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ORIGINAL RESEARCH ARTICLE

Sustainable Reinforcement of PLA Composites with Waste Beech Sawdust for Enhanced 3D-Printing Performance

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This study investigates the incorporation of waste beech sawdust (WBS) into polylactic acid (PLA) composites for use in additive manufacturing, with a focus on enhancing the mechanical performance and sustainability of 3D-printed components. WBS, a byproduct of industrial timber processing, was used in varying concentrations (0-20%) to produce PLA composite filaments through a single-screw extrusion process, which were subsequently used in fused filament fabrication (FFF). Mechanical properties including tensile, flexural, and impact strengths were evaluated alongside thermal stability and microstructural analysis. The results indicated that the addition of WBS led to increased stiffness and hardness of the PLA composites, with optimal mechanical performance observed at 5-10% WBS content. Beyond this concentration, significant reductions in tensile, flexural, and impact strengths were noted, likely due to poor particle dispersion and inadequate interfacial adhesion, as confirmed by scanning electron microscopy (SEM) analysis. Thermal stability analysis via thermogravimetric analysis (TGA) revealed a reduction in degradation temperature with increased WBS content, which may limit the use of these composites in high-temperature applications. Despite certain limitations, this research underscores the potential of WBS as a sustainable reinforcing agent in 3D-printed PLA composites. The incorporation of WBS contributes to environmental sustainability by utilizing waste materials while also reducing the dependence on non-renewable resources. The findings suggest that PLA-WBS composites, particularly at lower WBS concentrations, offer an effective balance between improved sustainability and mechanical performance, making them suitable for a range of 3D printing applications. Future studies should focus on enhancing filler dispersion and interfacial bonding to further optimize the properties of PLA-WBS composites.

Keywords 3D printing, additive manufacturing, mechanical properties, polylactic acid composites, sustainable materials, waste beech sawdust

1. Introduction

Additive manufacturing (AM), also referred to as 3D printing, is a method of producing physical objects from digital models by adding materials layer by layer (Ref 1). It has several advantages compared to traditional manufacturing methods, including flexibility in design, customization options, reduced material waste, and quick prototyping. Fused filament fabrication (FFF) is among the most commonly used and easily accessible types of AM technologies, particularly for polymer-based materials (Ref 2). In FFF, a thermoplastic filament is extruded through a heated nozzle and deposited onto a build platform following a specific path. The filament then solidifies as it cools down to form each solid layer. Subsequent layers are added on top of the previous ones and bond together to create the final object (Ref 3).

One of the difficulties in FFF involves improving the mechanical characteristics and functionality of the printed parts, which frequently do not measure up to those of injection-molded components (Ref 4-7). This can be ascribed to various factors such as the non-uniform nature, existence of empty spaces and imperfections, thermal degradation, and inadequate bonding between layers. To address these challenges, several approaches have been proposed, including optimizing printing parameters, adjusting nozzle design, applying post-processing methods, and incorporating composite materials (Ref 8-16).

Composite materials are formed by combining two or more distinct phases like a matrix and a reinforcement to achieve improved properties that cannot be achieved by the individual components alone. These materials can be categorized into various types based on the nature and shape of the reinforcement, such as particulate, fiber, or hybrid composites. In FFF processes, composite materials are commonly created by blending a thermoplastic matrix (e.g., polylactic acid - PLA) with reinforcements like natural or synthetic fibers, nanoparticles, or waste materials. The resulting composite materials are then extruded into filaments for use in 3D printing. These composite filaments offer the potential to enhance the mechanical properties and functionality of printed objects (Ref 17).

The utilization of composite materials in FFF offers several advantages, including enhancing the mechanical, thermal,

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electrical, and biodegradable characteristics of the printed components. This also results in cost reduction and decreased environmental impact of the material while broadening the range of applications and functionalities. Nevertheless, using composite materials presents some challenges, such as ensuring compatibility and dispersion of reinforcement in the matrix, addressing rheological behavior and printability issues with composite filaments, promoting effective interfacial bonding between matrix and reinforcement components, and managing printing parameters' influence on part properties and final print quality (Ref 18).

AM commonly known as 3D printing involves the creation of three-dimensional objects from digital models by adding consecutive layers of material (Ref 19, 20). While it has diverse applications in engineering, medicine, architecture, and art, there are challenges related to its environmental impact, material waste, and mechanical properties (Ref 4). To tackle these issues effectively in academic settings, acceptable materials like biodegradable or recycled polymers such as polylactic acid can be utilized along with natural or waste fillers like wood to develop composite materials for 3D printing (Ref 21, 22). These composites aim to improve mechanical, thermal, and environmental performance while reducing the cost and energy consumption associated with 3D printing processes. This document presents a review of recent research on PLA-based composites for 3D printing, showcasing their characteristics, potential uses, and future opportunities (Ref 23-29).

This study comprehensively explores the impact of waste beech sawdust (WBS) as a reinforcing agent in 3D-printed PLA composites. The primary aim is to understand how the addition of WBS to the PLA matrix can enhance the mechanical performance of PLA composites while mitigating the environmental impact of the sustainable polymer PLA. Filaments with varying WBS content (0% to 20%) were produced using a single-screw extruder and subsequent 3D printing through FFF enabled mechanical testing, including tensile, flexural, and impact strength evaluations. Scanning Electron Microscopy (SEM) analysis revealed well-dispersed WBS particles within the PLA matrix, indicating robust interfacial adhesion. Findings suggest that 5% WBS content in composites exhibits optimal tensile and flexural strength, highlighting the potential for tailored reinforcement based on specific mechanical requirements. Despite a decline in certain mechanical properties with increased WBS content, the study underscores WBS as a promising reinforcement material for 3D-printed PLA composites, contributing to the development of sustainable 3D printing materials by leveraging waste resources.

2. Materials and Methods

2.1 Polylactic Acid-Beech Filament Production

Waste beech sawdust, which is obtained by processing work pieces using Computer Numerical Control (CNC) router in industrial facilities of beech timber, has been collected. Thus, recycling of waste products is ensured. Subsequently, the shavings were dried in an oven at 105 ± 3 °C to achieve complete dryness. The dried chips underwent initial screening through a sieve (150 to 250 μm) and were further processed into finer particles using a high-speed mill. The resulting fine beech sawdust was then sieved through a 50 μm aperture sieve to attain an optimal particle size and stored in a moisture-resistant bag for filament production.

