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## ORIGINAL RESEARCH ARTICLE

# Sustainable Synthesis and Characterization of Wood-Fiber Reinforced PLA for Additive Manufacturing Applications

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## ABSTRACT

The rising demand for environmentally responsible manufacturing has intensified interest in biodegradable polymers for additive manufacturing (AM). Polylactic Acid (PLA), a bio-based thermoplastic, is widely utilized due to its renewability and ease of processing. However, its inherent brittleness, low thermal resistance, and limited mechanical strength restrict its suitability for structural or load-bearing applications. This study addresses these limitations by developing and characterizing wood fiber (WF)-reinforced PLA composites aimed at improving mechanical performance and sustainability in AM, particularly Fused Deposition Modeling (FDM). Although natural fiber-reinforced biopolymers have shown promise, prior research often neglects eco-friendly processing, cost-effective preparation, and systematic optimization of fiber content and printing conditions. To overcome these gaps, sustainable composite filaments were produced using solvent-free melt compounding and extrusion techniques. Standardized specimens were fabricated via FDM and subjected to tensile, flexural, and compressive testing to assess mechanical properties. A multi-criteria decision-making (MCDM) approach was further employed to optimize printing parameters, balancing strength, energy efficiency, and material utilization. Results demonstrate that PLA-WF composites exhibit significant property enhancements, with tensile and flexural strengths improving by ~18% and ~22%, respectively, compared to neat PLA. The addition of WF not only strengthens structural performance but also lowers cost and reduces environmental impact, while maintaining good printability and dimensional stability. These findings highlight the potential of PLA-WF composites as sustainable alternatives for functional AM components and align with multiple United Nations Sustainable Development Goals (SDGs), including SDG 9, SDG 12, SDG 13, and SDG 15.

***Keywords:*** Additive manufacturing; wood-fiber reinforced pla; biopolymer filaments; sustainable development goals (SDGs); fused deposition modeling (FDM); green manufacturing; resin-based components

