Fused Deposition Modelling of Wood-Plastic Composites: Materials, Processes, and Future Directions

Wan Sharuzi Wan Harun[1,2,3,4,*]

[1]Automotive Engineering Centre, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

[2]Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

[3]Department of Mechanical Engineering, Galgotias University, Greater Noida, Uttar Pradesh 203201, India

[4]Department of Mechanical Engineering, Universitas Negeri Jakarta, Jl. Rawamangun Muka, Jakarta 13220, Indonesia

Abstract: Fused Deposition Modelling (FDM) of Wood-Plastic Composites (WPCs) offers a compelling pathway towards sustainable manufacturing. However, the progression from prototyping to functional components is governed by a fundamental conflict: the pursuit of high wood content for sustainability directly opposes the thermo-rheological constraints of the extrusion process. This review critically analyses this conflict, arguing it is the primary source of the two main defects that limit structural applications: severe mechanical anisotropy from weak interlayer adhesion, and multi-scale porosity inherent to both the feedstock and the printing process. By deconstructing the material systems and process-structure-property relationships, this review synthesises current strategies to mitigate these challenges. Ultimately, this review argues that the future of the field depends on a paradigm shift towards intelligent manufacturing, integrating predictive modelling with novel bio-based materials and leveraging the unique properties of WPCs for functionally graded components and environmentally responsive 4D printing.

Keywords: Fused deposition modelling (FDM), Wood-Plastic Composite (WPC), Sustainable manufacturing, Mechanical anisotropy, Process optimisation, 4D Printing.

1. INTRODUCTION

The advent of Additive Manufacturing (AM), a key pillar of the fourth industrial revolution (Industry 4.0), has catalysed a paradigm shift in design and production across a multitude of sectors, including industrial manufacturing, automotive, and aerospace [1-3]. Among the diverse suite of AM technologies, Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF), has emerged as the most ubiquitous and accessible method [4, 1, 5, 6]. Developed by S. Scott Crump in the late 1980s and commercialised by Stratasys, the FDM process involves the layer-by-layer extrusion of a molten thermoplastic filament to construct a three-dimensional object from a digital model [7, 8]. Its widespread adoption is primarily attributed to its operational simplicity, low investment and operating costs, and a progressively expanding portfolio of compatible materials [1, 9].

However, the mechanical performance of parts produced by FDM is often inferior to that of their counterparts manufactured via traditional methods such as injection moulding or subtractive machining [1]. This performance deficit, coupled with a growing global imperative for sustainable manufacturing practices, has spurred intensive research into the development of polymer composites for FDM, aiming to enhance material properties and reduce environmental impact [10-12].

Within the domain of FDM composites, Wood-Plastic Composites (WPCs) represent a particularly compelling class of materials [13, 14, 12]. The incorporation of lignocellulosic fillers—such as wood flour, sawdust, or fibres from industrial forest residues—into a thermoplastic matrix offers a strategic pathway towards more sustainable manufacturing [15-18]. The rationale is multifaceted: wood is a renewable resource, biodegradable, and abundantly available, often as a low-cost waste stream from primary and secondary wood processing industries [19, 20]. By displacing a portion of the petroleum-derived polymer matrix, WPCs can reduce the overall cost and carbon footprint of the feedstock material, aligning with the principles of a circular economy [20, 18]. Furthermore, these composites can provide unique aesthetic qualities and, under certain conditions, improved material properties such as increased stiffness [21-25].

This review posits that while the FDM of WPCs holds significant promise, its maturation is governed by a fundamental tension, as depicted in Figure **1**. This

*Address correspondence to this author at the Automotive Engineering Centre, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia;
E-mail: sharuzi@umpsa.edu.my

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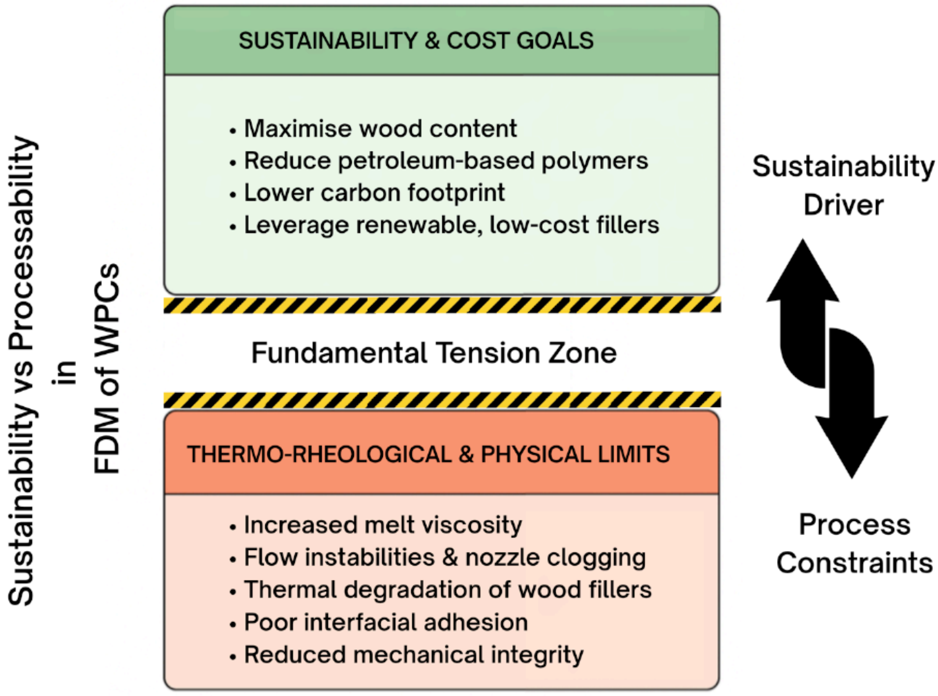

Figure 1: The fundamental conflict between sustainability goals and process constraints in the FDM of WPCs.

Note: The drive to maximise wood content for sustainability and cost-efficiency is fundamentally opposed by the thermo-rheological and physical constraints of the FDM process, leading to increased process difficulty and defect formation. This trade-off is the core challenge addressed by research in the field.

tension exists between the primary driver for using wood fillers—the pursuit of sustainability and cost-efficiency through high filler content—and the intrinsic thermo-rheological constraints of the FDM process, which demand exceptional flowability, thermal stability, and homogeneity in the feedstock. The entire research landscape in this field can be understood as an effort to manage this central conflict. The motivation to maximise wood content [20] is in direct opposition to the physics of FDM, which relies on the precise extrusion of a molten thermoplastic through a micro-scale nozzle [1, 26]. Wood particles are non-melting, thermally sensitive, hygroscopic solids [21]. Their inclusion inevitably increases melt viscosity, introduces flow instabilities, elevates the risk of thermal degradation into obstructive char, and presents a direct physical impediment to flow [27]. Consequently, every incremental increase in wood content introduces a corresponding penalty in processability and, frequently, in the ultimate mechanical integrity of the printed part [27, 28]. This inherent trade-off forms the central challenge that research in filament formulation, process optimisation, and interfacial engineering seeks to resolve. While previous reviews have catalogued materials and process parameters, this work provides a new synthesis by framing the entire research landscape through the lens of this central conflict. I critically analyse how this tension engenders the multi-scale defects—anisotropy and porosity—that currently limit structural applications, thereby offering a cohesive perspective on the field's primary challenges and future trajectory. This review will systematically deconstruct this complex interplay, critically analyse the inherent challenges, and conclude by surveying current applications and charting future research directions.

2. MATERIAL SYSTEMS FOR FDM OF WOOD-PLASTIC COMPOSITES

The performance and processability of WPCs in FDM are dictated by the properties of their constituent materials and, most critically, by the quality of the interface between them. This section dissects the WPC filament, examining the roles of the polymer matrix, the lignocellulosic filler, and the essential coupling agents that bridge the two.

2.1. Polymer Matrix Selection and Rheological Considerations

The polymer matrix serves as the continuous phase that encapsulates the wood filler, providing the necessary melt-flow characteristics for the FDM process and binding the structure together upon cooling.