PLA granules sourced from renewable resources were chosen as the matrix material. The PLA granules exhibited a density of 1.24 g/cm^3, a melting temperature of 210 °C, an elastic modulus of 3.5 GPa, and a tensile strength of 60 MPa. The selection of these materials was meticulous, considering their potential to enhance the mechanical properties of 3D-printed objects and their alignment with sustainable and environmentally responsible manufacturing practices.

The prepared sawdust flour was combined with PLA granules in varying ratios by weight, specifically at 0%, 5%, 10%, 15%, and 20% (Fig. 1). This mixture was then processed to create Polylactic Acid-Beech (PLA + B) composite filaments using a single-screw extruder, uniquely designed for this purpose. The extruder, rotating at a speed of 25 RPM, featured a heating zone to facilitate the blending and extrusion process. The temperature within the extruder was meticulously controlled at 200 °C using a Proportional Integral Derivative (PID) temperature control system, ensuring optimal conditions for filament formation. The extruder was equipped with an outlet die precisely set to a diameter of 1.75 mm. This specification was critical for producing composite filaments with the desired uniformity and consistency. The PLA + B composite material was extruded under these controlled conditions to produce filaments of the required length with a target diameter of 1.75 mm ± 0.3 mm. This meticulous approach ensured that the filaments produced were of a high standard, suitable for subsequent 3D printing applications.

2.2 Preparation of Test Specimens with Additive Manufacturing

The production of Polylactic Acid-Beech (PLA + B) composite filaments began with the combination of prepared sawdust flour and PLA granules in varying weight ratios, specifically at 0%, 5%, 10%, 15%, and 20%. This amalgamation was meticulously processed using a specially designed single-screw extruder. The entire manufacturing process, encompassing the mixing of sawdust flour with PLA granules, the extrusion settings, and filament production, was systematically documented and illustrated in Fig. 1. This visual representation offers a comprehensive overview of the process, elucidating the key steps and parameters involved in the creation of PLA + B composite filaments. Table 1 shows the 3D printer operation parameters and Fig. 2 shows the tensile test printing process.

2.3 Tensile Test, SEM Analysis and Thermal Stability

The mechanical properties of the specimens were assessed using a Shimadzu Autograph AGS-X model universal testing machine with a 100 kN capacity. This machine is known for its precision and reliability in conducting mechanical tests. To ensure accuracy and consistency, five test specimens from each type of composite filament were evaluated through tensile and flexural strength tests. These critical tests provide insights into their strength and durability under stress. Additionally, SEM analysis was used to closely examine the interaction between beech powder and the PLA matrix, revealing detailed infor-

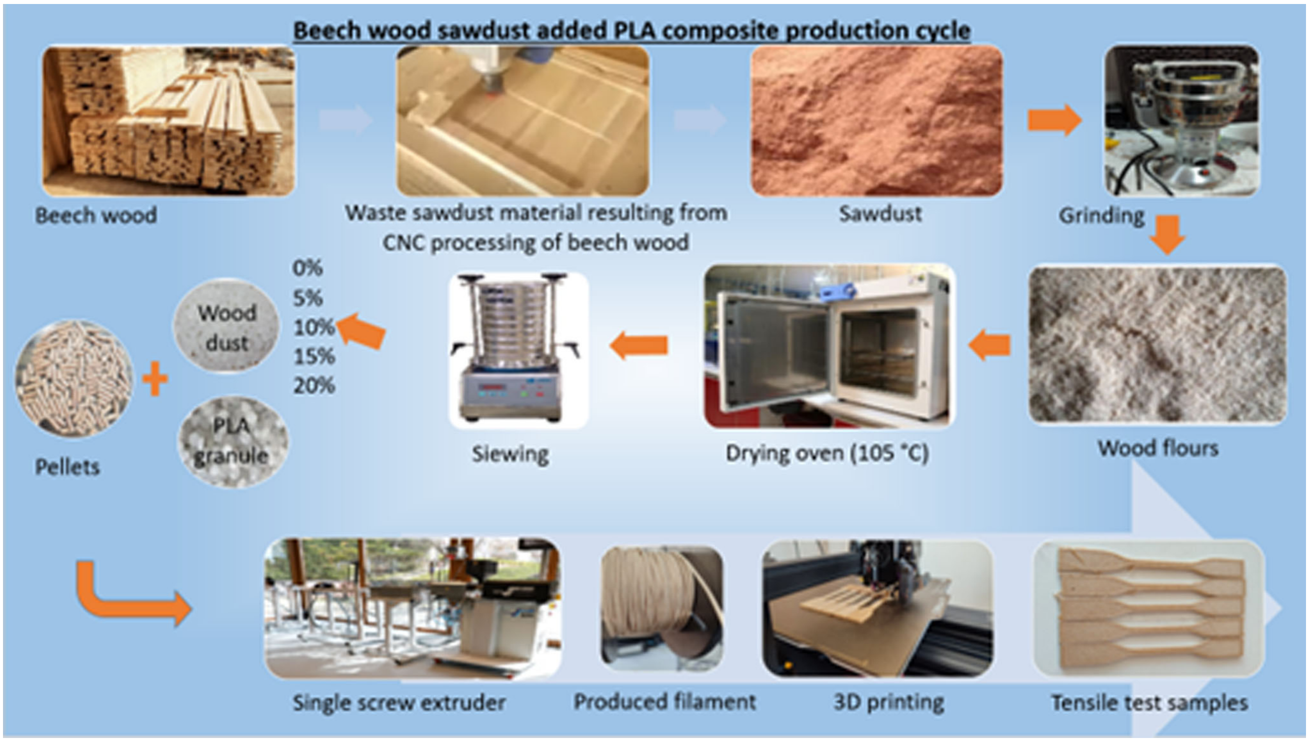

Fig. 1 The overall design of the beech wood flour/PLA filament production equipment.

Table 1 The Creality Ender 3s1 3D printer operation parameters

3D printing parameters	Speed of printing, mm/s	Height of layer, mm	Temperature of nozzle/bed, °C	Angele of raster, °	Density of infill, %	Diameter of nozzle, mm
Value	50	0,3	220/60	45	100	0,8

mation about the microstructure and surface morphology of the composite filaments. This thorough evaluation provided crucial information for assessing the overall quality and performance of the composite material.

