Mechanical properties of PLA–wood dust composites fabricated by FDM

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Abstract. Fused deposition modeling is an additive manufacturing technique that enables complex structures to be fabricated layer by layer using thermoplastic filaments. The most common usage is based on the fact that polylactic acid is biodegradable and renewable and can be printed when using the fused filament production methods. The solution to reinforcing PLA with lignocellulosic fillers like wood dust is an environmentally friendly and cost-effective composite material solution. This paper will discuss fabrication techniques and processing considerations for producing wood-dust-reinforced PLA filaments in additive manufacturing. The process of composite preparation includes drying, controlled mixing, compounding, and extrusion by single or twin screws. Hygroscopic wood particles must be maintained at a good moisture level since bubbles, voids, and unstable extrusion of melts can occur during the extrusion. Nozzle temperature, print speed, cooling conditions, and layer thickness are some of the critical printing parameters that greatly affect interlayer bonding and dimensional accuracy. The mechanical properties of the printed composites are normally determined through tensile, flexural, and impact testing. Thermal analysis indicates that addition of fillers causes small variations in the glass transition temperature and thermal stability. Microscopic observation evidence shows that there is a correlation between fracture morphology and internal microstructural dispersion of wood particles. Nevertheless, the useful considerations such as the blockage of the nozzle, the sedimentation of the particles, and changes in the filament diameter are significant challenges during the processing. Consistent quality of filament requires standardized drying methods, controlled conditions of compounding, and standardized process windows. These composites have potential in lightweight structural components, consumer products, and interior components that demand sustainable material solutions.

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1 Introduction

This ability to minimize material wastage and make complex geometries has significantly influenced design and production methods in manufacturing in various sectors [1]. Fused Deposition Modeling (FDM) is a widely used additive manufacturing technology, which does not need to be expensive in operation, has a variety of materials, and can be used very easily [2]. The technology is used to create three-dimensional objects by depositing thermoplastic filaments in layers, and so it is the best choice in the case of a single prototype or small-volume production [3].

FDM components have technical limitations such as lack of interlayer adhesion, formation of internal voids, and surface roughness, which deactivate their application in load-bearing structural components [4]. Consequently, significant studies have been focused on balancing the process parameters, such as extrusion temperature, infill pattern, and printing speed, to enhance the structural quality and mechanical performance of the printed components [5].

Polylactic acid (PLA) is among the most marketable commercial FDM materials because of its biodegradability, renewability of feedstock, and high printability [6]. Nonetheless, PLA possesses inherent brittle characteristics and low impact strength and cannot be used in more rigorous engineering applications [7]. The solution to these limitations was to develop sustainable biocomposites by reinforcing PLA with natural fibers and particle fillers [8]. Among these materials, wood dust and wood fibers are remarkable since they enhance stiffness, surface properties, and material sustainability and reduce the production costs [9]. When uniformly dispersed in the PLA matrix, the mechanical stability and elastic response of printed composite structures can be enhanced by wood particles [10]. Moreover, the lignocellulosic waste, e.g., sawmill waste, reduces the environmental impact and enhances the idea of a circular economy by enabling maximum resource efficiency [11].

In order to ensure consistent processing behavior, PLA-wood composites are normally made through controlled mixing, drying, and sifting before extruding the filaments [12]. Controlling moisture is important because the fillers used are lignocellulosic, which are highly hygroscopic and sensitive to the level of humidity in the air [13]. The behavior of the fillers on the melt rheology and uniform dispersion during fused deposition printing is largely affected by the particle size distribution and uniform dispersion of fillers [14]. Moreover, the correct processing windows should be ensured in order to attain consistent extrusion behavior and interlayer bonding. The past studies have indicated that extrusion temperatures of 180 to 210°C coupled with controlled infill techniques can enhance interlayer bonding as well as the surface of printed composite parts [15]. The salient contribution is the fabrication and processing methods for wood dust reinforced PLA filaments for use in FDM printing, developed in this paper. It provides an overview of how drying methods, filler dispersion quality and a number of printing parameters influence the mechanical and thermal performance. It, therefore, consists of published tensile, flexural and impact test results as well as correlations from microstructural work carried out on microscopy. It also categories frequent processing issues (e.g. moisture uptake, nozzle blockage), and offers guidance for research goals that will lead to the advancement of a standardized, sustainable composite filament resin system.