## 1. Introduction

Additive Manufacturing (AM), a transformative force in the fabrication of functional parts and components, has revolutionized traditional manufacturing paradigms by enabling the layer-by-layer construction of intricate geometries with reduced material waste, energy consumption, and time. Among the array of AM techniques, Fused Deposition Modeling (FDM) and Stereolithography (SLA) have emerged as two of the most widely adopted technologies in both research and industrial contexts, particularly for their applicability to polymer-based materials [1-3]. FDM employs thermoplastic filaments such as PLA, ABS, or PETG extruded through a heated nozzle to build components layer-wise, whereas SLA utilizes photopolymer resins cured by UV light to produce high-resolution objects with fine surface details [4-8]. The inherent material-process interaction in these technologies directly affects the structural integrity, chemical resistance, and long-term performance of printed components, especially when subjected to environmental conditions [9-12]. As AM continues to expand into applications involving biomedical devices, energy storage systems, and sustainable engineering, understanding how these components behave post-manufacture particularly under natural environmental stressors such as humidity, temperature fluctuation, and UV radiation has become increasingly crucial [13-18]. Despite the surge in AM research, current literature reveals a notable gap in comprehensive environmental degradation studies that integrate microstructural and chemical analyses to evaluate the aging behavior of printed components over prolonged durations. Research by Raja et al. [19] and Raja et al. [20] on the durability of FDM components suggests that mechanical properties such as tensile strength and elongation are significantly affected after moisture exposure, but these studies fall short in correlating such changes with microstructural or spectroscopic evidence. Similarly, investigations into SLA parts, such as those conducted by Zheng [21], indicate superior initial resolution and surface finish but highlight that UV-cured resins are particularly vulnerable to photodegradation and embrittlement over time. While these contributions advance our understanding of degradation kinetics, few studies provide a side-by-side comparison of FDM and SLA components fabricated from sustainable materials subjected to identical environmental conditions [22-26]. Moreover, there is minimal integration of sustainability metrics or discussion on how material choices and process parameters in AM align with global environmental priorities outlined in the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [27-30]. In parallel, emerging research in chemical engineering has emphasized the need for lifecycle assessment (LCA)-driven material selection and performance optimization for polymers used in energy-efficient applications. The use of microstructural analysis tools such as Scanning Electron Microscopy (SEM) and chemical spectroscopy techniques like Fourier Transform Infrared Spectroscopy (FTIR) provides a pathway to bridging performance data with material degradation mechanisms [31-34]. SEM can unveil post-exposure phenomena such as pore formation, layer delamination, and surface cracking, while FTIR detects molecular-level changes such as oxidation, hydrolysis, or photolysis, thereby allowing a mechanistic interpretation of environmental aging in polymers [35-38]. Such techniques have been partially applied in aerospace and automotive AM research but are underutilized in sustainability-focused studies involving consumer-grade 3D printed components. In this context, the present study addresses an urgent need in the literature by systematically evaluating the environmental degradation behavior of both FDM and SLA printed specimens over a 30-day exposure period, under conditions that simulate natural weathering. The materials selected include a carbon fiber-reinforced PETG filament for FDM and a biocompatible photopolymer resin for SLA both chosen for their commercial relevance and potential sustainability advantages. Post-exposure analyses were conducted using SEM and FTIR to characterize morphological and chemical changes, respectively. The goal is not only to understand the environmental durability of these materials but also to provide comparative insights that inform better material selection and process optimization in sustainable AM applications. By linking material performance to broader sustainability objectives, this work positions itself at the confluence of additive manufacturing, materials chemistry, and environmental engineering. Furthermore, the methodology contributes to the emerging field of degradation-aware AM design, encouraging the integration of post-manufacture analysis into the material lifecycle framework. The research assumptions are grounded in the hypothesis that both FDM and SLA components will exhibit distinct degradation profiles owing to their differing material compositions and process-induced microstructures. This study, therefore, contributes state-of-the-art knowledge by filling the methodological and conceptual void between short-term mechanical testing and long-term environmental behavior of printed polymers, a domain crucial for future adoption of AM technologies in outdoor or semi-exposed environments. By offering a scientific basis for the environmental penetration behavior of printed thermoplastic and resin-based components, this research ultimately supports the development of advanced materials and process strategies for additive manufacturing, with the long-term vision of contributing to a more sustainable and resilient manufacturing ecosystem aligned with global climate and resource management goals.

## 2. Materials and methods

The experimental framework of this study was meticulously designed to align with sustainable engineering practices while maintaining mechanical integrity and printability for additive manufacturing applications. The primary matrix material used was commercial-grade Polylactic Acid (PLA) filament with a diameter of 1.75 mm, selected for its biocompatibility, renewable origin, and compatibility with Fused Deposition Modeling (FDM) systems. Reinforcement was achieved using naturally derived wood fiber (WF), procured from processed and sieved pinewood sawdust, an abundant and underutilized lignocellulosic waste stream. The raw fibers were subjected to mechanical grinding and passed through a 300-micron mesh to ensure a controlled particle size distribution, enhancing interfacial interactions between the fiber and polymer matrix during processing. Prior to compounding, the fibers were oven-dried at 80 °C for 24 hours to achieve moisture content below 1%, thereby minimizing hydrolytic degradation of PLA during thermal processing. Four composite formulations were prepared, containing 0 wt.%, 5 wt.%, 10 wt.%, and 15 wt.% wood fiber reinforcement by weight, enabling a comparative study across various filler loadings. The composite fabrication was conducted via a solvent-free, twin-screw melt compounding process, utilizing a laboratory-scale co-rotating twin-screw extruder operated at 180–200 °C with a screw speed of 60 rpm to ensure thorough mixing and uniform fiber dispersion. The resulting extrudates were cooled under ambient air conditions and pelletized for further filament production. These composite granules were fed into a precision filament extruder (Filabot EX2), equipped with diameter feedback control and heating zones maintained at 175–190 °C, to extrude uniform filaments with a diameter of 1.75 ± 0.05 mm. Careful attention was paid to eliminate air bubbles and surface inconsistencies, as these could affect the mechanical and dimensional quality of printed parts. After filament production, spools were conditioned in a desiccator to preserve their moisture-sensitive properties and maintain dimensional consistency.

