JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2021;15:241–255

Available online at www.sciencedirect.com

jmr&t
Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Review Article

A review on wood powders in 3D printing: processes, properties and potential applications

Atanu Kumar Das*, David A. Agar, Magnus Rudolfsson, Sylvia H. Larsson

Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, SE 901 83, Umeå, Sweden

ARTICLE INFO

Article history:
Received 29 March 2021
Accepted 24 July 2021
Available online 10 August 2021

Keywords:
Additive manufacturing
Formative methods
Wood powders
Filament
3D object properties

ABSTRACT

Three-dimensional (3D) printing is a technology that, for a multitude of raw materials, can be used in the production of complex structures. Many of the materials that currently dominate 3D printing (e.g. titanium, steel, plastics, and concrete) have issues with high costs and environmental sustainability. Wood powder is a widely available and renewable lignocellulosic material that, when used as a fibre component, can reduce the cost of 3D printed products. Wood powder in combination with synthetic or natural binders has potential for producing a wide variety of products and for prototyping. The use of natural binders along with wood powder can then enable more sustainable 3D printed products. However, 3D printing is an emerging technology in many applications and more research is needed. This review aims to provide insight into wood powder as a component in 3D printing, properties of resulting products, and the potential for future applications.

1. Introduction

Interest in 3D printing is on the rise in several fields [1–3]. Three-dimensional (3D) printing technology, also known as additive manufacturing (AM), is defined as "the manufacturing of solid objects by the deposition of layers of material (such as plastic) in accordance with specifications that are stored and displayed in electronic form as a digital model" [4]. This layer-by-layer manufacturing technology is entirely different from traditional (e.g. formative, joining and subtractive) methods [5–7] and provides opportunities to produce low cost customised products [8,9] with efficient raw material utilisation [2]. A wide variety of materials can be used in 3D printing [10–12]. Examples of commonly used polymers are polyvinyl alcohol (PVAc), polyamide, polylactic acid (PLA), and acrylonitrile butadiene styrene (ABS) [2,13,14]. Inorganic materials include metals such as titanium, stainless steel, silver, and gold, as well as gypsum, ceramics, sand and concrete [15]. The use of expensive materials, such as ultra violet (UV) curing resins and environmentally hazardous synthetic compounds, however, have limited the proliferation of 3D printing [13].

Wood is a natural abundant renewable lignocellulosic material, and the use of woody biomass in 3D printing increases the attractiveness of the technology from a sustainable development perspective [16,17]. Biomass, in combination with plastic and gypsum [15], biopolymer [18] and multifunctional nanocomposites [19], can help to mitigate the high cost and carbon footprint of 3D printed objects [11,13,20,21]. In addition, uses of wood in 3D printing can print environmentally friendly parts [22]. To use wood as a

* Corresponding author.
E-mail address: atanu.kumar.das@slu.se (A.K. Das).
https://doi.org/10.1016/j.jmrt.2021.07.110

component in 3D printing, it must be milled to a fine powder [23,24]. It is then mixed with a binder (e.g. adhesives, plastics, gypsum, cellulose, cement and sodium silicate) to make a filament [13,15]. Filaments are used in the printing operation through various techniques. Complex forms, containers, supports and moulds, for example, can be fabricated in this way [13]. Mixture of wood powder and binder can be used to print 3D objects as well. An overview of the path from tree to wood powder based 3D printed objects is depicted in Fig. 1.

3D printing is fast-growing technology, which is literally bringing new dimensions and applications to many different fields. It is an attractive technology also for wood-based industries because they have access to the needed raw materials.

This review aims to provide an overview of the potential of wood powders in 3D printing. It focuses on the properties of wood powders and 3D printed objects, the procedures used in manufacturing and the challenges faced in development.

2. 3D printing techniques and technologies

3D printing is a type of computer aided design (CAD) or computer aided manufacturing (CAM) because it is possible to produce physical objects with digital designs via a computer [25]. A topological optimisation approach can be used to design components for 3D printing [10]. 3D scanning of an object can be carried out or unique designs can be made or configured with a computer. The design is then converted to a stereolithography (STL) or additive manufacturing file (AMF) type. The important design features, such as dimensions, colour, material type, are included in the files. The file is then transferred to the 3D printer to print the object according to the printing process. Upon completion, the object is removed from the device and post-processing is required. It may include treatments (e.g. chemical or thermal) and machining to obtain the final product.

There are currently seven types of 3D printing technologies but only those relevant to wood powder use in previous investigations are presented. These include material extrusion, powder bed fusion, material jetting and binder jetting technologies which are described in Fig. 2. Based on existing literature, the advantages and disadvantages of the technologies have been tabulated in Table 1.

2.1. Material extrusion

Material extrusion technology is a commonly used in hobby and domestic 3D printers [26]. This technique uses the material in spool form. Upon deposition of each new printed layer, the nozzle moves in one plane (e.g. horizontally) while the platform moves in another (e.g. vertically). Deposition occurs in a continuous stream by a nozzle under constant pressure. The material is melted in the liquefaction chamber prior to entering the nozzle. Layer is deposited sequentially up to the completion of the object. Material melting enhances fusion to make a bond between layers [25]. The layer thickness is in the range of 178–356 μm [27].