2 Fabrication methods

For the manufacture of wood-dust-reinforced PLA filaments, the raw materials must be well conditioned before the extrusion process: (i) collection, sieving, and drying of wood powder to eliminate any residual moisture responsible for bubble generation, unmelted zones, or an insufficient flow during processing [16]. With the help of suitable curing temperatures and drying conditions, which do not prematurely degrade the lignocellulosic constituents, ensuring even compounding behavior leads to a constant melt flow [17]. PLA granules are mixed with wood dust in controlled weight percentages from 5 to 30% to have predictable mechanical and thermal properties that enable the designing of stiffness, strength, and resiliency based on the application needs [18]. Evenly dispersed fillers, by mechanical stirring or pre-blending before extrusion, are necessary for the stability of composites and help to prevent agglomeration as well as maintain consistent rheological properties of the compounded melt [19]. Particle size (usually less than 200 μm) is a key parameter in additive manufacturing. It increases filament flow, decreases nozzle clogging, and also modulates the resolution of print versus build time on FDM-based systems [20]. The production of the filaments generally starts with melt homogenization for the compound before deformation through a die by single-screw or twin-screw extruders since remarkably higher mixing efficiency and fiber dispersion can be assured by the latter for large (industrial) scale throughput [21]. Although twin-screw devices offer better homogeneity, single-screw extruders are also beneficial for laboratory production and prototype design since they are cost-effective and simple to operate [22]. After extrusion, the filaments undergo controlled cooling, drawing, and spooling procedures aiming at an average diameter of approximately 1.75 mm that is essential to ensure compatibility with commercial FDM printers and to avoid dimensional changes, which might result in disruptive deposition accuracy [23]. A schematic of the FDM printing system and its major components is illustrated in Fig. 1 [24]. Extrusion temperature and screw speed play an important role in the homogeneity of the wires and printability, according to which when it is too high, wood cellulose will be destroyed (browning and lower mechanical strength) with polymer agglomeration due to a larger flow [25]. Therefore, precise control of extrusion conditions, drying time, and filler loading is necessary to achieve consistent filament quality, good processability, and stable mechanical performance in the following FDM 3D printing processes.

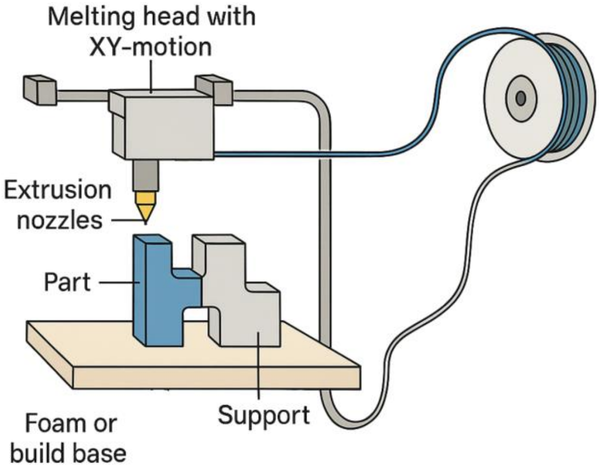

Fig. 1. FDM printer components: melting head, dual nozzles, material spools, and Z-axis build platform.

Table 1: Summary of fabrication methods and processing conditions reported in literature.

Filler Type / Size	**Filler wt. %**	**Extrusion Temp (°C)**	**Screw Type**	**Key Outcome**
Wood/PLA (~150 µm)	10–30	190–210	Single-screw	Uniform dispersion improved strength
Short natural fibres	5–25	180–200	Twin-screw	Better fibre–matrix bonding
Poplar wood flour	15	200	Twin-screw	Enhanced flexibility with modifiers
Natural fibres (mixed)	10–20	185–205	Twin-screw	Improved fibre dispersion and stability
Wood fibre (fine)	20	200	Single-screw	Stable extrusion and smooth surface