2.1.1. Dominance of Polylactic Acid (PLA)

The vast majority of research and commercial activity in FDM of WPCs utilises Polylactic Acid (PLA) as the matrix material [19, 22, 6, 29]. The pre-eminence of PLA is due to a confluence of favourable properties. Firstly, it is a biodegradable and bio-based aliphatic polyester, which aligns with the sustainability objectives of using wood fillers [15, 17]. Secondly, and perhaps more importantly from a processing standpoint, PLA possesses a relatively low melting temperature (typically 170-180 °C) and glass transition temperature (around 60 °C) [19, 30]. This low processing window is crucial as it mitigates the risk of thermal degradation of the lignocellulosic components of wood (*e.g.*, hemicellulose, lignin), which can begin to degrade at temperatures approaching 200 °C [21, 31, 18]. Thirdly, PLA exhibits low thermal expansion and shrinkage during cooling, which reduces the propensity for warpage and improves dimensional accuracy, making it highly compatible with the open-format, desktop FDM printers commonly used for these materials [32]. It has also shown promise as a sacrificial template material due to its clean burnout characteristics [33]. While other commodity thermoplastics such as Acrylonitrile Butadiene Styrene (ABS) and Polypropylene (PP) are also explored, they typically require higher processing temperatures, which poses a greater challenge for incorporating thermally sensitive wood fibres [1, 20].

2.1.2. Rheological Impact of Wood Fillers

FDM is a rheologically driven process. The thermoplastic filament must be heated to a semi-molten state where its viscosity is low enough to be extruded through a fine nozzle by the force exerted by the printer's drive mechanism [10]. The introduction of solid, non-melting wood particles into the polymer matrix invariably increases the viscosity of the composite melt [32, 20, 17]. This increase in complex viscosity and storage modulus restricts the mobility of polymer chains and disrupts flow [34, 17]. This requires a greater extrusion force and narrows the viable processing window. The temperature must be high enough to sufficiently lower the viscosity of the polymer matrix to facilitate flow but must remain below the threshold for significant thermal degradation of the wood filler [21, 35]. Interestingly, some studies have found that smaller wood particle sizes can lead to a decrease in the viscosity of the composite, enhancing its flowability [36]. This delicate balance underscores the importance of precise thermal control during both filament extrusion and the 3D printing process itself. An alternative approach involves the use of direct pellet extruders, which can process granulated WPC material directly, bypassing the energy-intensive filament production step and potentially accommodating materials with higher filler content or larger particles that are otherwise difficult to form into a consistent filament [20, 37].

2.2. The Influence of Lignocellulosic Fillers

The wood filler is the defining component of a WPC, and its characteristics—quantity, size, shape, and origin—have a profound impact on the final properties of both the filament and the printed part. Beyond simple wood particles, research is also exploring the use of refined wood components such as cellulose, lignin, tannins, and nanocellulose to create advanced bio-composites [20, 38].

2.2.1. Filler Loading Level

The weight percentage (wt%) of wood filler is a primary design variable that dictates a trade-off between sustainability, cost, and performance. At low loading levels, typically between 5 wt% and 10 wt%, wood particles may act as a mild reinforcing agent, with some studies reporting a slight increase in tensile strength compared to the neat polymer [19, 22]. However, as the wood content increases to higher levels (*e.g.*, 20% to 50 wt%), the mechanical behaviour often changes dramatically [27]. The effect of increasing wood content presents a complex mechanical trade-off. While a consensus exists that tensile strength significantly decreases beyond an optimal point due to poor stress transfer and particle agglomeration [17, 27], the impact on flexural properties is less straightforward. In contrast to tensile behaviour, some studies report an improvement in flexural modulus or strength [23, 39, 40]. This divergence suggests that the dominant failure mechanism is mode-dependent: in tension, failure is initiated by interfacial debonding, whereas in flexure, the composite's bulk stiffness provided by the wood particles plays a more significant role. Concurrently, higher wood content generally leads to a decrease in the density of the composite, which can be advantageous for lightweight designs [27]. However, it also correlates strongly with increased surface roughness and the formation of internal voids, compromising both the aesthetic quality and structural integrity of the printed part [21, 28].

2.2.2. Particle Size and Aspect Ratio

The physical dimensions of the wood particles are of paramount importance, particularly for the reliability of the FDM process. There exists a fundamental contradiction between the principles of reinforcement in traditional, macro-scale composites and the process constraints of FDM. In conventional WPC manufacturing methods like injection moulding, literature suggests that larger particles or fibres can, in some cases, lead to improved mechanical properties due to more effective stress transfer [32]. However, the FDM process is physically constrained by the micro-scale geometry of the nozzle, which typically has a diameter of 0.4 mm [10]. This constraint completely inverts the conventional wisdom regarding particle size.

For FDM of WPCs, larger particles and fibres with high aspect ratios dramatically increase the probability of mechanical bridging and jamming within the narrow extrusion path, leading to intermittent flow or catastrophic nozzle clogging [27, 41]. Research by Beran *et al*. [42] established that for spherical fillers, a stable arch leading to a complete clog only developed if the ratio of nozzle diameter to filler diameter was less than or equal to 6.2. Experimental studies confirm that increasing wood particle size leads to a clear and significant increase in the extrusion force required, and beyond a critical size threshold, renders the composite unprintable [32]. Furthermore, research investigating the link between particle size and tensile properties in FDM-printed WPCs has found no clear correlation, a direct contradiction to findings from macro-scale composites [32, 36].

This leads to a crucial realisation: the optimisation of particle size for FDM-WPCs is not governed by the principles of mechanical reinforcement but is instead dictated by the physical limitations of the process itself. The critical design question is not "What is the optimal particle size for strength?" but rather "What is the largest and most effective particle size that can be reliably processed without causing failure?". This reframes the material design challenge, placing processability as the primary constraint that must be satisfied before mechanical performance can be considered. As a practical guideline, it has been recommended that wood particle sizes should range from one-fifth to one-half of the nozzle diameter to ensure reliable extrusion [32, 36].

2.2.3. Wood Species and Pre-treatment

The source and condition of the lignocellulosic filler also play a significant role. Various wood species, including beech, poplar, pine, aspen, paulownia, and even coconut, have been investigated, each imparting slightly different characteristics to the composite [27, 43]. Beyond the species itself, pre-treatment of the wood particles can significantly enhance the properties of the final composite. Thermal modification, for example, involves heating the wood in a controlled atmosphere to alter its chemical structure. This process can reduce the wood's inherent hygroscopicity (tendency to absorb moisture), which improves dimensional stability and reduces the formation of voids during the high-temperature extrusion process [44, 20]. Studies have shown that filaments made with thermally modified wood particles exhibit better extrusion behaviour, lower surface roughness, and reduced porosity, leading to 3D-printed parts with improved tensile strength compared to those made with non-modified particles [21, 35]. The improved compatibility is visually evident in Figure **2**, which shows enhanced penetration of the polymer into the wood cell structure after thermal modification.

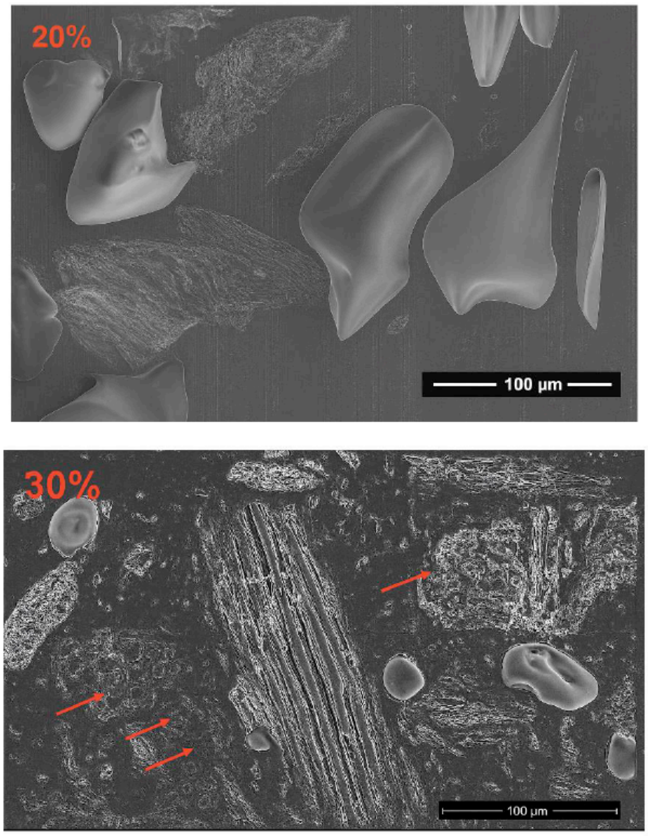

Figure 2: Effect of Thermal Modification on Wood-Polymer Interfacial Bonding.