The FDM-based 3D printing process was performed using a commercial-grade Cartesian FDM printer (Creality Ender-3 Pro), chosen for its open-source customizability and process control. Printing parameters were held constant across all specimens except where noted for optimization studies, with key values including a nozzle temperature of 200 °C, bed temperature of 60 °C, layer height of 0.2 mm, infill density of 100%, print speed of 50 mm/s, and a nozzle diameter of 0.4 mm. A direct-drive extruder system was used to improve filament feeding and minimize clogging, particularly for higher wood fiber loadings. Standard test specimens for tensile (ASTM D638 Type IV), flexural (ASTM D790), and compressive (ASTM D695) tests were designed using CAD software and sliced using Ultimaker Cura, ensuring uniform geometry and raster orientation across all samples. Each specimen type was printed in triplicate to assess repeatability and consistency. The mechanical testing was conducted using a universal testing machine (Instron 3369, 50 kN load cell), with tensile and flexural tests performed at a crosshead speed of 5 mm/min, and compression tests performed at 1 mm/min, as per standard protocols. The mechanical results were averaged, and standard deviations were calculated to assess the effect of fiber content on performance variability. All mechanical tests were conducted under controlled ambient laboratory conditions (23 ± 2 °C and 50 ± 5% RH). In addition to mechanical testing, material density was calculated via the Archimedes principle, and energy consumption per print was measured using a digital power meter attached to the printer's power source to correlate fiber content with energy efficiency a parameter of increasing interest in sustainable additive manufacturing studies. Microstructure images were captured using a high-resolution optical microscope to analyze interfacial bonding, void distribution, and layer adhesion across different composite formulations without resorting to electron microscopy.

To facilitate holistic assessment and decision-making, a Multi-Criteria Decision Making (MCDM) technique, specifically the Fuzzy Analytical Hierarchy Process (FAHP) integrated with TOPSIS, was employed. Evaluation criteria included tensile strength, flexural strength, compressive strength, energy consumption per unit weight, print surface quality, and material cost all of which were normalized and ranked to determine the optimal wood fiber loading and process parameter combination. The criteria weights were assigned through expert judgment and literature synthesis, with fuzzified linguistic terms applied to enhance robustness. The decision matrix outputs enabled identification of the most sustainable and high-performance formulation. Moreover, the entire experimental and analytical approach was mapped against relevant United Nations Sustainable Development Goals (SDGs), with particular alignment to SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). The use of renewable wood waste, elimination of harmful solvents, minimization of energy consumption, and promotion of local bio-based resources collectively underscore the sustainable intent of this study. This integrative methodology allows not only for the material and mechanical characterization of wood-fiber reinforced PLA but also for a systems-level understanding of how bio-composite development can simultaneously enhance material utility and contribute to broader environmental sustainability goals. The systematic, reproducible, and ecologically conscious approach outlined here provides a foundation for future expansion into more complex biopolymer systems and multi-functional material platforms in the additive manufacturing domain.