3 Process parameters and drying effects

Several processing parameters, such as nozzle temperature, print speed, layer height, and infill percentage, play a transformative role in the quality of printing and mechanical properties in PLA-wood composites processed by FDM [26]. The temperature of the nozzle directly influences the feed of melt and interlayer fusion, whereby too low heat causes poor adhesion and too high volume makes discoloration and thermal degradation by lignocellulosic filler [27]. Extrusion stability is highly influenced by the print velocity; excessively high printing speeds may lead to under-extrusion and incomplete deposition, and low in areas of detail, resulted in under-extruded (porous section) or unfinished parts, while experimental studies for speeds between 40 and 70 mm s^{-1} were reported to provoke smooth continuous deposition [28]. Thickness of a layer also affects the structural strength, fineness of surface finish, and other properties. A thinner layer will allow stronger bonding between layers as well as a smoother surface but may cause longer build times or stress to accumulate inside the finished material [29]. Similarly, infill density needs to be regulated such that low infills can reduce stiffness and energy absorption of additively produced parts [30], whereas high infills lead to increased material use and printing time. The synchronizing of these conditions establishes the effective processing window where continuous material deposition, homogenous bond strength, and a low defect build are observed during printing [31]. Additional consolidation increases and heat are maintained up to a bed of approximately 60°C, without risking degradation of the filler [32]; this generally does occur, reportedly leading to increases in mechanical properties since the material can be extruded if no concentration rises thermally close to consolidation. PLA–

wood matrices may exhibit improved mechanical performance under optimized conditions. In addition, raster orientation and build direction influence fatigue resistance and anisotropy, with optimized patterns leading to a more homogeneous load distribution among the printed geometry [33]. In Figure 2, the nozzle temperature, print speed, and layer height affect the interlayer bonding quality and overall structural integrity of printed parts [34].

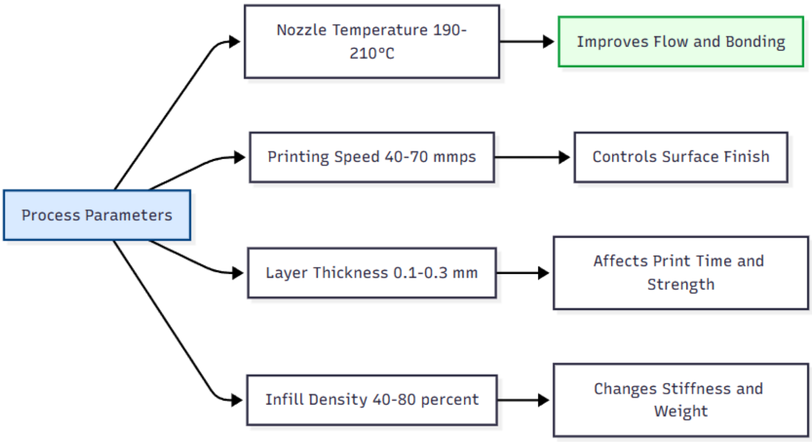

Fig. 2. Influence of process parameters on printed part quality and layer adhesion.

Moisture control is also important because lignocellulosic fillers are characterized by high hygroscopic capacity that will absorb ambient humidity, resulting in a reduction of the dimensional stability and melt processibility during extrusion [35]. Material that has not been vacuum-dried ahead of the manufacturing itself will contain moisture after thermal processing, leading to bubble formation, voids, and non-uniform filament diameter [36]. To avoid moisture-related degradation, drying at 80-90°C for several hours is generally suggested to obtain stable flow performance during melting [37]. High residual moisture content promotes PLA hydrolysis during the melting process, which then reduces the molecular weight and tensile strength of the printed composite [38]. Taking post-extrusion storage with desiccant drying methods and sealed containers into account, a future goal would be to reduce filament integrity and print consistency [39]. The shrinkage behavior, temperature resistance, and dimensional accuracy during cooling are also affected by the environmental humidity changes. The relative humidity less than 40% showed better surface polish and interlayer bonding [40]. Table II summarizes the typical nozzle diameters (ND), speeds, and drying conditions investigated in PLA wood-dust composites.