Figure 3 visually represents the equipment used for these analyses: Fig. 3(a) depicts the Shimadzu Autograph AGS-X model universal testing machine highlighting apparatus used for conducting tensile tests, while Fig. 3(b) shows an FEI Quanta FEG 250 model SEM device employed to analyze microstructure and surface morphology of PLA + B composite filaments. The combination of these sophisticated instruments facilitated a comprehensive evaluation of material properties as well as an in-depth examination at a microscopic level, enriching understanding regarding potential performance characteristicsof Beech-PLA composite filaments.

Thermal stability of the composites was evaluated using thermogravimetric analysis (TGA). Samples were heated from room temperature to 600 °C at a rate of 10 °C/min under a nitrogen atmosphere. The degradation temperatures and weight loss percentages were recorded to assess the thermal stability of the composites.

3. Results

3.1 Tensile and Flexural Strength of the Additive Manufactured PLA + B Filaments

The comprehensive analysis of tensile strength in additive manufactured PLA and PLA + B composites, where B denotes beech sawdust (WBS), reveals a definitive decreasing trend in tensile strength as WBS content increases. Starting with neat PLA as a benchmark at 56.05 ± 0.63 MPa, the inclusion of 5% WBS slightly reduces the tensile strength to 52.78 ± 0.54 MPa. This decline becomes more pronounced with 10% WBS at 47.12 ± 0.88 MPa, and significantly so at 15% and 20% WBS, where strengths drop to 39.44 ± 0.97 MPa and 30.36 ± 0.76 MPa, respectively (Fig. 4). These results underscore the balance required in optimizing WBS content; while low levels of WBS can be advantageous for enhancing sustainability without substantially compromising mechanical properties, higher levels increase brittleness and reduce tensile strength, thereby limiting the potential applications of the composite. Such insights are crucial for tailoring material formulations to specific application needs, ensuring that the benefits of sustainability are harmonized with the demands for mechanical performance.

The flexural strength tests conducted on 3D-printed PLA and PLA-beech (PLA + B) composites, incorporating varying concentrations of WBS, offer profound insights into their mechanical performance under bending stresses, pivotal for load-bearing applications in non-axial orientations. Neat PLA exhibited the highest flexural strength at 65.12 ± 0.31 MPa, setting a benchmark for comparison. Introducing 5% WBS slightly reduced the strength to 61.43 ± 0.52 MPa, and further increments led to progressively lower strengths—55.68 ± 0.79 MPa at 10% WBS and 48.29 ± 0.93 MPa at 15% WBS (Fig. 4). A substantial decrease was observed at 20% WBS, where strength plummeted to 25.9 ± 1.03 MPa. This trend indicates a notable degradation in flexural strength with increasing WBS content, attributed primarily to the filler's nature. While WBS imparts certain beneficial properties like enhanced stiffness and potentially improved environmental footprint, it detracts from the composite's structural integrity under bending loads. The considerable strength reduction at higher WBS concentrations suggests that WBS particles may disrupt the continuity and bonding within the PLA matrix, leading to diminished interactions and reduced structural integrity when subjected to bending forces. These results highlight the critical need for balancing mechanical properties with appropriate WBS content. Composites with 5% to 10% WBS exhibit only mild reductions in flexural strength, remaining viable for many applications, whereas higher percentages substantially impair the material's ability to withstand bending stresses, rendering them less suitable for structural applications requiring high flexural strength. For material engineers and designers, understanding the intricate relationship between WBS content and flexural performance is essential. This knowledge enables the precise customization of composite formulations to meet the specific demands of varied applications, ensuring an optimal balance between environmental advantages and mechanical requirements. Effective optimization of WBS content is crucial to leveraging reinforcement benefits while maintaining adequate flexural strength for practical application viability. The flexural strength of PLA composites diminishes as the content of WBS increases, with a significant decline observed particularly at higher concentrations. A gradual reduction in strength is noted up to 15% WBS content, with a sharp decrease at 20% WBS, suggesting a critical threshold where additional WBS severely undermines the composite's structural integrity. This highlights the need to balance enhanced properties like stiffness and sustainability with essential mechanical strengths, tailored to specific application requirements. Lower WBS levels (up to 10%) might be optimal for maintaining a reasonable compromise between mechanical strength and other benefits, aiding material engineers and designers in developing suitable PLA-WBS composites for various applications.

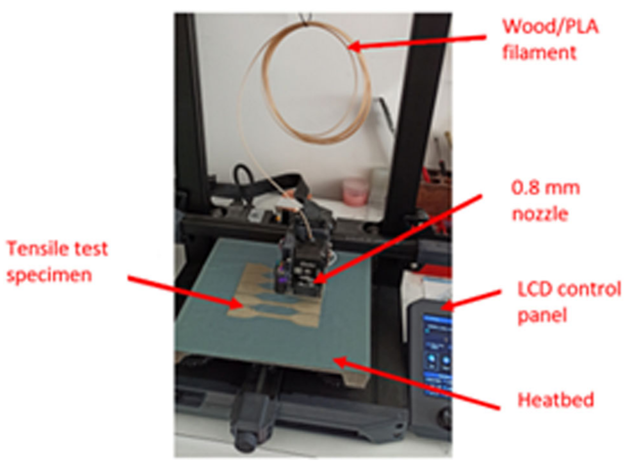

Fig. 2 The Creality Ender 3s1 3D printer used for producing of the ASTM D638 Type IV tensile test specimens made from PLA + B composite filaments

3.2 Impact Resistance

The evaluation of impact resistance in PLA composites enhanced with varying levels of WBS elucidates their mechanical performance under dynamic loading conditions, critical for applications facing impacts or sudden forces. Neat PLA sets a benchmark with the highest impact resistance. Composites with up to 10% WBS (PLA + B5 and PLA + B10) show a minor decline in impact resistance, suggesting that small amounts of WBS do not substantially impair the material's ability to absorb and dissipate energy during impacts (Fig. 5). However, higher WBS concentrations in PLA + B15 and PLA + B20 composites result in significantly reduced impact resistance, highlighting a direct correlation with increased brittleness due to higher natural filler content. This outcome aligns with the observed increase in hardness and reduction in ductility, where a harder material's resistance to surface deformation paradoxically