Note: Scanning electron microscope (SEM) micrographs of filament cross-sections. The above image shows a composite with 20% untreated beech wood, highlighting process-induced voids and poor interfacial contact. The below image shows a composite with 30% thermally modified beech wood; the arrows indicate the significant penetration of the polymer matrix into the wood cell lumens, demonstrating a superior interfacial bond and improved compatibility. This enhanced interface is critical for improving the mechanical properties of the final printed part [35].

2.3. Interfacial Engineering

The performance of any composite material is fundamentally dependent on the quality of the bond between the reinforcement (wood) and the matrix (polymer). In WPCs, achieving a strong interface is a significant chemical challenge.

2.3.1. The Hydrophilic-Hydrophobic Mismatch

The core problem lies in the chemical incompatibility between the two phases. Wood fibres are rich in cellulose and hemicellulose, which contain abundant polar hydroxyl (-OH) groups, making their surface hydrophilic (water-attracting) [45, 46]. In contrast, common thermoplastic matrices like PLA and PP are non-polar, making their surfaces hydrophobic (water-repelling) [47]. This fundamental mismatch results in very poor natural adhesion between the wood and the polymer.

Without intervention, the interface becomes a weak boundary, unable to effectively transfer stress from the flexible polymer matrix to the stiffer wood fibres. This leads to premature failure under load, poor resistance to moisture, and overall inferior mechanical properties. This poor interfacial adhesion is clearly visible in micrograph analysis of fracture surfaces, as shown in Figure **3**, where gaps between the wood particles and the polymer matrix are evident [45, 17].

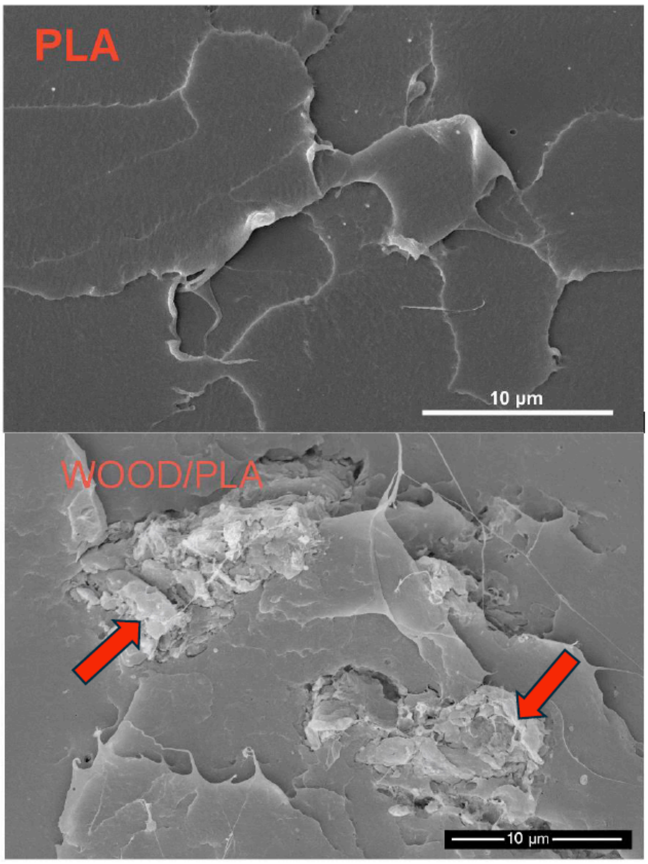

Figure 3: Poor Interfacial Adhesion at the Wood-Polymer Boundary.

Note: A scanning electron microscope (SEM) micrograph of the fracture surface of a wood flour/polylactic acid (WF/PLA) composite. The arrows indicate exposed wood flour particles. Visible gaps and debonding between the wood particles and the PLA matrix. This weak interface acts as a failure point and prevents effective stress transfer, leading to reduced overall strength and toughness in the composite [22].

2.3.2. Mechanism and Application of Coupling Agents

To overcome this incompatibility, coupling agents (or compatibilisers) are introduced into the composite formulation. These are typically bifunctional molecules designed to act as a molecular bridge across the hydrophilic-hydrophobic divide [46, 48]. One functional group on the coupling agent is designed to react with or form strong secondary bonds (*e.g.*, hydrogen bonds) with the hydroxyl groups on the wood surface. The other end of the molecule, often a long polymer chain, is non-polar and is designed to physically entangle with or, in some cases, co-crystallise with the polymer matrix [45]. By creating this robust connection, as illustrated in Figure **4**, the coupling agent facilitates efficient stress transfer, significantly improving the composite's mechanical properties, including tensile and flexural strength [45, 49]. These agents are typically incorporated during the compounding process when the wood and polymer are melt-blended to create the filament feedstock [45]. Recent work by Han *et al*. [50] has demonstrated the efficacy of using glycidyl methacrylate (GMA) grafted onto PLA as a reactive compatibiliser for bagasse cellulose composites, leading to a dramatic increase in toughness and enabling higher filler loading.

2.3.3. Common and Emerging Agent Chemistries

By far the most widely used and effective class of coupling agents for WPCs are maleic anhydride grafted polymers, such as maleic anhydride-grafted polypropylene (MAPP) or maleic anhydride-grafted PLA [45, 46, 48]. The anhydride groups readily react with the wood's hydroxyl groups to form strong ester linkages, while the polymer backbone ensures excellent compatibility with the matrix [45, 49]. Other chemical families, including silanes and isocyanates, are also employed and function through similar principles of forming covalent or strong secondary bonds at the interface [45]. In line with the overarching goal of enhancing sustainability, there is a growing body of research focused on developing effective bio-based and eco-friendly coupling agents and binder systems. Promising research has demonstrated the efficacy of agents derived from natural polymers like chitin and chitosan [47], as well as systems based on natural oils and other engineered biopolymers [51]. The successful development of these green coupling agents is a critical step towards creating fully biodegradable and renewable WPC filaments for FDM.

3. THE PROCESS-STRUCTURE-PROPERTY PARADIGM

In Fused Deposition Modelling, the final properties of a component are not determined by its material composition alone. They are a direct consequence of the internal structure and microstructure created during the layer-by-layer fabrication process. This internal architecture—comprising the orientation of deposited rasters, the bonding between layers, and the distribution of voids—is, in turn, controlled by a complex set of user-defined process parameters [52,