Table.2. Typical printing parameter ranges used for PLA/wood dust composites

Parameter	Typical Range	Notes / Observations	Reference
Nozzle Temperature (°C)	190–210	Higher temperature improves flow but may degrade wood fibre above 210 °C	[26]
Bed Temperature (°C)	50–65	Reduces warping and improves first-layer adhesion	[27]
Printing Speed (mm/s)	40–70	Lower speeds give smoother surfaces; high speeds risk under-extrusion	[28]
Layer Thickness (mm)	0.1–0.3	Thinner layers improve bonding but increase build time	[29]
Infill Density (%)	40–80	Higher infill increases stiffness and weight	[30]
Drying Temperature (°C)	80–90	Necessary to remove moisture before extrusion	[31]
Drying Duration (h)	3–6	Longer drying reduces bubble and void formation	[32]
Ambient Humidity (%)	< 40	Lower humidity limits moisture absorption and print distortion	[33]
Raster/Build Orientation (°)	0–90	Orientation strongly affects anisotropy and fatigue resistance	[34]
Polymer Moisture Content (%)	0.1–0.5	Moisture accelerates PLA hydrolysis and reduces strength	[35]
Environmental Shrinkage (%)	0.2–1.5	Humidity fluctuations alter dimensional stability and shrinkage	[36]
Storage Conditions (RH %)	10–30	Sealed containers and desiccants maintain filament quality	[37]
Temperature–Flow Interaction (°C window)	190–205	Excess heat degrades cellulose and weakens the composite	[38]
Printability Window (°C / mm/s)	195–205 / 40–60	Stable deposition achieved near 200 °C with ~60 °C bed	[39]
Overall Process Optimization (wt.% filler)	10–20	Moisture–temperature control improves density and reproducibility	[40]

4 Polymers, composites, and testing methods

Polylactic acid (PLA) is a renewable and biodegradable polymer that is widely used in additive manufacturing because it is highly reliable when printing. It is also found that PLA has a high level of dimensional accuracy and predictability in its fused deposition modeling processes [40]. Nevertheless, PLA is inherently brittle and has low impact strength, which is incompatible with structural uses that are demanding. Consequently, wood dust lignocellulosic reinforcement has been mostly researched to enhance sustainability and mechanical responsiveness [41]. Wood particles have cellulose, hemicellulose and lignin which when properly treated can help to facilitate interfacial interactions with PLA [42]. However, the hydrophilic property of wood dust can reduce the adhesion with PLA but enhance interfacial debonding. Modulus has been promoted in similar bio-based systems by the addition of fillers up to 19 wt.% without compromising integrity [43]. The filler dispersion is highly important in composite performance, as agglomeration generates cracks and microcracks, decreasing toughness. Conversely, same-distribution may enhance stress transfer, thermal stability and efficiency of loads transfer, when the same applies [44]. Based on the trends reported, tensile and flexural responses may be enhanced under moderate filler contents of 10 to 20 wt.% but outcomes are inconsistent. Anisotropic FDM characteristics are offered by variation in build orientation, raster angle, infill technique and drying control [45]. The scales, the location of failure, and the quality of dispersion should be all taken into account when defining the representative fracture-surface features in Fig. 3 [46]. Tensile, flexural, and impact tests were conducted according to ASTM D638, ASTM D790, and ASTM D256 standards. are commonly used in mechanical evaluation to measure the strength, stiffness and energy absorption [47]. The flexural responses often rise at intermediate filler loadings, whereas bonding advantages of treatments may be compromised in the impact resistance to reduced ductility [48]. The other crucial factors in determining fatigue performance include anisotropy and void content, with better performance when the dispersion is uniform and the faults are limited [49]. DSC Thermal and TGA characterization usually generate small shifts in Tg and small changes in stability, which depend on the processing and degradation exposure [50]. Consequently, Table III summarizes literature-reported ranges whereas contemplating inter-study variability, and Table IV gives comparison standards. Lastly, the property trends in Fig. 4 are to be interpreted as a combination of explained situations, but not as orientation-independent and universal behavior.

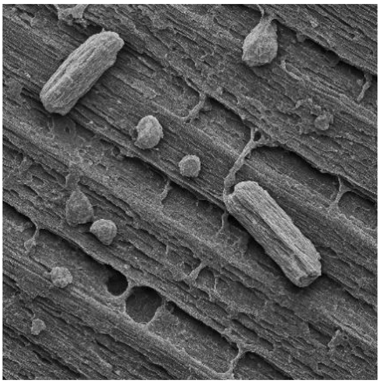

Fig. 3. Microstructural morphology and fracture surface characteristics of wood-dust–reinforced PLA composite after tensile failure.