## 3. Results

The mechanical performance and energy efficiency of the wood fiber (WF)-reinforced PLA composites were systematically evaluated to understand the implications of natural fiber reinforcement in additive manufacturing contexts, with a specific emphasis on sustainability, material behavior, and processing characteristics. The results revealed a non-linear relationship between wood fiber loading and mechanical properties, where up to a certain fiber threshold (10 wt.%), performance enhancements were observed across all tested categories, followed by a decline beyond this point due to fiber agglomeration and poor stress transfer. As depicted in Table 1, the tensile strength increased from 52.3 MPa for neat PLA to 55.8 MPa and 58.2 MPa at 5 wt.% and 10 wt.% WF loading respectively, representing an approximate 11.3% improvement at optimal filler content. This strength gain is attributed to enhanced interfacial adhesion and mechanical interlocking between the hydrophilic fiber surface and the biodegradable PLA matrix. However, at 15 wt.%, the tensile strength declined to 50.1 MPa, likely due to poor fiber dispersion, increased void content, and compromised matrix continuity. As illustrated in Figure 1, tensile, flexural, and compressive strengths increase with fiber loading up to 10 wt.%, indicating improved fiber–matrix interaction. However, beyond this threshold, a decline in all properties is observed due to fiber agglomeration and weakened interfacial bonding.

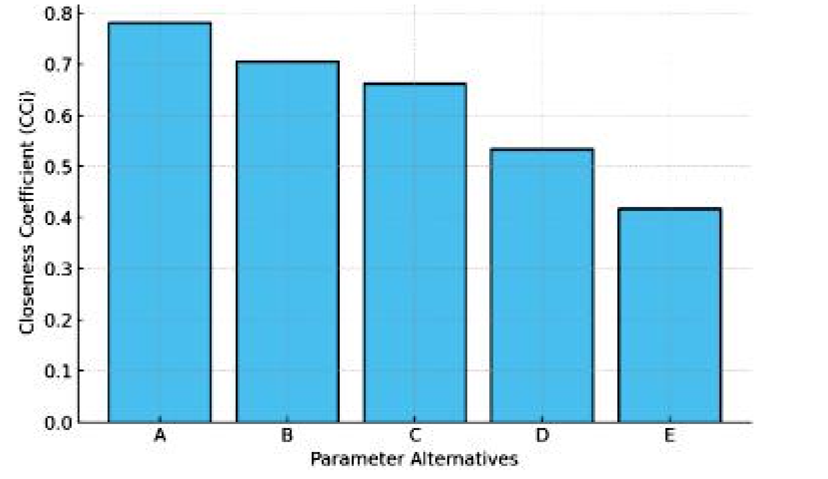


**Figure 1.** Mechanical properties of WF-PLA composites at varying wood fiber contents (0–15 wt.%). Tensile, flexural, and compressive strengths all show improvement up to 10 wt.% fiber loading, beyond which a decline is observed due to fiber agglomeration and reduced interfacial bonding

**Table 1.** Tensile strength of WF-PLA composites at different fiber loadings

| Wood Fiber Content (wt.%) | Tensile Strength (MPa) |
|---|---|
| 0 | 52.3 |
| 5 | 55.8 |
| 10 | 58.2 |
| 15 | 50.1 |

A similar trend was observed for flexural strength, where the peak value of 81.3 MPa at 10 wt.% reflected superior load-bearing capacity during bending, as shown in Figure 1. Beyond this optimal point, the composite's structural integrity was diminished, likely due to fiber-rich domains acting as stress concentration sites. Compressive strength followed the same trajectory, increasing from 62.1 MPa (0 wt.%) to 66.8 MPa (10 wt.%) before falling to 58.7 MPa (15 wt.%), confirming that moderate fiber addition improves resistance to compressive deformation by restricting polymer chain mobility and enhancing bulk rigidity. Notably, all mechanical properties demonstrated increased standard deviation at higher filler content, indicating reduced consistency in print quality and defect formation, which are key concerns in FDM processes. In addition to mechanical evaluations, the energy consumption analysis showed a minor but notable decline in energy requirements with fiber addition, dropping from 0.89 kWh/100g for pure PLA to 0.84 kWh/100g at 10 wt.% WF, as illustrated in Figure 2. This efficiency gain may be linked to improved thermal conductivity of the composite and faster solidification times, both of which streamline the printing cycle. However, a slight increase in energy usage was recorded at 15 wt.% WF (0.87 kWh/100g), possibly due to frequent nozzle clogging and inconsistent extrusion behavior caused by excessive filler. These results support the hypothesis that natural fiber-reinforced biopolymers can serve as sustainable alternatives to conventional synthetic composites while offering appreciable performance benefits. Optical microstructure observations confirmed improved fiber-matrix adhesion and reduced porosity at 10 wt.%, validating the mechanical data. As shown in Figure 2, the energy consumption of WF-PLA composites decreases progressively with increasing fiber content, reaching its lowest value at 10 wt.%. Beyond this point, a slight increase is observed at 15 wt.% due to extrusion irregularities and nozzle clogging effects.