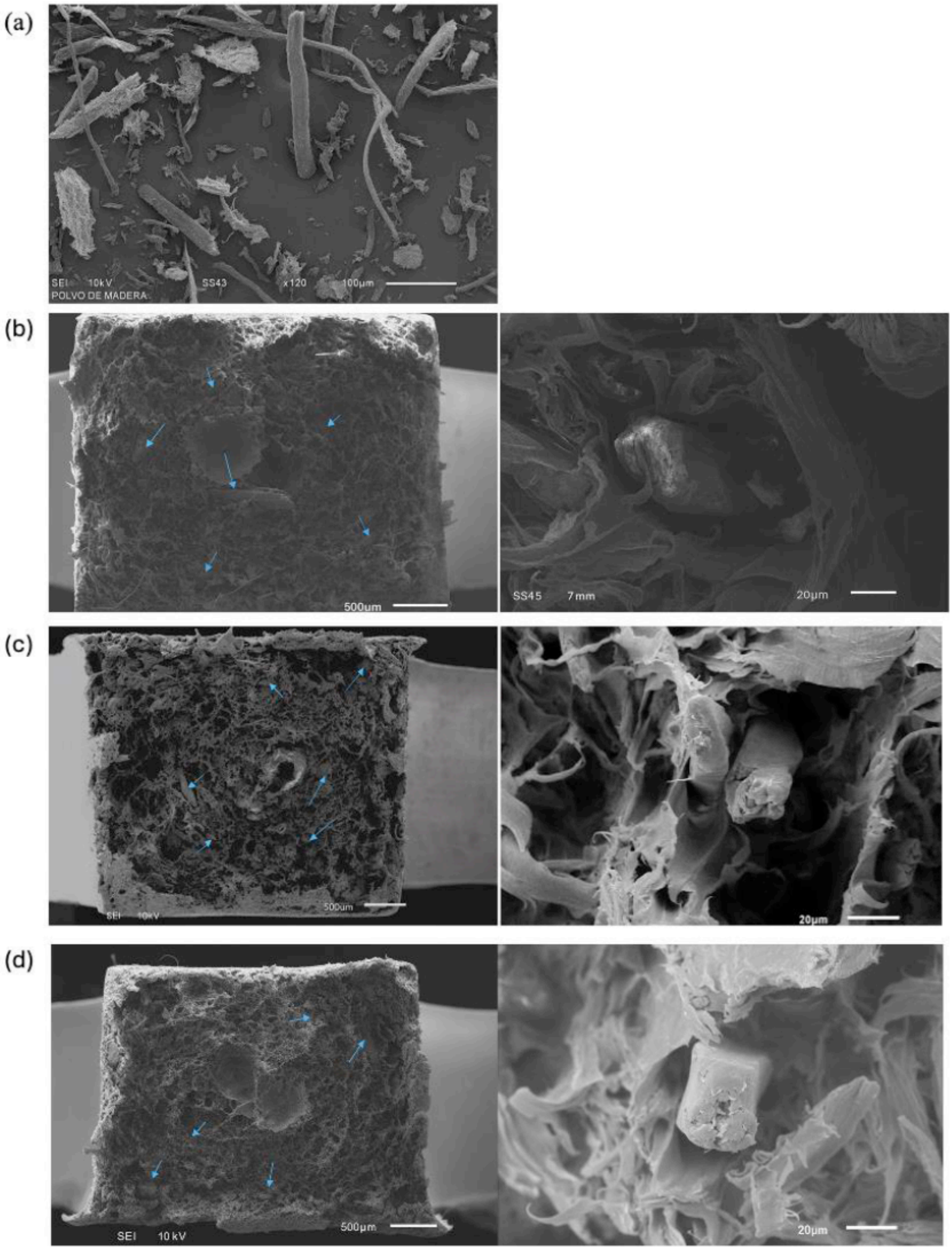

Figure 4: Influence of Coupling Agents on the Fracture Surface Morphology of PP/Wood Flour Composites.

Note: Scanning electron microscope (SEM) micrographs showing (a) wood flour (WF) particles, and the fracture surfaces of polypropylene/wood flour composites made with three different coupling agents: (b) PP/WF-5901, (c) PP/WF-5951, and (d) PP/WF-0218. Note the improved matrix coverage and reduced pull-out in (c) and (d) compared to (b), highlighting the critical role of coupling agent selection in enhancing interfacial adhesion. The significantly improved matrix coverage and reduced fibre pull-out in composites (c) and (d) demonstrate their superior performance compared to agent (b) [49].

53]. Understanding and mastering this process-structure-property relationship is the key to unlocking the full potential of FDM for WPCs. Machine learning is increasingly being used to model these complex relationships and optimise printing processes for both 3D and 4D printed polymer composites [54].

3.1. Optimisation of Core Printing Parameters

The quality, performance, and efficiency of the FDM process are governed by a multitude of adjustable parameters, each with a distinct and often interactive effect on the final part [10, 4]. The most critical of these include nozzle temperature, print bed temperature, printing speed, layer height, and raster (or road) width [10, 55]. The degree of overlap between printed filaments, often controlled by a 'printing width' parameter, also plays a crucial role in determining internal cohesion and final part properties [28]. The optimisation of these parameters is not a straightforward task, as they are highly interdependent.

For instance, the nozzle temperature is perhaps the most critical parameter, as it directly controls the viscosity of the WPC melt. A higher temperature reduces viscosity, promoting better flow and enhancing the thermal diffusion and bonding between successive layers, which is crucial for strength in the vertical (Z) direction [27]. However, for WPCs, an excessively high temperature can lead to the thermal degradation of the wood filler, causing discoloration, charring, and the release of volatile compounds that can create porosity and compromise structural integrity [56, 20]. Indeed, some studies suggest an optimal printing temperature exists, beyond which mechanical properties may decline due to material degradation [30].

Printing speed, the velocity of the extruder head in the X-Y plane, presents another trade-off. Higher speeds are desirable as they reduce the total build time, but they also shorten the time available for the extruded material to melt completely in the hot end and to form a strong thermal bond with the underlying layer [56, 57]. The influence of printing speed reveals a nuanced relationship between thermal history and mechanical performance. The general consensus is that higher speeds are detrimental, as they reduce the time for interlayer thermal fusion, leading to weaker bonds and reduced strength [56, 58]. However, this is not a universal finding. For instance, Yang and Yeh [58] made the contrasting observation that while compressive strength degraded with speed, tensile and flexural properties remained largely unaffected. This discrepancy suggests that for WPCs, the failure mode under tension may be less sensitive to the quality of the interlayer bond than failure under compression. A possible explanation is that tensile failure is dominated by the intrinsic properties of the raster itself, whereas compressive failure is more dependent on the structural stability provided by strong interlayer adhesion.

Layer height (or thickness) is a dominant factor influencing the trade-off between build speed, surface quality, and mechanical strength. Thicker layers (*e.g.*, 0.3 mm) allow for faster printing but result in a more pronounced "stair-stepping" effect on curved or angled surfaces, leading to a rougher finish [10]. Conversely, thinner layers (*e.g.*, 0.1 mm) produce a much smoother surface but significantly increase the print time. Critically, layer height has been shown to have a significant impact on mechanical properties; studies have demonstrated that tensile strength can decrease as layer thickness increases, likely due to changes in the geometry of the bond between layers and the associated stress concentrations [58, 25, 59, 43]. Layer thickness is also a major contributor to the final dimensional accuracy of the printed part [10, 60]. This intricate web of interactions makes the optimisation process a multi-objective challenge where improving one outcome (*e.g.*, speed) often comes at the expense of another (*e.g.*, strength or surface finish). Table **1** provides a consolidated summary of the influence of these key parameters, highlighting the critical trade-offs involved.

3.2. The Internal Architecture

A unique capability of FDM is the ability to fabricate parts that are not fully solid. The process allows for the creation of a solid outer perimeter (or shell) while filling the interior volume with a lower-density structure, defined by the infill density and infill pattern [62]. Infill density, expressed as a percentage, is a powerful tool for resource optimisation. For non-structural or lightly loaded components, using a low infill density (*e.g.*, 25%) can drastically reduce the amount of material consumed, the total print time, and the final weight of the part, with corresponding cost savings [62].

For WPCs, this parameter takes on an additional function: tuning thermal and acoustic properties. A lower infill density results in a structure with a higher volume of trapped air, which is an excellent thermal and acoustic insulator. Research has shown a strong correlation between infill rate and the thermal conductivity and sound absorption of printed WPC parts, allowing for the design of components with tailored insulation and acoustic performance [65, 59].

Beyond density, the geometric infill pattern can be selected to optimise for specific mechanical responses. Common patterns include linear (rectilinear), grid, triangular, and bio-inspired structures like honeycomb or gyroid [62, 66]. Different patterns provide varying levels of support and strength in different directions. For instance, honeycomb and gyroid patterns are known for their high compressive strength and energy absorption capabilities, making them suitable for lightweight core structures or protective components [67-69]. The selection of an appropriate infill pattern, therefore, transforms the interior of a printed part into a designed metamaterial, allowing for performance to be tailored to the specific application.