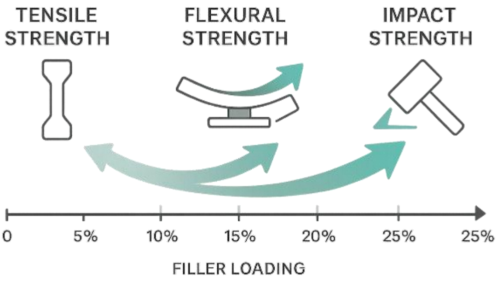

Fig. 4. Influence of filler loading (0–25%) on tensile, flexural, and impact strength performance of PLA–wood dust composite materials.

Table.3. Summary of mechanical and thermal test results

Property / Test	Typical Range / Observation	Key Findings
Tensile Strength (MPa)	45–62	Reported strength varies with loading, orientation, and processing; upper bounds depend on study conditions.
Flexural Strength (MPa)	70–90	Modulus and stiffness improvements are typically reported at moderate loadings under controlled printing conditions.
Impact Strength (kJ/m²)	2.0–3.5	Impact strength often decreases with filler addition due to reduced ductility; coupling agents may mitigate losses.
Fatigue Life (cycles)	10^4–10^5	Fatigue response is reported to improve when dispersion is uniform and void formation is minimized.
DSC – Tg (°C)	58–63	Tg changes are generally small and attributed to restricted chain mobility with filler incorporation.
TGA – Degradation Temp (°C)	310–340	Thermal stability differences are typically modest; excessive thermal exposure can accelerate lignocellulosic degradation.
Density (g/cm³)	1.18–1.25	Density generally increases slightly with filler loading, consistent with particulate reinforcement effects.

Table.4. Comparison of PLA/wood dust composites with other reinforced PLA composites

Reinforcement Type	**Filler wt.%**	**Tensile Strength (MPa)**	**Flexural Modulus (MPa)**	**Key Characteristics**
Wood Dust (Sawdust)	10–20	45–62	2200–2700	Baseline natural filler system; properties sensitive to moisture control and dispersion quality [24,25,26].
Flax Fibre	15	55–68	2400–3000	Higher strength potential; printability and porosity sensitivity reported across studies [9,16,25].
Bamboo Fibre	20	60–70	2500–3200	Improved response reported with appropriate dispersion and processing control [17,25,42].
Sisal Fibre	15	50–65	2300–2800	Energy absorption benefits reported; surface roughness and void sensitivity may increase [16,25,45].
Hemp Fibre	10	52–60	2100–2600	Lightweight reinforcement; properties depend on fibre dispersion and print settings [16,25,32].
Carbon Fibre (comparison)	10	70–80	3000–3500	Included for performance benchmarking; non-biodegradable and sustainability-limiting relative to natural fillers [30,38].
Aluminium Fibre (comparison)	10–15	62–75	2800–3500	Included only as non-natural benchmark; requires explicit scope justification in text [19,38].
Brass Fibre (comparison)	10	55–68	2600–3300	Included only as non-natural benchmark; increases density and metallic surface finish [35,38].
Copper Fibre (comparison)	10	50–65	2400–3200	Included only as non-natural benchmark; increases thermal conductivity but adds mass [47,38].

5 Conclusion

PLA reinforced with wood dust is an emerging eco-friendly filament material that has potential as the material in fused deposition modeling. Reported tests show that 10-20 weight percent filler loadings are acceptable in terms of printability and strength. The need to have a constant filament diameter and flow requires a high level of accuracy in compounding, extrusion conditions and full pre-drying. Interlayer bonding and flaws depend on nozzle temperature, speed of printing, and layer thickness, as well as infill density. Lignocellulosic fillers may take up moisture leading to the formation of bubbles, cavities and nozzle fouling during the printing process. Through thermal characterization, it is common to find small differences in glass transition and degradation behavior after reinforcement. Data obtained with microscopy relates the quality of dispersion and interfacial adhesion to reduction of porosity and fracture morphology. However, the property ranges reported between research are not discontinuous, and the current variability does not allow ranking performance clearly. The systematic experimentation on various particle sizes and loadings with set build orientations should be included in the future studies. Further mechanistic analysis of interactions between processing parameters and filler behavior is required. Figures should show clearly scale bars and failure characteristics backed up by recapable imaging protocols. The environmental claims need to have clear life-cycle limits that clearly show drying and extrusion energy requirements. When the machine learning frameworks are maintained, they must be attested regarding quantifiable monitoring, and control gains. Altogether, wood dust PLA composites will undergo industrial trials and intensive testing in order to be applied practically.

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