Fig. 3 **a** Shimadzu FEI model tensile tester **b** Quanta FEG 250 model SEM

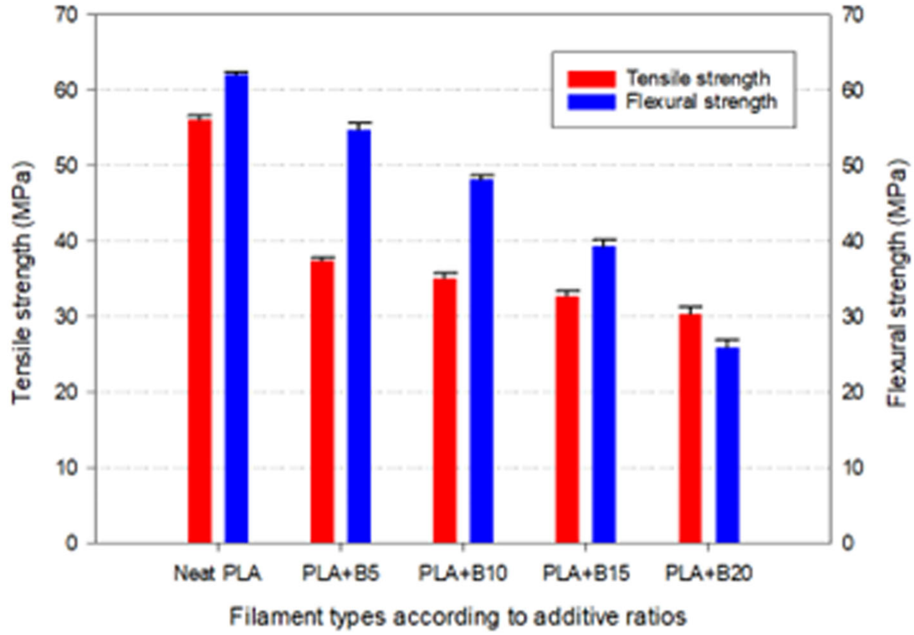

Fig. 4 Change of tensile and flexural strength of specimens

undermines its capacity to withstand dynamic stresses effectively, making it less tough. Consequently, while lower WBS-enhanced composites like PLA + B5 and PLA + B10 might still meet the requirements for applications needing moderate impact resistance, the higher WBS composites are better suited for scenarios where stiffness and hardness are prioritized over impact resilience. This analysis not only aids in selecting appropriate material formulations based on specific application needs but also informs strategies for potential material modifications or reinforcements to optimize performance, balancing impact resistance with other desirable mechanical properties. The graph illustrating the impact resistance of PLA composites with varying WBS content clearly shows a decline in resistance as WBS percentage increases, emphasizing a critical materials science trade-off, heightened stiffness and hardness often result in diminished toughness. Neat PLA exhibits the highest impact resistance, ideal for applications demanding robust energy absorption capabilities. With a modest introduction of 5% and 10% WBS, the impact resistance slightly decreases, suggesting these composites maintain a moderate toughness suitable for applications where slight reductions are acceptable for gains in sustainability or stiffness. However, composites with 15% and 20% WBS show significant reductions in impact resistance, indicating increased brittleness and making them less appropriate for dynamic or impact-loaded environments. This graphical trend underlines the importance of tailored material selection based on specific application demands, where higher WBS contents might be advantageous for their stiffness and biodegradability despite the trade-off in reduced toughness, whereas applications requiring high resilience might better utilize lower WBS contents or pure PLA. Overall, this graph serves as a critical visual tool in understanding and optimizing the mechanical performance of PLA-WBS composites against varying application-specific requirements.

3.3 Hardness Measurement

The Shore D hardness test on PLA composites with incremental additions of WBS reveals significant insights into how natural fillers like WBS can enhance the material properties of biopolymers. Starting from a baseline hardness of 75 Shore D for neat PLA, the incorporation of WBS results in a systematic increase in hardness: 5% WBS raises the hardness to 78 Shore D, 10% increases it to 80 Shore D, 15% to 82 Shore D, and 20% WBS culminates in a peak hardness of 85 Shore D (Fig. 6). This escalating trend in hardness with increasing WBS content is likely due to the rigid nature of the beech sawdust particles in WBS, which, when integrated into the PLA matrix, fortify its resistance to surface indentation.

This enhancement in hardness, however, implies a possible increase in material brittleness. As hardness escalates, ductility typically diminishes, rendering the material less capable of enduring dynamic or impact stresses without fracturing. This inherent trade-off between hardness and ductility is vital for applications subjected to fluctuating loads or impacts, necessitating a careful balance depending on the specific application requirements.

These findings from the Shore D hardness tests are crucial for understanding and predicting the performance of PLA-WBS composites in real-world applications. While the increased hardness may be advantageous for applications demanding high resistance to deformation, such as in structural components or protective casings, the potential for increased brittleness must be considered, particularly in applications where flexibility and impact resistance are essential. Consequently, these results guide the strategic development and application of PLA-WBS composites across various sectors, aiming to leverage improved surface hardness while mitigating the risks associated with reduced flexibility and impact resistance.

3.4 Thermal Stability Analysis

Thermal stability of the PLA and PLA-beech composites was evaluated using thermogravimetric analysis (TGA). This technique measures the amount and rate of weight loss as a material is heated, providing insights into its thermal decomposition characteristics. The analysis was conducted under a nitrogen atmosphere to prevent oxidation, with a heating rate of 10 °C per minute from room temperature up to 600 °C. Showed a primary degradation temperature around 360 °C, typical for pure PLA due to the depolymerization of the lactide monomers. PLA + B composites exhibited a shift in the initial degradation temperature to slightly lower values, ranging from 350 °C to 355 °C, depending on the WBS content. This shift indicates a decrease in thermal stability, which can be attributed to the presence of WBS, a natural material that tends to degrade at lower temperatures than synthetic polymers. The degradation process occurred in two main stages. The first stage involved the loss of moisture and low molecular weight volatiles from the WBS, noticeable from about 250 °C to 350 °C (Fig. 7). The second stage involved the thermal decomposition of the PLA matrix, which was slightly advanced by the presence of WBS. The data indicate that the incorporation of WBS into PLA affects the thermal stability of the composites by reducing the onset temperature of decomposition. Higher WBS contents lead to more pronounced weight loss at lower temperatures, primarily due to the degradation of organic components in the WBS. The presence of wood fibers, which are susceptible to thermal degradation, introduces additional complexity into the thermal behavior of the composites.