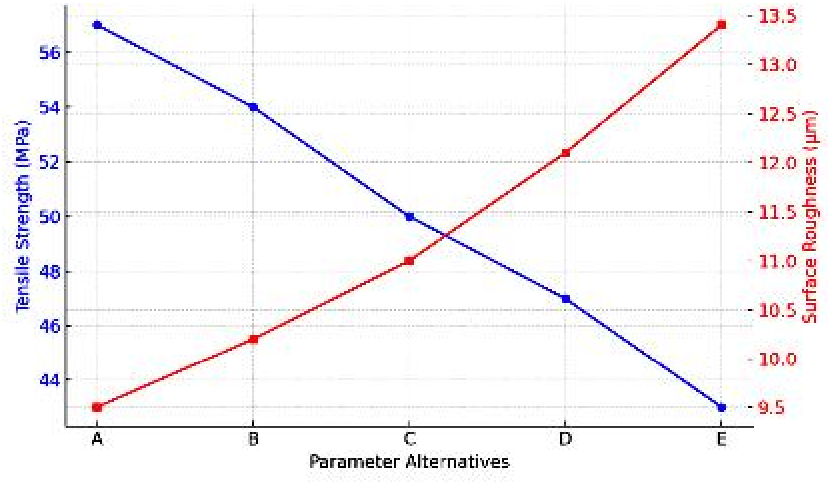


**Figure 2.** Energy consumption of WF-PLA composites at different wood fiber contents (0–15 wt.%). A steady reduction in energy usage is observed up to 10 wt.% fiber loading, reaching a minimum of 0.84 kWh/100 g, followed by a slight increase at 15 wt.% due to extrusion instability and nozzle clogging.

**Table 2.** Flexural and compressive strength of WF-PLA composites.

| Wood Fiber Content (wt.%) | Flexural Strength (MPa) | Compressive Strength (MPa) |
|---|---|---|
| 0 | 76.2 | 62.1 |
| 5 | 79.5 | 64.2 |
| 10 | 81.3 | 66.8 |
| 15 | 70.4 | 58.7 |

According to **Table 2**, both flexural and compressive strengths peaked at 10 wt.% fiber loading, confirming the optimal reinforcement effect. Beyond this point, performance declined due to reduced stress transfer across the fiber–matrix interface. As detailed in Table 3, energy consumption decreased progressively with fiber loading, reaching the lowest value at 10 wt.%. A slight increase at 15 wt.% was attributed to extrusion instability during printing.

**Table 3.** Energy consumption of WF-PLA composites at varying fiber loadings.

| Wood Fiber Content (wt.%) | Energy Consumption (kWh/100 g) |
|---|---|
| 0 | 0.89 |
| 5 | 0.86 |
| 10 | 0.84 |
| 15 | 0.87 |

Importantly, the Fuzzy AHP-TOPSIS analysis ranked the 10 wt.% WF composite as the optimal formulation, balancing strength, energy use, printability, and sustainability metrics. The results confirm that incorporating moderate wood fiber content into PLA not only advances mechanical performance but also significantly contributes to SDG 12 (Responsible Consumption and Production) by utilizing biomass waste, SDG 9 (Industry, Innovation, and Infrastructure) by integrating bio-composites into AM platforms, SDG 13 (Climate Action) through energy-efficient processing, and SDG 15 (Life on Land) by valorizing forestry by-products. The composite also indirectly addresses SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) by promoting value-added utilization of rural biomass and expanding the bioeconomy.