2.2. Powder bed fusion

The powder bed fusion printing uses direct metal laser sintering (DMLS), electron beam melting (EBM), selective heat sintering (SHS), selective laser melting (SLM) and selective

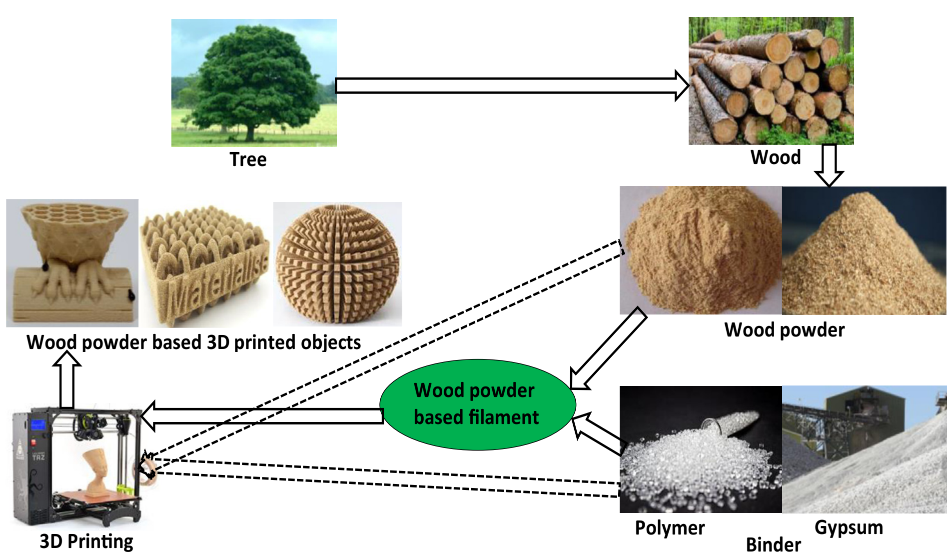


Fig. 1 – The path from tree to 3D printed object (Source of images: Tree (http://clipart-library.com/clipart/Bigrqp8rT.htm), Wood (https://kalingatv.com/state/illegal-saw-mill-raided-in-sambalpur-huge-cache-of-wood-seized/), Wood powder (https://www.indiamart.com/proddetail/wood-powder-14851372748.html), Polymer (https://www.shutterstock.com/image-photo/plastic-granules-polymer-pellets-isolated-on-1191886450), Gypsum (https://www.gettyimages.com/detail/photo/gypsum-plant-royalty-free-image/172515235?adppopup=true), 3D Printing (https://www.3dbeginners.com/lulzbot-taz-6-review/), Wood powder based 3D printed objects (https://www.globalsources.com/gsol/I/Interior-engineered/a/9000000137307.htm, https://i.materialise.com/blog/en/3d-printed-wood-is-coming-to-i-materialise/)).

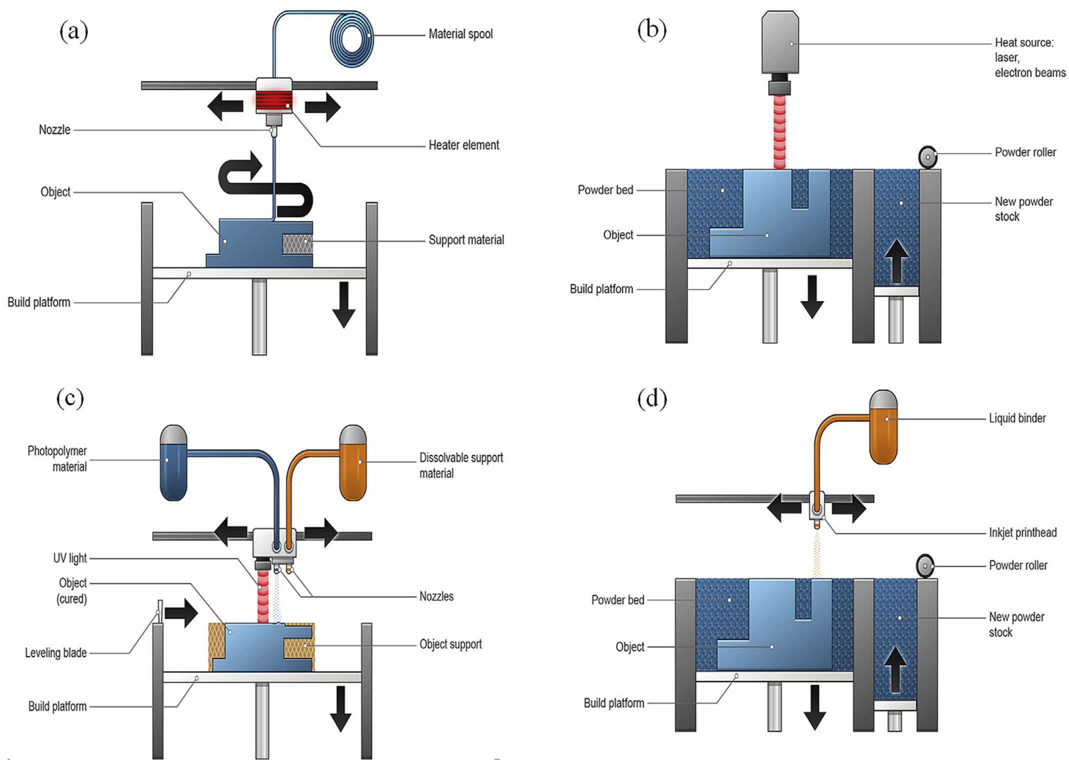


Fig. 2 – Schematic diagrams of the different 3D printing technologies: a) material extrusion, b) powder bed fusion c) material jetting and d) binder jetting [26,28].

laser sintering (SLS) to fuse together layers of material powder [25]. The powder layer of 100 μm thickness is placed on the build platform. A laser is used to fuse the top or cross section of the first powder layer and consecutive powder layers are spread on the first by a powder roller. Each new layer or cross section is fused by the electron beam or laser. Upon completion, the unfused powders are removed in a post curing process [26].