Table 1: Influence of Key FDM Process Parameters on WPC Part Properties

Parameter	Typical Range (for PLA-Wood)	Primary Influence	Key Finding & Practical Trade-off	References
Nozzle Temperature	180 - 210 °C	Controls melt viscosity and interlayer bonding.	An optimal temperature exists. Below 180°C, viscosity is too high; above 210°C, the wood filler risks thermal degradation (charring), leading to clogs and porosity.	[27, 30, 56]
Printing Speed	40 - 80 mm/s	Determines build time and thermal history for layer fusion.	Speeds above 60 mm/s significantly reduce print time but often result in poor interlayer fusion and weaker parts, especially in the Z-direction.	[58, 57]
Layer Height	0.1 - 0.3 mm	Affects build speed, surface finish, and mechanical strength.	Thicker layers (*e.g.*, 0.3 mm) are much faster but create a rougher finish and can reduce tensile strength due to inferior bond geometry between layers.	[10, 59]
Bed Temperature	50 - 65 °C	Influences first-layer adhesion and mitigates warpage.	Must be set near the polymer's glass transition temperature (approx. 60°C for PLA) to prevent the part from detaching or warping during the print.	[61]
Infill Density	20 - 100%	Controls part weight, material use, and mechanical properties.	Lower density saves material and time, creating lightweight parts with better insulation, but at the cost of significantly reduced overall strength.	[62, 63]
Raster Angle	+/- 45°, 0°/90°	Defines the orientation of filaments, impacting directional strength.	Alternating angles (*e.g.*, +/-45°) is critical for creating quasi-isotropic properties in the XY-plane and managing the material's inherent anisotropy.	[64]
Raster Width	100-120% of nozzle diameter	Determines the overlap between adjacent filaments.	Setting the width slightly larger than the nozzle diameter (a negative 'air gap') is crucial for reducing inter-raster voids and improving part density and strength.	[28]

Note: This table summarises the primary effects and associated trade-offs for nozzle temperature, print speed, layer height, bed temperature, infill density, raster angle, and raster width.

3.3. Advanced Optimisation Methodologies and their Implications

Given the large number of interacting process parameters, a traditional one-factor-at-a-time (OFAT) experimental approach is inefficient and often fails to capture the complex interdependencies that govern the FDM process [53]. To address this, researchers have increasingly adopted more systematic and statistically rigorous methodologies [53]. Techniques such as Design of Experiments (DoE), including full factorial and fractional factorial designs, allow for the simultaneous investigation of multiple parameters and their interactions [70]. The Taguchi method, which uses orthogonal arrays, provides a highly efficient way to study the effect of numerous variables with a minimal number of experimental runs, making it well-suited for screening and optimising FDM parameters [44, 55].

A particularly crucial development is the application of multi-objective optimisation techniques, such as Grey Relational Analysis (GRA) [71, 60]. The FDM process for WPCs is inherently a multi-response problem; the goal is often to simultaneously achieve high strength, excellent dimensional accuracy, low porosity, and a smooth surface finish. A critical finding from studies employing these advanced methods is the demonstrated superiority of multi-parametric optimisation over monoparametric strategies [71, 60]. Research has shown that optimising for a single objective—for example, tuning parameters to achieve the best possible dimensional accuracy—can lead to highly undesirable outcomes in other critical properties, such as an increase in internal porosity [71]. This underscores the fallacy of a singular optimisation approach and highlights the absolute necessity of a holistic strategy that seeks a balanced and satisfactory compromise among all competing performance objectives.

4. OVERCOMING INHERENT CHALLENGES IN FDM OF WPCS

Despite its promise, the application of FDM to wood-plastic composites is fraught with inherent challenges that stem directly from the physics of the layer-by-layer extrusion process and the heterogeneous nature of the material. These challenges—mechanical anisotropy, porosity, nozzle clogging, and warpage—represent fundamental barriers that must be understood and overcome to transition the technology from prototyping to the reliable production of functional parts.

4.1. Mechanical Anisotropy and Interlayer Adhesion

The most significant and well-documented limitation of FDM-produced parts is their mechanical anisotropy [1, 72, 73, 29]. The term refers to the directional dependence of a material's properties. In FDM, parts exhibit their highest strength and stiffness in the direction parallel to the printed rasters (within the X-Y plane) and are substantially weaker in the direction perpendicular to the layers (the Z-axis) [10, 28]. This behaviour is particularly pronounced in the upright build orientation, which consistently yields the poorest mechanical performance [74].

4.1.1. Mechanisms of Anisotropy

This anisotropy is a direct consequence of the manufacturing process. Within a single extruded filament, the polymer chains are continuous, providing intrinsic strength. However, the bond between adjacent layers is formed not from continuous polymer chains but rather through a process of thermal fusion [75, 30]. As a new layer of molten material is deposited onto the previously solidified layer, heat is transferred, causing the surface of the lower layer to re-melt or soften. The polymer chains from the two layers must then diffuse across this interface and entangle before the material cools and solidifies—a process known as neck growth and molecular diffusion [76]. This thermally-driven bond is invariably weaker than the bulk material of the filament itself, creating a plane of weakness at every layer interface [1, 77]. When a tensile load is applied along the Z-axis, it acts to pull these weak interfaces apart, leading to premature failure at a fraction of the material's intrinsic strength [75]. This profound weakness in the build direction, which can be analysed using principles of linear elastic fracture mechanics [78], is the single greatest obstacle to the use of FDM parts in structurally demanding, load-bearing applications [79, 80].

4.1.2. Mitigation Strategies

Mitigating anisotropy primarily involves strategies aimed at improving interlayer adhesion. From a process perspective, this means optimising parameters to maximise the extent of thermal fusion. This typically

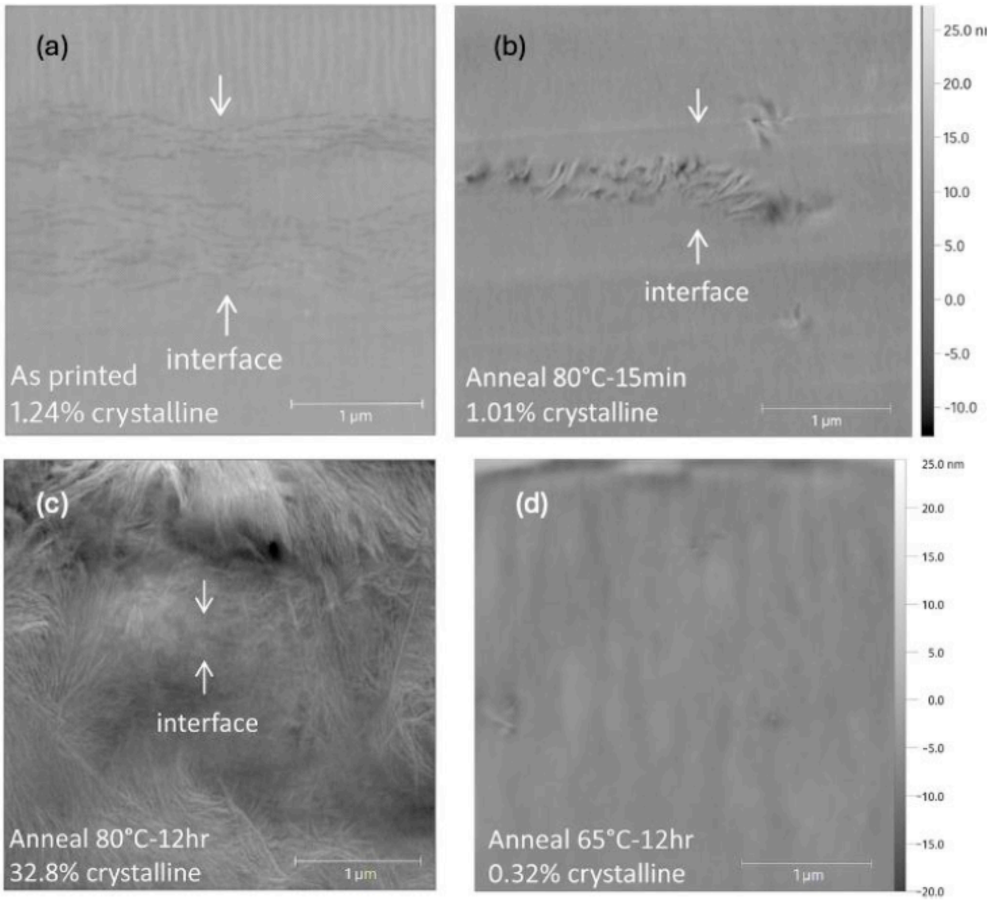

Figure 5: Microscopic view of the interlayer bond in printed PLA after different thermal annealing treatments.

Note: Atomic force microscopy (AFM) images showing the weld regions between printed PLA filaments under different annealing conditions. (a) The as-printed sample shows a distinct interface. (b) After annealing at 80°C for 15 minutes, spherulites (crystalline domains) begin to form. (c) After 12 hours at 80°C, spherulites are widespread, but the original interface remains visible. (d) After 12 hours at 65°C, the interface has "healed" and is no longer discernible, indicating improved interfacial fusion. This demonstrates that lower-temperature annealing for a longer duration can be more effective at healing the weak interlayer bond than high-temperature annealing, which primarily affects bulk crystallinity [83].

involves using a higher nozzle temperature to increase the thermal energy available for re-melting the substrate, and a slower printing speed to allow more time for heat transfer and molecular diffusion to occur [81].