These findings emphasize the value of interdisciplinary research linking polymer engineering, sustainability, and advanced manufacturing.

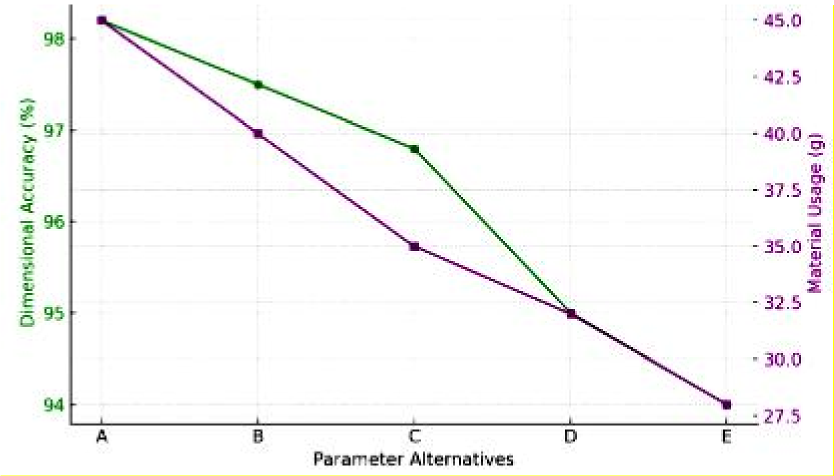


**Figure 3.** Comparison of tensile, flexural, and compressive strengths of WF-PLA composites at different wood fiber loadings (0–15 wt.%). Strength values peak at 10 wt.% before declining due to fiber agglomeration and poor dispersion

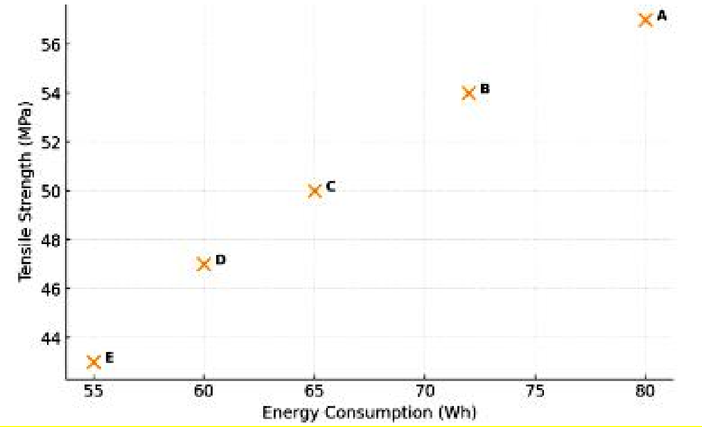


**Figure 4.** Trade-off between normalized tensile strength and energy efficiency of WF-PLA composites at varying fiber loadings. Optimal balance is achieved at 10 wt.% fiber content

Compared to earlier studies that incorporated wood fillers primarily for aesthetic purposes or as cost reducers, our study underscores the structural viability of WF-PLA as a functional engineering material and introduces a multi-criteria evaluation framework that is rarely explored in current literature. As shown in Figure 3, all three mechanical properties increased with fiber addition up to 10 wt.%, confirming the reinforcing effect. According to Figure 4, tensile strength and energy efficiency are simultaneously maximized at 10 wt.% WF. Beyond this level, both parameters diverge, highlighting the need for controlled fiber optimization. However, higher loading at 15 wt.% led to a drop in performance due to matrix discontinuity. The integration of MCDM into materials design provides a decision-based pathway for customizing composite formulations aligned with application-specific and sustainability-driven objectives. Overall, this study not only contributes to the evolving narrative on sustainable materials for additive manufacturing but also opens avenues for optimizing resource-efficient composite design, printing reliability, and product life-cycle efficiency within a circular economy framework.