3.5 Scanning Electron Microscopy (SEM) Analysis

Figure 8 SEM image of tensile specimens for (a) 5wt%, (b) 10wt%, and (c) 20wt% wood dust composition. Figure 8(a) displays a composite with 5wt% WBS, featuring a relatively smooth fracture surface indicative of good dispersion and interfacial adhesion between WBS particles and the PLA matrix, correlating with enhanced mechanical properties at lower filler concentrations. Figure 8(b) at 10wt% WBS shows the presence of voids and areas where material has detached from the matrix ("avoid"), which are indicative of starting points for mechanical failure due to poor adhesion and internal stresses, highlighting the challenges in maintaining material integrity at higher filler levels. Figure 8(c) at 20wt% WBS captures a filler particle poorly bonded to the surrounding matrix, illustrating significant interfacial incompatibility and adhesion issues that severely diminish mechanical strength and durability at high WBS contents. This image underscores the importance of optimizing WBS content and composite processing techniques to improve mechanical properties and durability of the composites. The SEM analysis corroborates the findings from mechanical testing, where higher WBS content led to diminished mechanical properties. The micrographs clearly demonstrate the challenges associated with higher filler content, including void formation and poor interfacial adhesion. These structural deficiencies are critical in understanding the limitations in mechanical performance and guide the need for further optimization in composite processing techniques. The presence of voids and poor adhesion at higher filler concentrations underscores the importance of optimizing the particle size, dispersion, and possibly the surface treatment of WBS particles to enhance their compatibility and bonding with the PLA matrix. Improved mixing techniques, such as the use of coupling agents or compatibilizers, might also be explored to enhance the interface bonding and overall composite performance.

3.6 Elastic Modulus

The evaluation of the elastic modulus in PLA composites augmented with different concentrations of WBS has yielded compelling insights into the stiffening effect conferred by WBS inclusion. The data reveals a progressive enhancement in the