Post-processing techniques, such as thermal annealing (heating the part in an oven after printing), have been investigated as a means to promote further polymer chain mobility and crystallisation across the layer interfaces [82]. However, the results have been mixed. While annealing can increase the overall crystallinity of the polymer matrix, studies using advanced microscopy have shown that this does not necessarily translate to co-crystallisation across the weld interface. As shown by the Atomic Force Microscopy (AFM) images in Figure **5**, the original boundary between layers often remains visible even after extensive high-temperature annealing, suggesting that annealing may strengthen the bulk material of each layer without significantly improving the weak bond between them [82, 83].

4.2. Porosity and Void Formation

Porosity, or the presence of voids within a printed part, is another critical defect inherent to the FDM process. These voids are detrimental to performance, acting as stress concentration sites that initiate cracks and significantly reduce tensile strength, fatigue life, and overall structural integrity [75, 28, 84].

As illustrated in Figure **6**, these pores can exist at multiple scales and locations, each impacting different mechanical properties. The origins of this porosity are multi-scalar, ranging from microscopic voids at the filler-matrix interface to mesoscopic gaps between deposited rasters [85].

4.2.1. The Fundamental Microstructure

A critical and often overlooked source of porosity is that which is inherent to the feedstock filament itself. High-resolution imaging techniques, particularly X-ray micro-tomography (µCT), have revealed that WPC filaments are not perfectly dense solids.

Instead, they contain a significant volume fraction of pre-existing porosity, with voids distributed throughout the polymer matrix, as shown in Figure **7**. This intrinsic porosity originates during the filament extrusion process, where factors such as moisture content in the wood filler, entrapped air, and incomplete polymer melt consolidation contribute to void formation. Liu *et al*. [85] used µCT to characterise a commercial PLA/PHA-wood filament and quantified this inherent porosity at approximately 25% by volume, with an average pore size of 35 µm.

This finding is fundamental to understanding the performance limitations of FDM-WPCs. It establishes that the material entering the 3D printer is already a porous composite foam, not a solid. The FDM process then superimposes its own characteristic mesoscopic voids upon this already-porous microstructure, compounding the problem. This insight reframes the challenge of porosity control: it is not merely a matter of optimising print parameters to minimise inter-raster

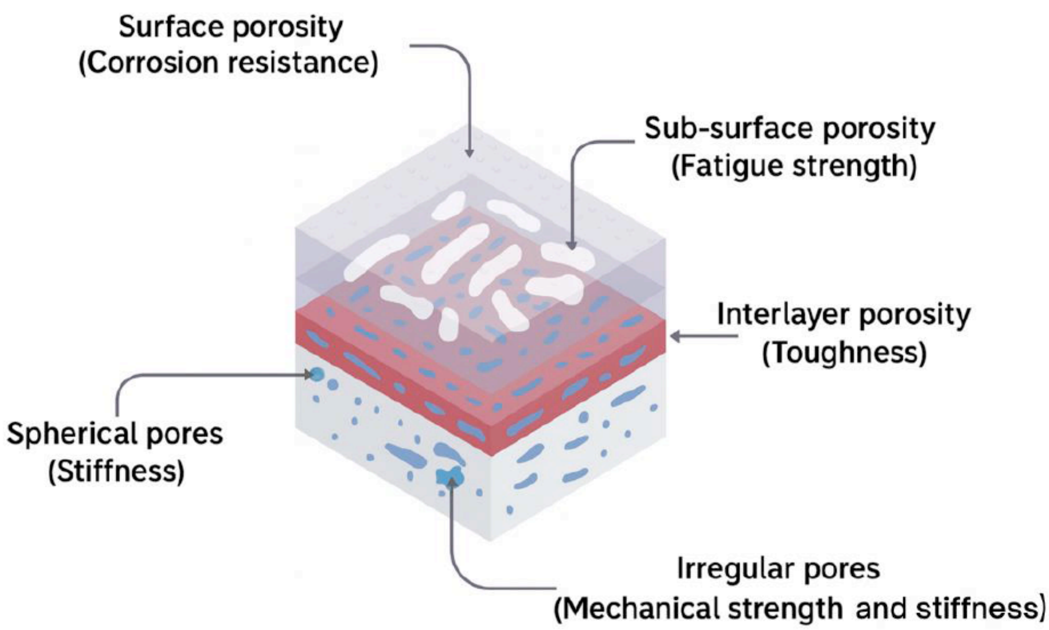

Figure 6: A schematic illustrating the different forms of porosity in FDM parts and their primary effect on mechanical properties.

Note: A schematic representation of the different types and locations of porosity in additively manufactured parts and their primary influence on mechanical properties, including surface, sub-surface, interlayer, spherical, and irregular pores [84].

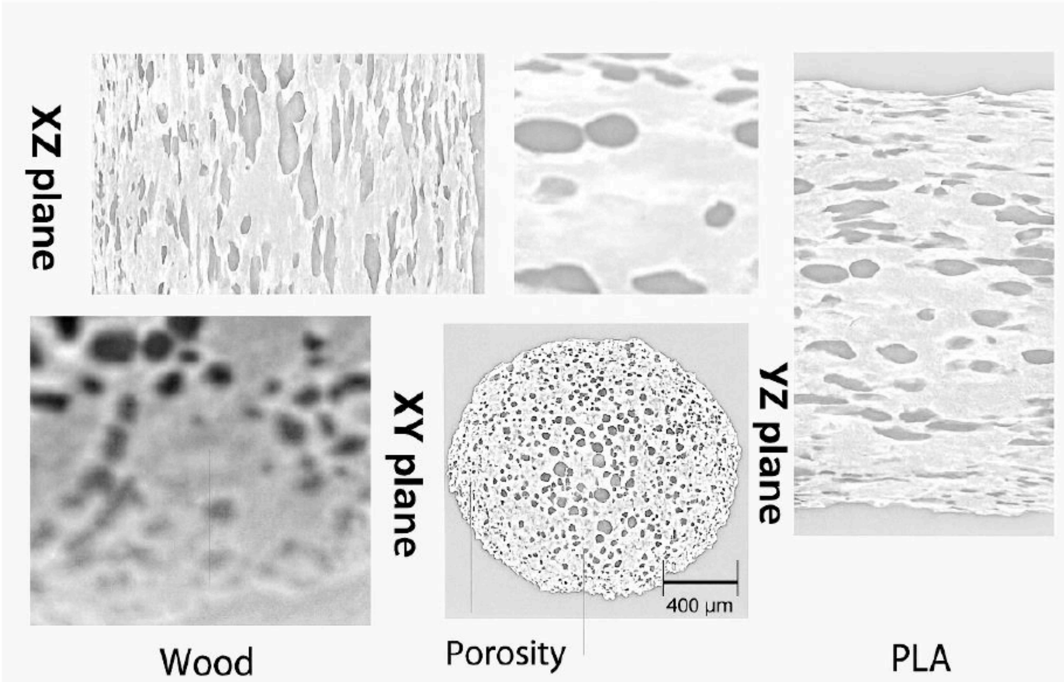

Figure 7: Inherent Porosity within a WPC Filament Revealed by X-ray Micro-tomography.

Note: X-ray micro-tomography (μCT) of a commercial PLA/PHA-wood filament reveals the fundamental microstructure prior to printing. The image clearly shows the polymer matrix (light grey), embedded wood particles (dark grey), and a significant volume of inherent porosity (black voids) distributed throughout the filament. This pre-existing porosity is a critical defect that is carried into the final printed part [85].

gaps, but a multi-scale problem that begins with the quality and density of the feedstock filament.

4.2.2. Origins of Porosity at Multiple Scales

Voids in FDM-WPC parts manifest at multiple scales [84].

I. Macroscopic Voids

These are intentionally created as part of the infill strategy. A part printed with less than 100% infill will have a designed, porous internal structure ([86]). While beneficial for reducing weight and material, this macro-porosity defines the part's bulk mechanical properties.