2.3. *Material jetting*

Material jetting is similar to two-dimensional ink jet printing. Material is deposited by a nozzle on a surface using a drop on demand (DOD) or continuous process [25]. The nozzle moves in a horizontal plane across the surface. A thermal or piezoelectric process is used to deposit the material whose layers are cured using UV light. The unused droplets are circulated

Table 1 – Advantages and disadvantages of existing 3D printing technologies [25–32].

Printing technology	Advantages	Disadvantages
Material extrusion	• Inexpensive and widespread technique • Allows use of ABS plastic to improve structural properties	• Constant pressure needed to maintain quality • Slow and less accurate compared to other techniques • Limited nozzle diameter limits resolution of printed object
Powder bed fusion	• Applicable for a wide range of materials • Inexpensive and SHS can be used in small scale • Powders work as integrated support structure • Useful for visual models and prototyping	• Comparatively slow, especially for SHS • Limited in size • High powder consumption • Powder particle size determines finished resolution
Material jetting	• Highly accurate printing • Less loss of material • Allows different materials and colours in same process • Inexpensive	• Limited material types i.e., polymer, waxes • Requires supporting material for most designs
Binder jetting	• Several materials possible i.e., metal, polymers and ceramics • Wide range of colours • Comparatively fast process • Range of different powder and binding agent blends for achieving different mechanical properties	• Time consuming • Requires extra post curing process • Binding material can't allow for structural parts for all the time

back to the printing system. A sodium hydroxide (NaOH) solution or a water jet is used to remove the object from the supporting material [26].

2.4. *Binder jetting*

The binder jetting technique utilises powder based material and a liquid binding agent, which acts as an adhesive between powder layers. A powder roller spreads the powder on a build platform and the print head, which moves horizontally through the X–Y plane, depositing the binding agent on the powder. The build object is lowered progressively according to the deposited layer thickness and the object is formed in the area where binding agent is placed. Layers are spread consecutively. The excess powder remains around the object. A post curing process is required to provide better structural and mechanical properties [25]. The process can be accelerated by heating the built chamber which improves material viscosity [27].

Printing technologies use different types of raw material, i.e., wood-based filaments or mixer of wood powder and binding agent for 3D printing. Filaments are made by combining the wood powder with a binder and, after mixing, the material is extruded to form a filament.

A flow diagram of the wood powder based 3D printing process is presented in Fig. 3.

3. Wood powder use in 3D printing

Finely milled wood having particles similar in grain is referred to as wood powder [33]. In practice, a more precise definition of wood powder is wood particles passing through a 850 μm screen size (US standard mesh size of 20) [34]. Many researchers have gone beyond these definitions and classified biomass and other particles more concisely [35,36]. Wood is one of many lignocellulosic materials and Barakat et al. [37] and Mayer-Laigle et al. [38] have classified them using different categories (Table 2). It describes particle size classification in a generic sense, which includes wood and lignocellulosic materials.

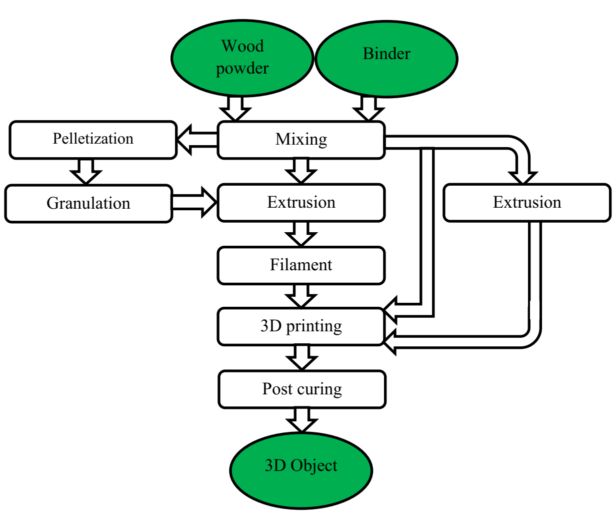


Fig. 3 – The 3D printing process based on wood powder.

Wood powders have been studied as an additive in 3D printing [2,9,15,40,41]. The powders investigated have come from common commercial species of hardwoods and softwoods. For example, Kariz et al. [9,13,40] and Ayrilmis [42] have used beech (*Fagus sylvatica* L.) wood powder 237 μm. On the other hand, Rosenthal et al. [43] have used 250 μm and 400 μm beech wood powder. Tao et al. [24] have used aspen (*Populus adenopoda*) wood powder 14 μm. Spruce (*Picea abies*) wood powder, size 800–2000 μm was used by Henke and Treml in the 3D printing process [15]. Bi et al. [44,45] have used 150 μm poplar wood powder for their study on 3D printing. Chawla et al. [46] have used 50 μm wood powder obtained from saw dust in their study. Lastly, Le Guen et al. [39] have used 125 μm pine wood powder (*Pinus radiata* D. Don).

Researchers have used different types of binding agents including urea formaldehyde (UF), gypsum, methyl cellulose, polyvinyl alcohol (PVA), polyactic acid (PLA), sodium silicate and cement for printing the object. Wood powder specifications, binders, printer technology and 3D printed objects from existing literature are presented in Table 3.

3.1. *Material extrusion technology*

3.1.1. *Fused deposition modelling*

3.1.1.1. *With filament*. Using filaments for 3D printing is referred to as fused filament or filament freedom fabrication (FFF), which is under the trademark of fused deposition modelling (FDM) [50,51]. FDM is the trademark of the company Stratasys [26]. Wood powder based filaments are made by mixing wood powder with a binding agent and then passing the mixture through an extruder [9,40]. Some of the researches have presented the filament fabrication process exclusively.