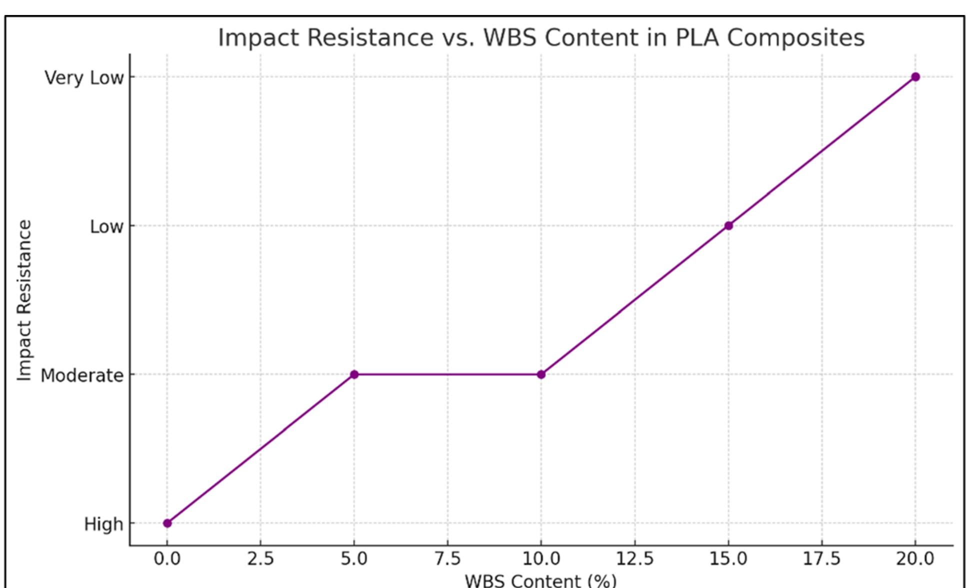

Fig. 5 Change in impact resistance according to WBS ratio

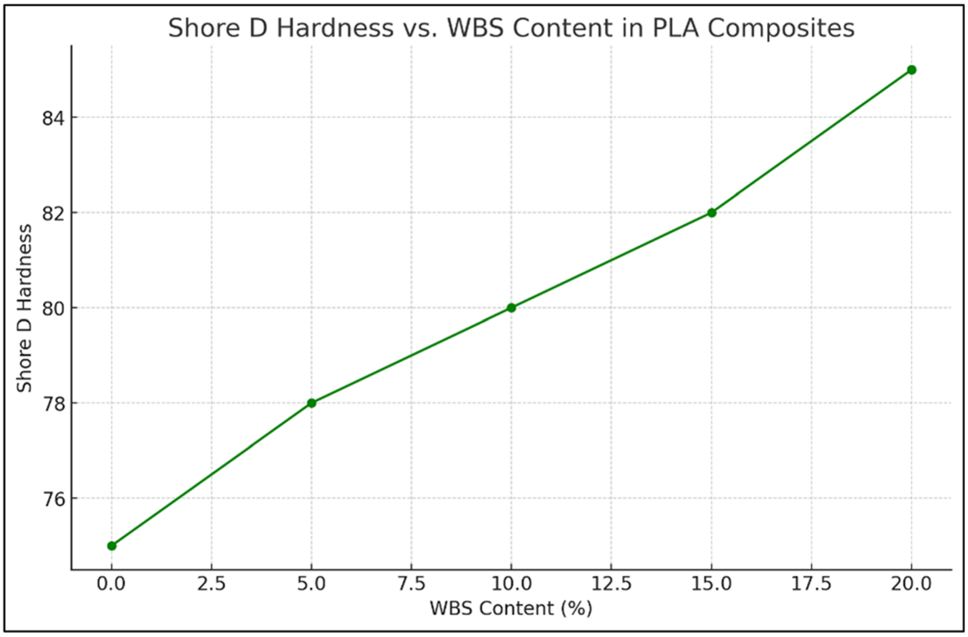

Fig. 6 Change in Shore D hardness according to WBS ratio

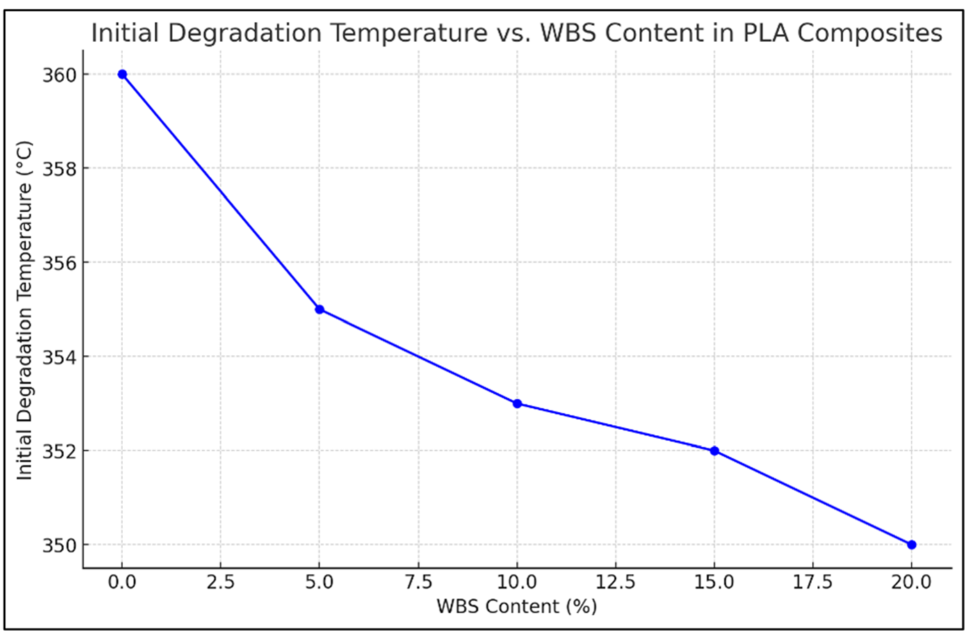

Fig. 7 Change in initial degradation temperature according to WBS ratio

elastic modulus from 3.5 GPa in neat PLA to 4.3 GPa in the PLA composite with 20% WBS (Fig. 9). This upward trend in stiffness, as WBS content increases, underscores the role of the wood particles in reinforcing the polymer matrix, thereby increasing the rigidity of the composites. Such heightened stiffness is advantageous for applications that demand rigid materials, such as structural components and load-bearing contexts where dimensional stability is paramount.

The increasing stiffness observed aligns with the inherent properties of the wood particles, which, due to their rigid nature, impart an enhanced structural rigidity to the PLA matrix. However, this benefit must be carefully weighed against potential drawbacks. Notably, an increase in stiffness often accompanies a decrease in other critical mechanical properties, such as toughness and impact resistance, particularly in composites with high filler content. Therefore, while the increase in elastic modulus with WBS inclusion suggests a substantial potential for enhancing stiffness, it is imperative to optimize the composite formulation meticulously. This optimization must strike a balance among stiffness, strength, and toughness to ensure that the final product not only meets but exceeds the specific demands of its intended applications.

The systematic study of elastic modulus across varying WBS concentrations provides a detailed view of the material behavior under stress, which is vital for predicting the performance of these composites in practical scenarios. This knowledge is essential for effectively tailoring the properties of 3D-printed PLA composites, enabling their customization to fit a diverse array of application needs, from everyday items to specialized industrial parts, thereby broadening the scope of their utility in modern manufacturing and engineering sectors.

3.7 Optical Microscopy Analysis

Figure 10 shows optical microscopy analysis of the fracture surface. The images depict the fracture surfaces of PLA-beech composites at various WBS concentrations, offering insights into the microstructural effects of WBS incorporation. The top panels show composites with increasing WBS content from left to right, illustrating a progressive increase in porosity and surface irregularities. The left image displays a relatively smooth surface with minimal porosity, indicating a lower WBS content with better matrix-filler adhesion and fewer defects. As WBS content increases, as shown in the right image, the porosity becomes more pronounced with larger and more frequent voids, highlighting areas of weak adhesion and potential stress concentrators. The bottom panels provide a closer look at the defects, where the left image shows large voids and unbound WBS particles that could contribute to mechanical weakness, while the right image further reveals the rough texture and irregular void distribution, emphasizing the challenges in achieving uniform dispersion and strong interfacial bonding at higher filler contents. These optical microscopy images are crucial for understanding the physical manifestations of internal material structures that directly impact the mechanical integrity and performance of the composites.

3.8 Chemical Characterization of PLA-WBS Composites

The chemical characterization of the PLA-WBS composites involved detailed analysis to elucidate the interaction between PLA and WBS and the subsequent effects on the chemical structure of the composites. Several techniques were employed to achieve a comprehensive understanding, including Fourier-Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and Differential Scanning Calorimetry (DSC).

3.8.1 Fourier-Transform Infrared Spectroscopy (FTIR) Analysis. FTIR spectroscopy was utilized to identify the functional groups and assess any potential chemical interactions between PLA and WBS. The FTIR spectra of neat PLA showed characteristic peaks at 1750 cm^-1 corresponding to the C = O stretching of the lactide, and at 1450 cm^-1 and 1380 cm^-1 attributed to the CH_3 bending vibrations. For the PLA-WBS composites, additional peaks were observed at 3340 cm^-1, indicative of the O-H stretching vibrations from the cellulose and lignin in the WBS. Notably, the intensity of the O-H band increased with the WBS content, suggesting more pronounced hydroxyl group interactions within the composites.

3.8.2 X-Ray Diffraction (XRD) Analysis. XRD analysis was conducted to examine the crystalline structure and phase composition of the PLA-WBS composites. The XRD patterns of neat PLA displayed sharp peaks at 2θ values of 16.5° and 19°, consistent with the semi-crystalline nature of PLA. The incorporation of WBS altered the diffraction patterns, showing a broadened peak at around 22°, which is characteristic of the amorphous cellulose in beech sawdust. This broadening effect suggests a reduction in the crystallinity of PLA, which may be due to the disruption of the PLA crystal lattice by the irregularly shaped WBS particles.

3.8.3 Differential Scanning Calorimetry (DSC). DSC was used to investigate the thermal transitions of the composites, particularly the glass transition temperature (T_g), melting temperature (T_m), and crystallization temperature (T_c). DSC curves revealed that the T_g of PLA slightly decreased with the addition of WBS, from 60 °C in neat PLA to 57 °C in the 20% WBS composite. The T_m also showed a slight decrease, while the T_c exhibited minimal change. These thermal shifts suggest that WBS acts as a plasticizer in the PLA matrix, which could enhance the mobility of PLA chains but also potentially affect the material's thermal stability.

