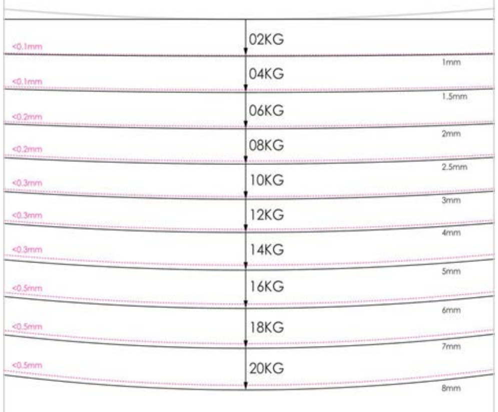

Figure 9
Comparison of Experimental Results and Software Simulations (Black: Experimental Results, Red: Simulation Results)

The printed triangular grid was subjected to a load-bearing test to verify its mechanical performance and alignment with the software simulation. The grid was placed on a triangular frame, ensuring a stable and controlled testing environment. A plumb line was attached to the grid to monitor its deformation during loading. A container was gradually filled with sand and placed uniformly on the grid to simulate a distributed load, as shown in Figure 8.

Figure 10
Load-Bearing Test of Composite Chair with Human Occupancy

Material As the load increased, the deformation of the grid was observed and measured by tracking the displacement of the plumb line. The experimental results closely matched the deformation predictions from the K2Engineering simulation, as shown in Figure 9.

The performance validation demonstrated the excellent physical properties of the 20:80 bamboo-PLA composite, including its ability to withstand substantial loads while maintaining structural integrity. This experiment highlighted the composite's potential for applications in lightweight yet durable architectural structures and other engineering fields.

In addition to this testing validation, the same composite formulation was previously applied in a research project, where it served as a 3D-printed reinforcement mesh in modular construction panels. Full-scale testing in that context confirmed the composite’s capacity to support static human loads, as shown in Figure 10. This project further demonstrated its mechanical feasibility and material strength in construction applications (Liu et al., 2025).

CONCLUSION AND PROSPECT

This study investigates the potential of 3D-printable bamboo-plastic composites (BPCs) by combining bamboo waste with polylactic acid (PLA) in varying ratios. The goal is to explore sustainable material alternatives that also meet the technical requirements of additive manufacturing. Among the tested mixtures, a 20:80 bamboo-to-PLA ratio emerged as the most effective, striking a favorable balance between ecological benefit and ease of fabrication. The composite exhibited smooth extrusion behavior and consistent layer adhesion, making it suitable for precise robotic 3D printing applications.

To validate the composite's structural performance, a large-scale triangular grid prototype was fabricated using a custom-designed extrusion tool mounted on a robotic arm. The prototype maintained structural integrity throughout the printing process, and mechanical load testing confirmed its ability to bear uniform stress. Deformation patterns observed during testing closely matched those predicted by digital simulations, reinforcing confidence in the material's reliability for lightweight structural applications. And the further validation tests from the seat load test showed that the bamboo-PLA composite successfully supported the static weight of the human body, proving its utility in real-world conditions. While these trials focused on non-structural uses such as furniture and reinforcement grids, future work could extend to interior flooring, acoustic panels, or partitions—elements requiring moderate strength, dimensional stability, and surface quality, all demonstrated here. The material's tactile and aesthetic qualities likewise suggest applications in industrial design and consumer products.

Beyond demonstrating material feasibility, this research also highlights a broader opportunity: the transformation of agricultural or industrial bamboo waste into high-value materials through digital fabrication. This not only helps mitigate environmental waste but also opens up new avenues for integrating circular economy principles into material development.

Looking ahead, future research could explore a broader range of biopolymer blends to fine-tune mechanical properties or biodegradability, and address challenges in upscaling for industrial use. Additionally, comprehensive lifecycle assessments will be important to evaluate the environmental footprint across sourcing, production, use, and disposal stages (Bierach et al., 2023). Finally, incorporating BPCs into modular, adaptive construction systems could further expand their potential in sustainable design practices, offering new tools for innovation in architecture, engineering, and manufacturing (Estakhrianhaghighi et al., 2023).

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