Kariz et al. [40] have prepared mixture of PLA and beech powder (237 μm) in preparing filaments. They have used wood powder fractions of 10–50%. Powders were prepared by drying with PLA granules prior to mixing. The authors then compounded and pelletized the wood powder and PLA mixture by twin-screw compounder. A 1.75 mm thick filament was produced from the pellets using a single-screw filament extruder (Noztek-pro, UK). Then three-layer 3D blocks ($80 \times 12 \times 4$ mm^3) were printed using a Zortax M200 3D printer, having a nozzle diameter of 0.4 mm (Fig. 4). A layer thickness of 0.19 mm, a printing speed of 30 mm s^{-1} and a printing temperature of 275 °C were used. The obtained objects were dried at 80 °C for 24 h to remove moisture and cured under different atmospheres; standard (RH 65% and 20 °C), humid (RH 87% and 20 °C) and dry (RH 33% and 20 °C) [40]. Kariz et al. [9] prepared 3D printed blocks ($40 \times 12 \times 4$ mm^3) following the aforementioned procedures used by Kariz et al. [40].

Tao et al. [24] produced their filaments using a mixture of 14 μm wood powder and PLA as a binder. The used wood powder fraction was 5%. In their study, the authors prepared pure PLA filaments at first by drying PLA pellets at 103 °C for four hours and extruding them using a desktop-class plastic extruder. Pure PLA filaments were sized for achieving <1.0 mm PLA particle. Then wood powders and PLA particles

Table 2 – Particle size classification in a generic sense based on previous researchers [37,38] and used wood powder size range in 3D printing [13,15,24,39].

Classification	Ultrafine	Fine	Intermediate	Course	Wood powders in 3D printing
Size range (μm)	<20	50–500	1000–10 000	>10 000	14–2000

were mixed after drying them at 103 °C. In the next, the mixture was extruded using aforementioned extruder while maintaining a mixture temperature of 175 °C, an extrusion temperature of 171 °C and an extrusion speed of 1.0 m min^{-1} for production of 1.75 mm diameter filaments. A FDM 3D printer was then used for printing test samples for determination of tensile properties and a barrel using wood powder and PLA composite filaments [24]. The observed printing conditions for 3D printed objects were a nozzle temperature of 210 °C and nozzle diameter of 0.4 mm [24]. In another study, wood powder, PLA and starch based filaments were prepared following two times extrusion mentioned above [52].

The studies of Ayrilmis [23] and Ayrilmis et al. [47] have used filaments containing 30% wood powder and 70% PLA (mass basis) produced by a filament manufacturer. Ayrilmis [23] printed four-layer 100 × 15 × 4 mm^3 samples using a Zaxe 3D printer with a base temperature 80 °C, printing temperature 200 °C, a nozzle diameter 0.4 mm, raster orientation 0° and parallel printing layers side by side. In this case, the authors used four sizes of layers having a thickness of 0.1, 0.2, 0.3 and 0.4 mm, and 3D printed samples were conditioned following the standard of ISO 291 (20 °C and RH 50%). Ayrilmis et al. [47] prepared wood-based 3D printed objects following the same process as described by Ayrilmis [23].

Ayrilmis et al. [42] have used 10–50% wood powder (237 μm) and PLA to prepare their filaments. The wood powder was dried until the moisture content was <1%, and then wood powders and PLA were compounded using a twin-screw co-rotating extruder having 10 zones. The temperature of feeding to die zone was 175 to 160 °C. The compounded products were cooled and granulated. The granules were then passed through a single-screw extruder, Noztek Pro™ filament extruder, to obtain 1.75 mm diameter wood powder based filaments. The filaments were then cooled in the air. The authors printed three-layer 40 × 12 × 4 mm^3 test samples with a Zortrax M200 3D printer following the ISO 291 standard (20 °C and RH 50%).

Bi et al. [45] dried thermoplastic polyurethane elastomer (TPU) and wood powder for 12 h at 103 °C, and EPDM-g-MAH was dried for 6 h at 80 °C. The authors have used 2 to 10 wt % EPDM-g-MAH with a wood powder/TPU blend ratio of 20:80 and the mixtures were blended for 10 min by a high-speed mixer. The mixtures were extruded by twin-screw extruder while maintaining a die temperature of 195 °C and screw speed of 20 rpm followed by natural cooling and grinding to form 4 mm composite particles. These composite particles were then extruded by a single-screw extruder having a 3.5 mm die, L/D ratio of screw 12:1, screw speed 25 rpm and temperature 190 °C following by 24 h natural cooling to obtain 1.75 ± 1 mm filament. Bi et al. [44] have utilised a similar technique to obtain composite particles and cure post extruded filament described as Bi et al. [45]. However, EPDM-g-MAH, POE-g-MAH, diphenylmethyl propane diisocyanate (MDI), PEG 6000 and chitosan and the wood powder contents were 10, 20, 30 and 40%, respectively in their filaments. Bi et al. [45] printed wood powder based 3D specimens (dumbbell-shaped with dimension 75 × 12.5 × 2 mm^3 and rectangular strip with dimension 80 × 8 × 1.2 mm^3) using MR300 3D printer having infill density 100%, filing structure rectilinear, filling angle 45°, layer thickness 0.2 mm, nozzle diameter 1 mm, nozzle temperature 230 °C, a build plate temperature 30 °C and a printing speed 25 mm s^{-1}. Bi et al. [44] also used FDM 3D printer to print tensile specimen, printed objects and mobile phone shell with a wood powder based filament. The used conditions for 3D printing consumable extrusion molding were water temperature 40 °C, mold temperature 185 °C, machine barrel 1 temperature 190 °C, machine barrel 2 temperature 165 °C, host speed 35 Hz and traction speed 15 Hz.