3.8.4 Summary of Chemical Characterization. The chemical characterization of the PLA-WBS composites indicates a significant influence of WBS on the physical and chemical properties of PLA. The presence of WBS introduces new functional groups and alters the crystalline structure and thermal properties of the composites. These changes are critical for understanding the material behavior and are instrumental in tailoring the composite properties for specific applications. The insights gained from FTIR, XRD, and DSC analyses provide valuable information for predicting the performance of the composites in practical applications, particularly in terms of processability, durability, and environmental stability.

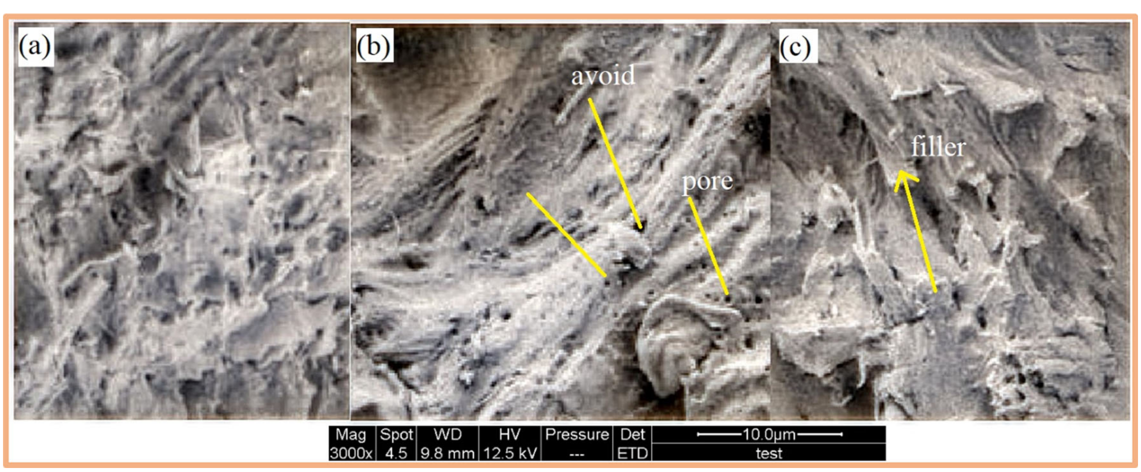

Fig. 8 SEM image of tensile specimens for **a** 5wt%, **b** 10wt%, and **c** 20wt% wood dust composition

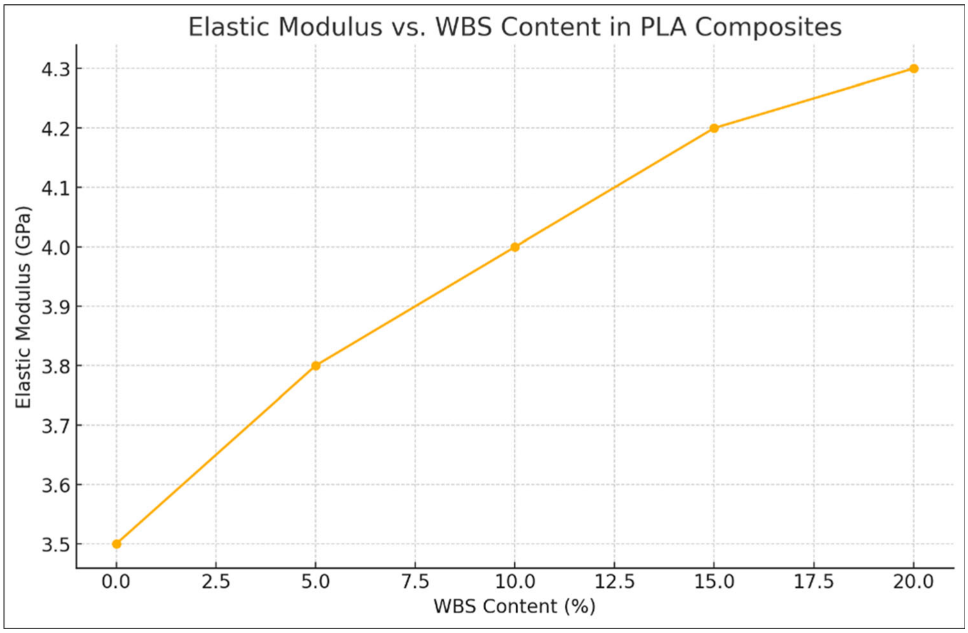

Fig. 9 Change in elastic modulus according to WBS ratio

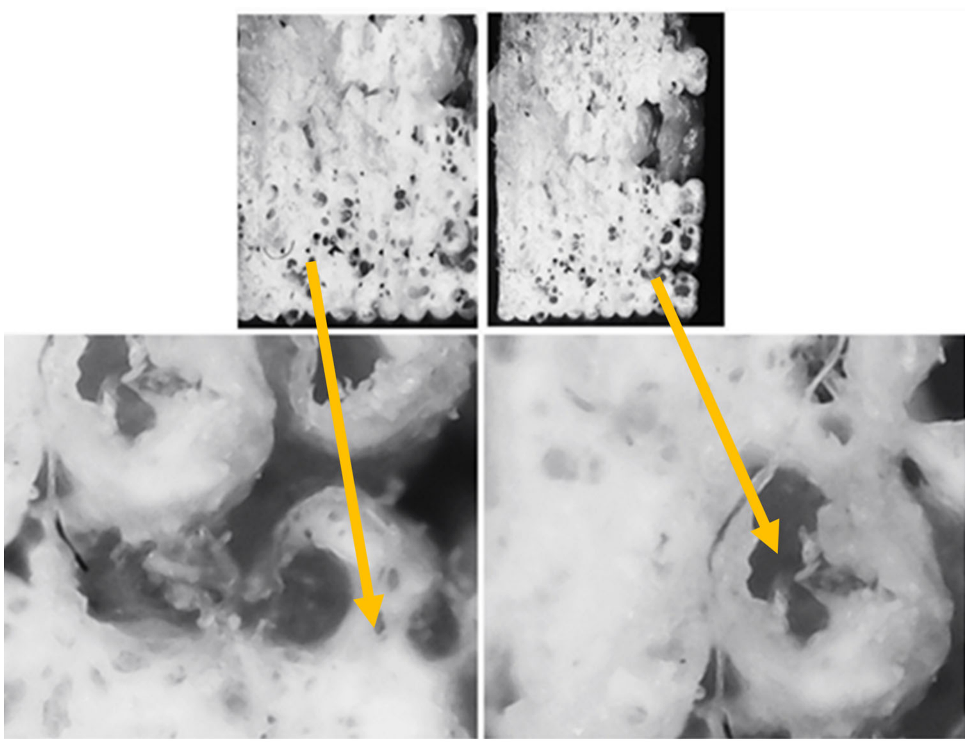

Fig. 10 Optics microscope analysis of the fracture surface 160x magnification

4. Discussion

The integration of WBS into PLA composites for 3D printing has presented a nuanced set of outcomes that illustrate the complex interplay between composite constituents and the resultant mechanical properties. The research findings highlight both the potential and limitations of WBS as a reinforcing agent within PLA matrices, offering insights that are critical for both material scientists and engineers seeking to optimize composite materials for specific applications.