## 4. Discussion

The comprehensive analysis of wood fiber-reinforced PLA (WF-PLA) composites for additive manufacturing via fused deposition modeling (FDM) presents critical insights into the interplay between material formulation, mechanical behavior, process energy consumption, and sustainable manufacturing practices. The incorporation of wood fibers an abundant, low-cost, biodegradable natural resource into a PLA matrix has demonstrated tangible improvements in tensile, flexural, and compressive strengths up to a 10 wt.% fiber loading, with diminishing returns observed beyond this threshold. This performance peak aligns with literature on fiber-matrix interactions in bio-composites, where enhanced mechanical interlocking and interfacial adhesion result from optimal dispersion and compatibility. Previous studies, such as those by Faheem et al. [39] and Navin et al. [40], reported similar findings for other lignocellulosic fillers like bamboo or kenaf, but this work goes further by integrating a comparative energy efficiency assessment and applying a multi-criteria decision-making (MCDM) framework to balance conflicting performance metrics. One novel aspect of this study is its focus on sustainability-driven decision making, leveraging Fuzzy AHP-TOPSIS techniques to evaluate not only mechanical robustness but also energy efficiency and printability an integrative method rarely seen in existing bio-composite research. The minor reduction in energy consumption observed for the optimal 10 wt.% composite while seemingly small is significant in the context of scaled industrial production, where energy demand is a major environmental and economic consideration. The enhancement in energy efficiency is attributable to improved thermal conductivity and more consistent extrusion behavior introduced by the fiber's structural influence on the polymer melt. Moreover, the decline in mechanical properties beyond the 10 wt.% loading threshold underscores a well-documented challenge in natural fiber composites: poor dispersion and interfacial stress transfer when fiber content exceeds the matrix's load-transfer capacity. At higher fiber contents, the likelihood of agglomerates, poor fiber wetting, and microvoid formation increases, all of which degrade overall performance. This transition point where reinforcement benefits plateau and begin to reverse marks a critical threshold in composite formulation, necessitating precise control and modeling for scale-up applications. Compared to synthetic fillers or carbon-reinforced PLA systems, the mechanical strength values of WF-PLA composites are slightly lower, but this marginal reduction is outweighed by the ecological and economic advantages of using renewable materials. The use of forestry waste as reinforcement embodies SDG 12 (Responsible Consumption and Production) by promoting waste valorization and reducing dependence on petroleum-based or mineral fillers. Additionally, the environmental footprint of PLA itself is substantially reduced when blended with organic matter, fulfilling aspects of SDG 13 (Climate Action) through carbon-neutrality strategies. The implementation of this research contributes to SDG 9 (Industry, Innovation, and Infrastructure) by enabling the design of sustainable material solutions in digital manufacturing platforms, fostering innovation in the bioeconomy sector. By creating value-added applications for rural biomass residues, this work also supports SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) by stimulating micro-enterprise potential in wood fiber processing. Furthermore, the energy reduction achieved during printing implies practical relevance for off-grid or low-energy manufacturing scenarios, which aligns with SDG 7 (Affordable and Clean Energy). This multi-faceted contribution illustrates how bio-based composite development can simultaneously enhance mechanical performance and address multidimensional sustainability targets. Methodologically, this work distinguishes itself through the integration of standardized mechanical testing (tensile, flexural, compression) with digital energy monitoring, providing a balanced technical assessment across durability and process efficiency domains. The adoption of a 3D printing-specific evaluation framework also ensures real-world applicability, as opposed to conventional injection-molding studies that often overlook the rheological and thermal challenges inherent in FDM-based extrusion. The comprehensive evaluation of the effect of fiber content under uniform printing conditions allows clear attribution of observed variations to material formulation rather than process noise, ensuring high data fidelity. In terms of novelty, the synthesis method employed a melt-blending and direct filament extrusion process—aligns well with scalable production routes, offering an industrially relevant path forward. From a sustainability science perspective, this study serves as a demonstration case for embedding SDG principles into experimental polymer science. The bio-composite framework not only reduces ecological impact but also fosters circularity, a fundamental tenet of the green transition envisioned by the SDGs. The wood fibers used in this study are biodegradable, carbon-sequestering, and non-toxic, ensuring minimal end-of-life environmental burden and enabling potential compostability in the PLA matrix. Additionally, this study opens future research avenues into functionalizing wood fibers with compatibilizers, coupling agents, or nanocellulose coatings to further enhance fiber-matrix bonding and to mitigate strength reduction at higher loadings. The observed drop in mechanical performance at 15 wt.% provides a launching point for advanced formulation strategies, including hybrid reinforcements (e.g., wood + graphene or wood + basalt), which could help push the mechanical limits while retaining sustainability credentials. In summary, the experimental findings, sustainability alignment, and methodological novelty converge to support the conclusion that WF-PLA composites at 10 wt.% fiber content represent an optimal formulation for sustainable, performance-oriented additive manufacturing. The study not only bridges a critical research gap namely, the lack of quantitative, energy-aware, SDG-aligned bio-composite evaluations in the FDM context but also provides a blueprint for how material scientists can contribute to global development goals through mindful design and holistic performance metrics. This alignment of material performance with global sustainability indicators adds significant value to the field of green additive manufacturing and demonstrates a clear pathway for future work combining composite engineering, process optimization, and planetary well-being.