Le Guen et al. [39] used 10 wt% wood powders in a mixture of PLA and wood powder (125 μm). The mixture was pelleted using a 26-mm scientific twin-screw co-rotating extruder LTE26-40 having a L/D ratio 40 and a vacuum crammer was fixed with the extruder. The hand mixed materials was fed into the volumetric feeder and the applied pelletization conditions were a feeding speed of 20 rpm, a extruder screw speed of 200 rpm, and a temperature of 190–200 °C (measured in the first and last 5 zones, respectively). The pellets were resized to 2 mm in length. A 1.75 mm filament was produced using twin-screw extruder while maintaining a temperature 160–200 °C, a screw speed 200 rpm, feed speed 8 rpm and haul-off unit speed 8–13 rpm and the pelletizer was replaced by a winding unit. Le Guen et al. [39] have printed 60 × 10 × 2.5 mm^3 rectangular beams by M2 FDM printer with a layer thickness 0.2 mm, no overlapping of strand, nozzle diameter 0.75 mm, nozzle temperature 210 °C, platform temperature 70 °C, and printing direction according to beam length 0° and 90°.

Kumar et al. [53–56] produced four types of 1.75 ± 0.05 mm diameter filament having different blends by twin-screw extruder following Kumar et al. [57]; the applied conditions were temperature 170 °C, screw rotation 45 r $min^{-1}$and load 5 kg. The blending ratio of pure PLA, PLA:PVC (polyvinyl chloride), PLA:Fe_3O_4, and PLA:wood powder was 100:0, 75:25, 80:20 and 95:5, respectively. Then Kumar et al. [53,54] used Repetier interfacing processing tool from slicer 3r software package tool for 3D modelling in computer prior to print the object by 3D printing machine (Model: Divide by Zero). The authors' printed six layers based object where the thickness of each layer was 0.53 mm. However, the layers were from different filaments; the bottom, second, third and fourth, and fifth and sixth layer were printed using pure PLA, PLA:PVC, PLA:wood powder and PLA:Fe_3O_4 filament, respectively. The infill density, angle and speed were in the range of 60–100%, 45–90° and 50–90 mm s^{-1}, respectively.

In another study, researchers prepared wood powder based filaments and measured the properties only [46,58]. Wood powder size 50 μm (2.5–10%) obtained from saw dust

Table 3 – Wood powder specifications, binders, 3D printer, 3D printing technology and 3D printed objects from existing literature.

Wood powder		Binding agent	3D printing technology	Printing conditions			3D object	Ref.
Species	Particle size (μm)			Printer model	Nozzle diameter (mm)	Printing temperature (°C)		
Beech	237	PVAc and UF	Material extrusion	home-made delta	3	NA	3D block	[13]
		PLA		Zortax M200	0.4	275	3D block	[9,40]
					NA	NA	Test specimen	[42]
Aspen	14	PLA		FDM	0.4	210	Barrel and Test specimen	[24]
NA	NA	PLA		Zaxe 3D	0.4	200	Test specimen	[23,47]
Poplar	150	TPU and modifier		MR300 3D	1	230	Test specimen	[44,45]
Pine	125	PLA		M2 FDM	0.75	210	Rectangular beam	[39]
Beech	NA	Copolyster, viscosity reducer and light stabilizer	Powder bed fusion	HRPS-IIIA type SLS	NA	NA	Ball and wrench	[48]
Spruce	800–2000	Methyl cellulose, gypsum, cement and sodium silicate		NA	NA	NA	Truncated cone	[15]
Beech	250 and 400 μm	Methyl cellulose	Liquid deposition	Cartesian 3D	NA	NA	Bending specimen and tower	[43]
Pine	45–100, 1050	PM-B-SR2-02	Binder jetting	RX-1	NA	NA	Filigree structures	[49]

Symbols refer to: NA – Not available; PVAc - polyvinyl alcohol; PLA – poly lactic acid; TPU - thermoplastic polyurethane elastomer; FDM - fused deposition modelling; UF - urea formaldehyde.

was mixed with 2° recycled ABS. Then the mixture was extruded by twin-screw extruder; the optimum conditions were load 10 kg, temperature 225 °C and speed 70 r min^{-1} [46]. Chansoda et al. [58] used commercial wood powder and wood powder obtained from the residue of furniture industry. In this case, the authors used 5–20% both types of wood powder with PLA for making filament. They have also used 5% coupling agent, i.e., maleic anhydride (MAH) and NaOH to enhance the compatibility of the filaments. The filaments of 1.5 mm diameter were prepared by twin-screw extruder maintaining the operation parameters, i.e., temperature 200 °C, rotational speed 140 r min^{-1}. The coupling agent didn't show any effect and there was no significant difference of filaments obtained from different types of wood powder.

3.1.1.2. *Without filament*. The FDM technique can also be done without the use of a filament (Fig. 5) where the mixture of wood powder and binding agent are extruded.

Kariz et al. [13] have used 237 μm beech wood powder, along with PVAc and UF as binding agents for printing 3D products. The used wood powder fractions were 12.5–25.0%. The mixture was prepared just prior to printing. Then Kariz et al. [13] have made simple blocks (150 × 30 × 8 mm^3) having 4 layers of 2 mm layer thickness, using a home-made delta type 3D printer (Fig. 5). The printer was consisted of a modified grease gun having several different diameters of interchangeable nozzle. The mixture was poured in the container and the piston using compressed air for the extrusion through the nozzle pressurized it. The authors used an extrusion force of 0.05–0.4 N mm^{-2} and a bed temperature of 80 °C. Their 3D printed objects were cured using a hot plate (50 °C for 2 h) and then put in a standard climate to solidify for a week [13].