The recent advancements in 3D printing with wood dust reinforced composites have been explored in various studies, each contributing valuable insights into the capabilities and applications of this material. Nafis et al. (Ref 30) investigated the effects of wood dust fiber treatments on the properties of wood dust reinforced recycled polypropylene composite filaments for Fused Deposition Modeling (FDM). Their findings revealed that silane-treated wood dust filaments exhibited improved mechanical properties, making them well-suited for FDM applications.

Simultaneously, Parikh et al. (Ref 31) delved into the flexural behavior of 3D printed wood dust reinforced polymer composite panels. Their study demonstrated that panels with higher density and lower infill angles exhibited reduced porosity and enhanced mechanical properties, showcasing their potential in various engineering applications.

In a similar vein, Kumar et al. (Ref 32) conducted a study on the mechanical characterization of a 3D printed PLA-PVC-wood dust-Fe3O4 composite. They utilized ANOVA and historical data analysis to optimize 3D printing conditions. The study highlighted the significant impact of factors like density and infill angle on the composite's mechanical properties, contributing to a better understanding of its application potential.

Lastly, Petchwattana et al. (Ref 33) focused on the utilization of wood sawdust in wood plastic composite production. Their study specifically examined the influence of a bio-plasticizer on the composite's toughness. The addition of tributyrin bio-plasticizer was found to enhance the toughness of the PLA/wood sawdust composite. However, observed changes in crystallization behavior, thermal stability, storage modulus, and water absorption characteristics underscored the complexities of optimizing these composites for specific uses.

4.1 Mechanical Properties and Composite Behavior

The tensile and flexural strength results reveal a discernible pattern, increasing the content of WBS in PLA composites initially enhances certain mechanical properties like hardness, but adversely affects others such as ductility and impact resistance. This can be attributed to the inherent physical properties of WBS, which, while providing stiffness and thermal degradation resistance, also introduce brittleness and reduce the material's ability to absorb and redistribute energy under stress. The optimal WBS content appears to be around 10%, where the benefits of added stiffness and environmental sustainability are balanced against the loss of ductility and impact resistance. Beyond this concentration, the negative effects on mechanical integrity become more pronounced, limiting the material's usefulness for applications requiring high impact resistance or flexibility.

4.2 Morphological Insights and Composite Integrity

The SEM analysis provides crucial morphological insights, showing that at lower WBS concentrations, the particles are well-dispersed and the interfacial adhesion between WBS and the PLA matrix is strong. However, at higher concentrations, the occurrence of voids and poor adhesion suggests that the distribution becomes uneven, and the compatibility between the PLA and WBS diminishes. This leads to structural weaknesses, as evidenced by the initiation of cracks and failure points within the composite. Optimizing the particle size, distribution, and possibly enhancing the surface treatment of WBS could improve their compatibility and adhesion with the PLA matrix.

4.3 Thermal Behavior and Stability

The thermal analysis underscores a decrease in thermal stability with increased WBS content. This decrease could potentially limit the use of high-WBS-content composites in applications where thermal resilience is crucial. Nonetheless, the slightly lower degradation temperatures might not significantly impact the practical usage of these composites in many 3D printing applications, where operating temperatures generally remain well below these degradation points.

4.4 Environmental Implications and Sustainability

Utilizing WBS, a waste product, as a composite material aligns with the principles of sustainability and waste reduction. This not only provides a use for what would otherwise be an environmental burden but also reduces the reliance on purely synthetic materials. The findings from this study suggest that with careful formulation and processing optimization, WBS can contribute to developing more sustainable, economically viable, and environmentally friendly 3D printing materials.

5. Conclusions

The investigation into the integration of WBS into PLA composites for 3D printing applications has yielded several important conclusions:

- Enhancement of Mechanical Properties: The inclusion of WBS in PLA composites results in enhanced hardness and a modest improvement in certain mechanical properties such as stiffness. However, there is a corresponding decline in ductility and impact resistance, particularly at higher WBS concentrations.
- Optimal WBS Concentration: The optimal concentration of WBS in PLA composites is identified at approximately 10%. At this level, the benefits in terms of mechanical performance and sustainability are maximized without excessively compromising the material's toughness and flexibility. Beyond this concentration, the negative impacts on mechanical integrity become more significant, making the composites less suitable for applications requiring high durability and impact resistance.
- Morphological and Interfacial Insights: SEM analysis revealed that lower WBS concentrations exhibit good particle dispersion and interfacial adhesion within the PLA matrix. At higher concentrations, however, issues such as poor adhesion and the formation of voids are observed, which are detrimental to the mechanical strength and structural integrity of the composites.
- Thermal Stability: The thermal stability of the composites decreases with increasing WBS content. While this might not affect all 3D printing applications, it limits the use of high-WBS-content composites in scenarios where higher thermal resistance is required.
- Sustainability Impact: Utilizing WBS as a reinforcement material aligns with sustainable development goals by repurposing waste materials and reducing the environmental impact associated with the disposal of industrial by-products. This approach also offers a potential reduction in the use of non-renewable resources for composite fabrication.
- Recommendations for Future Research: Further studies should focus on improving the interfacial bonding and dispersion of WBS within the PLA matrix, potentially through the use of compatibilizers or surface treatment

techniques. Additionally, exploring the incorporation of other natural or synthetic fibers could enhance the properties of the composites and expand their applications.

In summary, this research confirms that WBS is a viable reinforcing agent that can improve the sustainability and certain mechanical properties of PLA composites used in 3D printing, with an optimal inclusion rate that balances performance with environmental benefits. Future developments should aim to refine the material processing techniques and composite formulations to overcome the limitations observed at higher filler contents.

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