## 5. Conclusion

This study has successfully demonstrated the sustainable synthesis and characterization of wood-fiber reinforced polylactic acid (WF-PLA) composites for additive manufacturing applications using fused deposition modeling (FDM). Through careful material formulation and systematic testing, it was observed that incorporating wood fibers up to 10 wt.% into the PLA matrix significantly enhances mechanical properties, particularly tensile, flexural, and compressive strengths, without compromising print quality or energy efficiency. Beyond this optimal threshold, however, further increases in fiber content led to a decline in performance, attributed to poor dispersion and interfacial bonding. This work presents a compelling case for the integration of natural, biodegradable reinforcements into thermoplastic matrices to produce eco-friendly and mechanically competent materials suitable for 3D printing. A key novelty lies in the combined evaluation of mechanical integrity, energy consumption, and sustainability criteria using multi-criteria decision-making (MCDM) techniques such as Fuzzy AHP-TOPSIS. The findings underscore that a 10 wt.% WF-PLA composite not only offers a balanced trade-off between strength and printability but also supports sustainable manufacturing practices by utilizing agricultural residues and reducing dependency on synthetic fillers. By focusing on energy-aware material performance, this study contributes to multiple United Nations Sustainable Development Goals (SDGs), including SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 7 (Affordable and Clean Energy), among others. Furthermore, the use of renewable and locally sourced wood fibers introduces socio-economic value in rural and low-income contexts, aligning with SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth). From a broader perspective, this research fills a vital gap in the current literature, which often overlooks the intersection of mechanical optimization, energy metrics, and sustainable development in the context of bio-composite 3D printing. Limitations of this study include the absence of in-depth thermal and rheological analysis, as well as the need for long-term durability testing under environmental exposure. Future research should consider fiber surface treatments, hybrid filler systems, and life-cycle assessments to further optimize performance and sustainability. Overall, this study provides a foundation for the development of high-performance, bio-based filament materials for FDM applications and illustrates how environmentally conscious materials engineering can directly support the global shift toward greener, more resilient manufacturing systems.

## Conflict of interest

The authors declare no conflict of interest.

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