II. Mesoscopic Voids

These are unintentional gaps that form between adjacent rasters (intra-bead) and between successive layers (inter-bead) ([84]). They arise from the imperfect packing of the roughly cylindrical extruded filaments. The size and prevalence of these voids are highly dependent on process parameters such as layer height, raster width, and the air gap setting in the slicing software ([62]).

III. Microscopic Voids

These are specific to composite materials and can form at the interface between the wood filler and the polymer matrix. They can be caused by poor interfacial adhesion where the polymer fails to completely wet the wood particle, or by the volatilisation of moisture absorbed by the hydrophilic wood fibres during the high-temperature extrusion process [27, 30]. As established, they can also be an inherent characteristic of the filament manufacturing process itself [85, 28]. Figure **8** visually demonstrates how increasing wood content can exacerbate the formation of these interfacial voids.

4.2.3. Control and Mitigation

A comprehensive strategy to control porosity must address all its potential sources. The elimination of microscopic voids begins with material preparation: the WPC filament or its constituent materials must be thoroughly dried prior to printing to remove absorbed moisture [81]. The use of effective coupling agents is also critical to promote strong interfacial adhesion and prevent debonding at the wood-polymer boundary [45, 50]. The reduction of mesoscopic voids is primarily a matter of process optimisation. Fine-tuning parameters such as the extrusion multiplier (flow rate) and ensuring a slight negative air gap (forcing rasters to overlap) can help to pack the filaments more tightly and minimise the gaps between them [62]. Non-destructive evaluation techniques like X-ray micro-computed tomography (μCT) are invaluable for characterising and quantifying the internal void structure, providing crucial feedback for process optimisation efforts [82, 85].

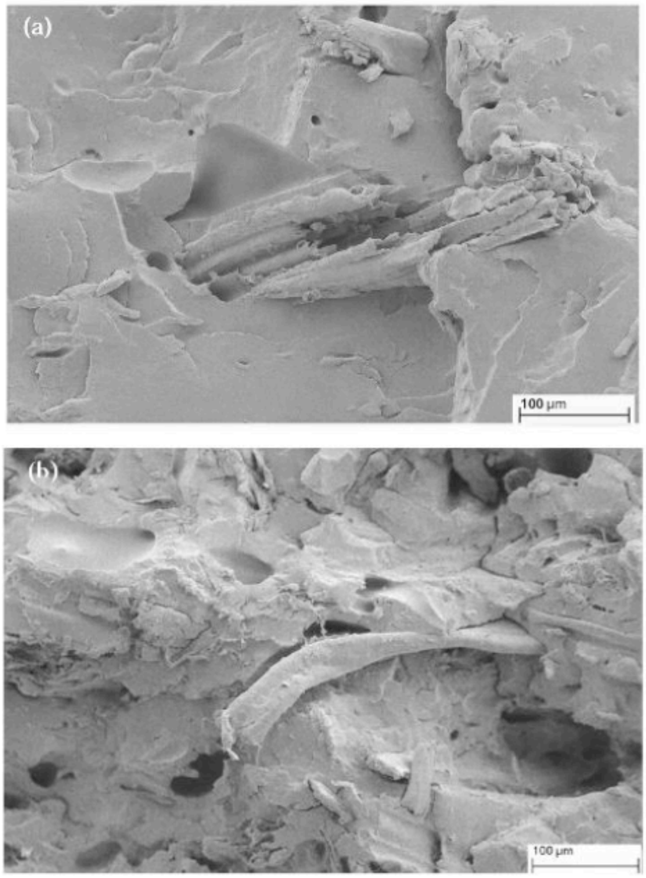

Figure 8: Effect of Wood Content on Interfacial Void Formation.

Note: Scanning electron microscope (SEM) images of the cross-sections of wood/PLA composite samples. (a) At 5% wood sawdust content, the filler is well-encapsulated by the polymer matrix with a largely void-free structure. (b) At 20% wood sawdust content, voids become apparent between the wood particles and the PLA matrix, indicating poorer interfacial adhesion and increased porosity at higher filler loadings. This is because at higher wood content, there is insufficient polymer matrix to fully wet out and encapsulate each particle, leading to the formation of voids at the interface [23].

4.3. Nozzle Clogging

Nozzle clogging is a catastrophic process failure that results in the complete cessation of material extrusion, ruining the print and requiring manual intervention. For WPCs, it is a particularly prevalent and challenging issue that represents a fundamental barrier to process reliability and automation ([41]). Clogging in WPC printing is not a single phenomenon but rather the result of several interconnected failure mechanisms:

I. Mechanical Jamming

This is the most direct cause, occurring when wood particles, either individually or as an agglomerate, are too large to pass through the nozzle orifice. This risk is exacerbated by a wide particle size distribution in the feedstock or poor dispersion of particles within the filament [27]. The physics of this process involves the formation of a stable "arch" of particles at the nozzle inlet [42].

II. Heat Creep

This failure mode, colloquially known as 'heat creep,' occurs when the thermal gradient across the extruder's transition zone is insufficient. Excessive heat conduction from the heater block prematurely softens the incoming filament above the melt zone, causing it to swell, buckle, and jam the feed path [87].

III. Thermal Degradation

If the nozzle temperature is too high or the material resides in the hot end for too long (*e.g.*, during slow printing), the wood component can thermally degrade, forming particles of char. This char is non-melting and can accumulate within the nozzle, eventually causing a blockage [88, 20].

IV. Rheological Failure

As filler content increases, the melt viscosity of the WPC rises sharply. If the viscosity becomes too high, the force required to push the material through the nozzle may exceed the maximum torque of the extruder's stepper motor, causing the drive gear to strip the filament instead of feeding it, effectively halting extrusion [42].

Preventing nozzle clogging requires a holistic approach encompassing material quality control, hardware selection, and process optimisation. Strict control over the wood particle size distribution and ensuring the maximum particle size is significantly smaller than the nozzle diameter is the most critical preventative measure [27]. Thorough drying of the filament is essential [87]. From a hardware perspective, using a larger nozzle diameter (*e.g.*, 0.6 mm) and ensuring efficient cooling are vital [87]. Finally, process parameters must be carefully optimised [88]. Advanced computational fluid dynamics (CFD) models are also being developed to simulate and predict clogging behaviour [89-91].

4.4. Thermomechanical Behaviour

The FDM process is inherently a thermomechanical one. As each extruded raster cools and solidifies, it undergoes thermal contraction. Because this newly deposited layer is bonded to the cooler, already-solidified layers beneath it, this contraction is constrained. This constraint leads to the build-up of internal tensile residual stresses in the cooling material [24, 92]. Non-uniform cooling rates lead to a differential distribution of these stresses. When the cumulative force of these internal stresses exceeds the part's structural stiffness or its adhesion to the build plate, it results in macroscopic deformation, most commonly manifesting as warpage [61, 24]. The presence of wood filler, with its different coefficient of thermal expansion and thermal conductivity, adds another layer of complexity, influencing the magnitude and distribution of these stresses [93].

Predictive computational modelling, particularly Finite Element Analysis (FEA), has become an essential tool for simulating the FDM process, predicting temperature fields, residual stresses, and the final deformed shape of the part [24, 61, 66, 94, 95, 64]. This powerful *in silico* approach allows for the virtual optimisation of printing strategies to minimise warpage [96, 92, 91]. Practical mitigation strategies include using a heated build plate [10], ensuring strong first-layer adhesion, optimising the print path [96, 64], and using an enclosure to maintain a high ambient temperature [24]. A summary of the key challenges and their respective mitigation strategies is provided in Table **2**.

5. APPLICATIONS, CHARACTERISATION, AND FUTURE HORIZONS

The practical utility of FDM-printed WPCs is ultimately determined by their final properties and performance. This section evaluates the current and potential applications of these materials, discusses the advanced techniques required for their thorough characterisation, and explores the transformative research frontiers that will shape the future of the field.

5.1. Advanced Morphological and Performance Characterisation

A comprehensive understanding of the link between processing, structure, and properties in FDM-WPCs requires a suite of advanced characterisation techniques.