3.1.2. *Fused layer modelling*

Fused layer modelling (FLM) is also a material extrusion technology [59] utilising a filament in 3D printing. Ecker et al. [60] have compounded wood powders (15 and 30%) and PLA using a twin-screw extruder (Brabender, Germany) with diameter 20 mm and length 40 times the diameter after drying for 12 h at 60 °C. The mixture was pelleted using the Econ underwater pelletizing system (EUP50) and the pellets were dried for 12 h at 60 °C. The authors extruded the pellets using a conical twin-screw extruder (Brabender, Germany) to make the filament. FLM printing was also studied by Ecker et al. [60] who produced a 3D object from a wood-based filament through a die diameter of 0.6 mm. Printing conditions used a temperature of 205 °C, a printing speed of 50 mm s^{-1} and a layer thickness of 0.3 mm. Printed objects were annealed at 105 °C for 1 h.

3.2. *Powder bed fusion technology*

3.2.1. *Without heat or laser*

In previous study, wood chips (800.0–2000.0 μm) and binders (methyl cellulose, gypsum, cement and sodium silicate) were blended and the best observed blend ratios, with regards to properties of 3D printed objects, were found to be chips: gypsum (1: 0.33),water: gypsum (1: 0.75), chips: cement (1: 0.15) and water: cement (1: 0.80) [15]. In this case, Henke and Treml [15] have mixed binding agent and wooden chips prior to mixing with binder at first. Then the authors prepared 3D

Fig. 4 – Two samples prepared for 3D printing in Z-Suite software with mesh structure inside (left), 3D printing the infill mesh structure (middle), 3D printed samples with different wood ratio (right) [40].

printed truncated cones with a layer thickness of 2.5 mm, and the authors also added water aerosol as an activator for each layer during 3D printing (Fig. 6a, b). For this, the authors placed first layer of mixture of 2.5 mm thickness on platform and used aerolised water based on needed amount for activation. The first layer was moved down after completion of bonding. The same process was continued to obtain the final shape of the product and the platform was got back into the starting point (Fig. 6b).

3.2.2. *Selective laser sintering*

In this technique, researchers used beech wood powder, copolyster hot-melt adhesive as binding agent, viscosity reducer, i.e., glass, graphite, talcum, calcium carbonate, or white carbon black powder and light stabilizer. A light stabilizer was used to reduce the aging effect caused by laser. The fraction of beech wood powder and copolyster, viscosity reducer and light stabilizer was 90, 5 and 2%, respectively (the fraction of beech wood powder and copolyster separately was not described). The authors printed a ball with an inner litter ball (ball diameter 30 mm and litter ball diameter 10 mm) and wrench (95×6 mm^2) using a HRPS-IIIA type SLS machine and the laser type was CO_2 laser. The 3D CAD model was developed in the computer prior to printing. The printing conditions applied in this study were wavelength 10.6 μm, output power 50 W, laser spot diameter 0.3 mm, layer thickness 0.2 mm, scan space 0.15 mm and scanning speed 2000 mm s^{-1}. The printed products were infiltrated with wax in the post processing [48]. A study was conducted to simulate the laser power for optimization during printing process [61].

3.3. *Liquid deposition modelling*

Studies using this technology have investigated relatively high wood powder content in produced 3D objects [43]. Authors have used 250 μm and 400 μm beech wood powders and methylcellulose as binding and lubricant agent in their study. Two types of gel-like methylcellulose blends (methylcellulose:water) were formed following the blending ratios of 1:20 and 1:30. The wood powder ratio was 84.5–89.0%. The Cartesian 3D printer with a self-made extruder was used for printing. The extruder was consisted of a cylindrical plastic cartridge having a 51 mm nozzle in length with 27 mm internal diameter and 8 mm outlet, and a lead screw worked as a piston (operated by a NEMA 17 linear stepper motor) to move the material towards the outlet. The dimension of three layers specimen was $200 \times 18 \times 12$ mm^3 with a layer thickness of 4 mm (Fig. 7a). The 40 mm diameter towers were consisted of 11 layers (Fig. 7b). The printing speed of both object types was 1 mm s^{-1}.

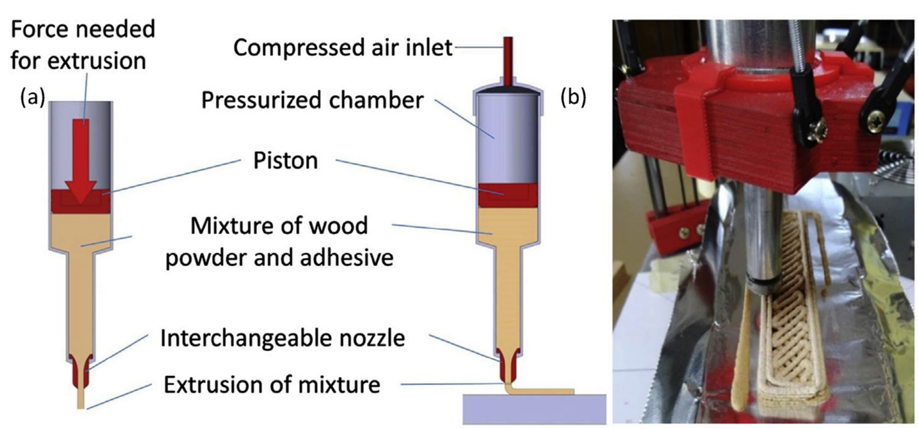
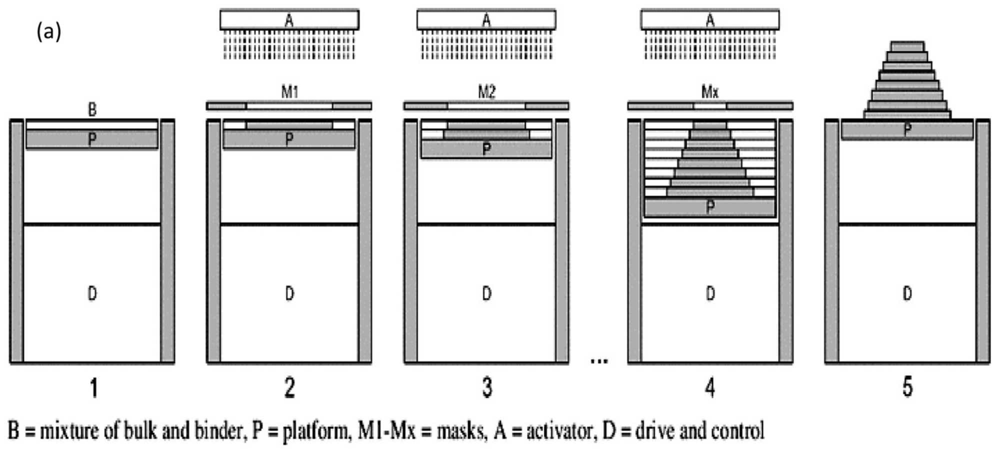


Fig. 5 – Wood powder based 3D printing by FDM without a filament; a) left side is for extrusion force measurement setup and right side is for pressurized chamber for 3D printing, b) 3D printing [13].

(a)



(b)

Fig. 6 – A truncated cone obtained from 3D printing; a) processing and b) products [15].

3.4. *Binder jetting*

Researchers have also used the binder jetting technique to print wood powder based 3D objects [49]. The powder was obtained from pine (*Pinus sylvestris*) wood by boring of European house borer (*Hylotrupes bajulus*) and drywood termite (*Incisitermes marginipennis*). Powder particle diameters were 45–100 and 1050 μm for European house borer and drywood termite, respectively. A commercial printer (RX-1, Prometal RCT GmbH, Augsburg, Germany) water-based binder (PM-B-SR2-02) was used for printing. Cross-linking was occurred during thermal curing of each printed layer. The layer thickness was 100 and 800 μm for European house borer and drywood termite wood powder, respectively.

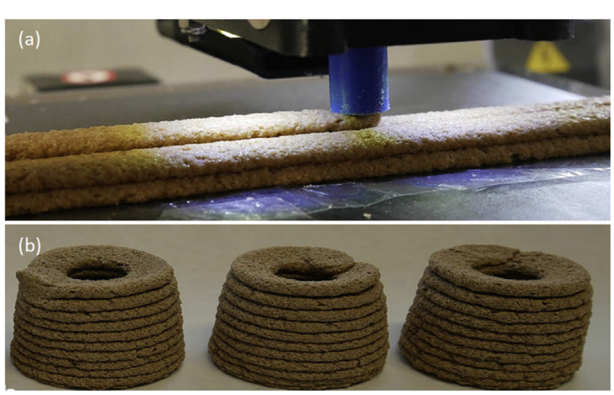


Fig. 7 – Liquid deposition modelling; a) bending specimen and b) towers [43].

4. Properties of wood powder based filaments and 3D printed objects

Determination of properties is important for the potential uses of 3D printed objects. Research has been conducted on wood powder based filaments and 3D printed objects and their physical, rheological and strength properties, i.e., modulus of elasticity (MOE), modulus of rupture (MOR). The authors have

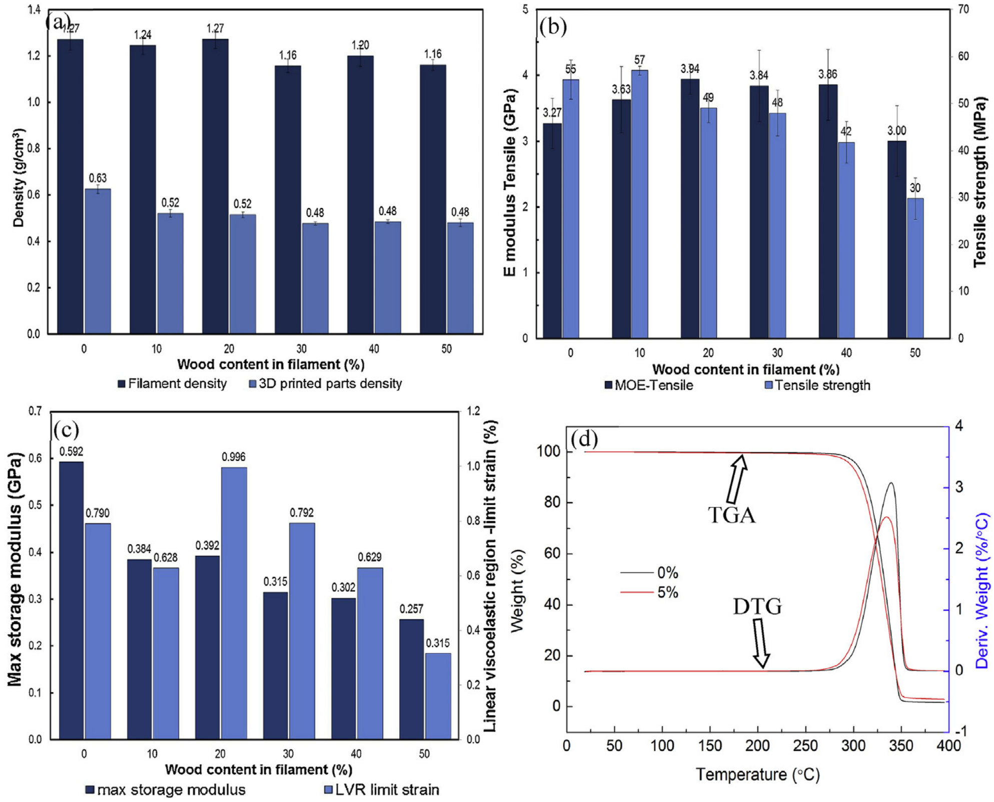


Fig. 8 – Wood powder content vs. properties of filament and printed objects; a) density of filament and objects [9], b) strength properties of filament [9], c) rheological properties [9] and d) thermal properties [24]. Symbols refer to MOE = modulus of elasticity, LVR = linear viscoelastic region, TGA = thermogravimetric analysis, DTG = derivative thermogravimetry and Deriv. = derivative.

studied the effect of wood powder content, binding agents and additives on the properties of wood powder based 3D printed objects.