I. Morphological and Microstructural Analysis

Scanning Electron Microscopy (SEM) is an indispensable tool for visualising the microstructure, examining fracture surfaces to assess the wood-polymer interface, identifying failure modes, and analysing voids [27, 98, 17]. For a non-destructive, three-dimensional view of the internal structure, X-ray micro-computed tomography (µCT) is exceptionally powerful, allowing for precise quantification of porosity

Table 2: Summary of Challenges and Recommended Mitigation Strategies in FDM of WPCs

Challenge	Primary Mechanisms	Key Finding & Recommended Mitigation Strategies	References
Mechanical Anisotropy	Weak thermal fusion between layers creates planes of weakness. The bond between layers is far weaker than the filament itself.	**Finding** Parts are always weakest along the build (Z) axis. **Strategy** Orient parts so that critical loads are aligned with the stronger XY-plane. Use higher nozzle temperatures and slower print speeds to maximise layer fusion.	[75, 74, 83, 73, 78]
Porosity / Voids	- Inherent porosity within the feedstock filament. - Moisture in wood turning to steam. - Imperfect packing of rasters.	**Finding** A significant volume of porosity can exist in the filament *before* printing, which is a primary source of weakness. **Strategy** 1) Thoroughly dry all filament before use. 2) Use effective coupling agents to ensure good interfacial bonding. 3) Optimise slicer settings (*e.g.*, extrusion multiplier) for tight packing.	[27, 30, 84, 85]
Nozzle Clogging	- Mechanical jamming by oversized wood particles. - Thermal degradation (charring) of wood. - "Heat creep" prematurely softening the filament.	**Finding** The most common cause of failure is wood particles being too large for the nozzle. **Strategy** 1) Ensure the maximum particle size is significantly smaller than the nozzle diameter (*e.g.*, < 1/3). 2) Use a larger nozzle (>0.5 mm) for better reliability. 3) Ensure efficient extruder cooling to prevent heat creep.	[88, 42]
Warpage / Residual Stress	Constrained thermal contraction of cooling layers builds up internal stresses, causing deformation.	**Finding** Warpage is caused by non-uniform cooling. **Strategy** Maintain a stable, high-temperature environment using a heated build plate and an enclosed build chamber. Ensure strong first-layer adhesion using a brim or raft.	[61, 97, 24, 95]

Note: This table outlines the primary mechanisms and mitigation approaches for mechanical anisotropy, porosity/voids, nozzle clogging, and warpage/residual stress.

[82, 85]. Atomic Force Microscopy (AFM) offers even higher resolution for visualising morphology at the weld interface between printed filaments [82, 83].

II. Thermomechanical and Performance Analysis

Thermal properties are evaluated using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) to determine thermal stability and key transition temperatures [19, 17]. Dynamic Mechanical Analysis (DMA) probes the viscoelastic properties (storage modulus, loss modulus), providing insights into stiffness and damping capabilities [63]. Standardised mechanical tests (tensile, flexural, compression) are essential, and it is imperative that these tests are conducted on specimens printed in multiple build orientations to quantify the degree of mechanical anisotropy [44, 29, 39].

5.2. Current and Emerging Applications

The current applications of FDM-printed WPCs are primarily in areas where geometric complexity, customisation, and aesthetics take precedence over high mechanical load-bearing capacity. The furniture and design industries, for instance, have been early adopters. Specific examples include the rapid prototyping of ergonomic designs, the creation of non-structural but intricate custom connectors for bespoke furniture assembly, and the production of one-off decorative pieces with wood-like textures [20, 99, 100]. A particularly strong example of its application is in sustainable design, where the technology is being used for the upcycling of discarded furniture by printing new, functional components directly onto old pieces [101]. Similarly, in architecture, the technology is used for creating detailed scale models and non-load-bearing decorative elements, such as custom facade panels or interior fittings [99, 102].

In the automotive sector, the focus is on rapid prototyping and manufacturing aids. WPCs are used to fabricate prototypes for interior components like dashboard panels and door trims, allowing for quick design iteration. They are also used to create lightweight, custom jigs and fixtures for use on assembly lines, where their low cost and rapid production are highly advantageous [7, 13].

More advanced functional applications are also emerging. For example, the ability to control the internal architecture allows for the fabrication of architected panels with tailored acoustic properties. Citing specific data to support this claim, studies have demonstrated that by optimising the infill pattern, these WPC panels can achieve significant sound absorption coefficients in targeted frequency ranges, making them suitable for noise-dampening applications [59]. Another innovative use is in lightweight sandwich structures with 3D-printed honeycomb cores, which offer high compressive strength for their weight [69].

The primary factor limiting use in more demanding, structural applications is their inferior and less predictable mechanical performance compared to parts made by conventional techniques [1]. The inherent defects of anisotropy and porosity lead to lower strength and reduced reliability, which are unacceptable for critical components [28, 84].

5.3. The Next Frontier

The future evolution of FDM for WPCs will be driven by advancements that transcend the limitations of current materials and processes, moving towards intelligent design and functional integration.

5.3.1. Computational Modelling and Simulation

The ultimate goal is to create a "digital twin" of the FDM process [103, 61]. Such models will integrate CFD to simulate melt flow and fibre orientation with thermomechanical analysis to predict heat transfer, residual stress evolution, void formation, and warpage [93, 104, 105, 91]. An important advancement is the use of µCT scans of actual printed parts to generate highly accurate FEA models that capture real-world manufacturing defects, leading to much more realistic performance predictions [85]. This comprehensive *in silico* approach, augmented by machine learning [54, 106], will enable virtual optimisation, reducing trial-and-error experimentation and paving the way for certified, high-reliability parts [103, 29].

5.3.2. Multi-Material and 4D Printing

The capability to print with multiple materials opens a vast design space for functionally graded materials [107, 108]. This could mean printing a rigid WPC frame integrated with a flexible thermoplastic elastomer hinge, or creating sandwich structures with strong WPC skins and a lightweight foam core [26, 37]. Perhaps the most revolutionary frontier is *4D printing*, where time is introduced as the fourth dimension [108, 57]. This paradigm leverages the hygroscopic nature of wood—its tendency to swell and shrink with moisture—as a mechanism for actuation [109, 20]. By strategically printing hygroscopic WPC alongside a passive polymer, a flat 2D sheet can be programmed to autonomously transform into a complex 3D shape when exposed to humidity [109, 28]. This allows for the creation of smart, environmentally responsive systems, such as adaptive building facades, self-assembling furniture, or soft robotics [20, 110].

5.3.3. Biomimicry and Advanced Structures

A further frontier lies in biomimicry, where the complex, hierarchical structures of natural wood are replicated through AM to create novel materials with optimised weight-to-strength ratios [20]. By using micro-computed tomography to scan and then 3D print wood's cellular architecture, researchers can design lightweight, high-performance cellular composites inspired by nature. This approach moves beyond simply using wood as a filler and instead uses its structural principles as a blueprint for superior material design [20].

5.3.4. Sustainability and the Circular Economy Perspective

While WPCs are positioned as an environmentally friendly material class, a rigorous and holistic sustainability assessment is required. A comprehensive Life Cycle Assessment (LCA) is necessary to quantify the true environmental impact, considering the entire product lifecycle from raw materials and printer energy consumption to the end-of-life scenario [21, 20]. FDM with WPCs aligns well with a circular economy, as the technology is uniquely suited to utilising recycled polymer feedstocks and waste wood streams [107]. The use of waste from the furniture industry as a feedstock for new filaments has been demonstrated, highlighting a direct path for upcycling [20, 18]. Closing this material loop is the final step towards establishing FDM of WPCs as a truly sustainable and circular manufacturing technology.

CONCLUSION

This review has framed the Fused Deposition Modelling of Wood-Plastic Composites around a core conflict: the push for sustainability through high wood content is fundamentally opposed by the physical constraints of the FDM process. This tension manifests as the key defects—mechanical anisotropy and multi-scale porosity—that currently limit the use of WPCs to non-structural applications. For the field to advance, progress must be made on three interconnected fronts. First is the development of advanced bio-based material systems that enhance both processability and interlayer adhesion. Second is the integration of predictive computational modelling to transform FDM into an intelligent and reliable manufacturing process. The final, and most crucial, is a shift in design philosophy away from simply replicating isotropic parts and towards exploiting the unique capabilities of the technology. By embracing functionally graded materials, biomimetic structures, and environmentally responsive 4D printing, the field can deliver on its promise of a new generation of sustainable, customised, and high-performance functional components.

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DECLARATION OF COMPETING INTERESTS

The author declares no competing interests.

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