4.1. *Physical properties*

The density of 3D printed objects has been decreased from 0.52 to 0.48 g cm^{-3} when the wood powder content increased from 10–50% (Fig. 8a) [9]. Ayrilmis et al. [47] have determined the density having different layer thicknesses. They found a decrease in density with increasing layer thickness. Actually, the higher proportion of wood powder used, the more voids were created, which might be the reason for lower density of filaments with increasing wood powder fraction. The blending of low and high-density material decreases the composite density compared to higher density material [62]. However, Rosenthal et al. [43] have observed that the density of the 3D printed objects have increased with increasing fraction of finer wood particles.

Wood powder based 3D printed objects are also less transparent when compared with 3D printed objects made from commercial filaments, and the roughness and porosity of the surface are increased with increasing fraction of wood powder [9]. Moreover, dark spots have been observed on the edges of 3D printed objects made by filaments containing 30–50% wood powder [9]. The use of wood powders results in more voids because of irregular flow (heterogeneous distribution of material) through the nozzle and clogging. These effects can cause poor surface properties [9]. The presence of wood powder over the surface and inner matrix of filament causes poor surface texture leading to higher porosity [55]. Ayrilmis [23] have observed that the roughness of the surface of 3D printed wood powder and PLA based samples have been increased with layer thickness. Tao et al. [24] and Kumar et al. [56] have observed that the fractured surface of 3D printed objects made from wood powder based filaments is rough and this is the reason for poor interfacial bonding between wood powder and PLA [24]. The hydrophilic nature of wood and the hydrophobicity of PLA also contribute to poor interfacial bonding between these materials [24]. In another study, Ayrilmis et al. [47] have observed higher porosity, gaps among filaments and powder exposure at the surface with increasing of layer thickness. Furthermore, microvoids are more numerous for wood powder based objects compared to PLA and this produces greater surface roughness with increasing wood powder content [42]. However, the post processing of SLS printed objects by infiltration of wax resulted in higher surface smoothness and density enhancement [48]. Optimal layer thickness can improve surface properties and it is 0.2 mm for 3D printed wood powder and PLA based specimens [23].

The extent of swelling of 3D printed objects has increased when using wood powders as additives in 3D printing mixtures [40]. Wood powders are hydrophilic, leading to enhanced swelling in objects made from wood powder based filaments [40]. The water absorption capacity clearly increases with wood fraction [60]. The wood powder based 3D printed samples have porous structure and thus, the samples uptake water and higher content of wood powder enhances the water absorption [60]. Surface roughness of printed objects plays a role in their increased wettability [42]. The wettability also depends on surface free energy [63], which for PLA and beech wood are 52.6 [63] and 84 mJ m^{-2} [64], respectively. Therefore, higher amount of wood powder causes higher wettability and water absorption. Ayrilmis [23] and Ayrilmis et al. [47] have observed that the wettability and water absorption of 3D printed samples increase, respectively with layer thickness. Generally, the hygroscopic nature of wood can also cause deformation of wood powder based 3D printed objects [65]. The effect of binder on the dimensional stability has been studied. Kariz et al. [13] have observed the shrinkage (22 %) of 3D printed object made by wood powder based filament has been higher for using UF as binding agent in comparison to the shrinkage (17%) of wood powder based 3D printed object made with PVAc binder; the used wood powder content in this study is more or less similar for both types of binding agents. However, the optimum layer thickness [23] and incorporation of smaller wood particle [43] can improve the wettability and dimensional stability of the 3D printed objects, respectively.

4.2. *Rheological properties*

The extrusion force increases with increasing amount of wood powder in the mixture, and the type of binder also affects the extrusion force. The required extrusion force for wood powder and PVAc mixtures is lower than for mixtures of UF and wood powder; the amount of wood powder was 17.5 and 20% with PVAc but 15 and 17.5% for UF mixtures [13]. In another study, Chawla et al. [46] have observed that the melt flow rate is decreased with the increasing of wood powder content in the filament.

Kariz et al. [9] have also studied the rheological properties, i.e., linear viscoelastic region (LVR) limit strain, storage modulus (elastic behaviour measurement) (Fig. 8c) and temperature sweep test. The highest and lowest LVR limit strain have been found to be 0.996 and 0.315% for printed objects made by filaments containing 20 and 50% wood powders, respectively [9]. The storage modulus of wood powder based objects decreases with increasing fraction of wood powder in the filament while the loss is less for the addition of 10–20% wood powder [9]. On the other hand, storage modulus and loss modulus have shown higher values for 3D printed samples made with EPDM-g-MAH containing wood powder based filament [44,66]. The reaction between EPDM-g-MAH and the powder and crosslinking of EPDM and TPU are the main driving forces for the better adhesion [67]. In another study, the fraction of wood powder in the samples has a lower influence on storage modulus [39].

4.3. *Mechanical properties*

Printed objects made with wood powder based filaments have poorer mechanical properties [9]. Studies have reported that small fractions of wood powder (10 and 20%) in mixtures have resulted in higher tensile strength (57 MPa) and MOE (3940 MPa) of the filaments, respectively, but larger fractions of wood powder (50%) have resulted in lower tensile strength (30 MPa) and MOE (3000 MPa) of the filaments (Fig. 8b) [9]. Similar effects of wood powder fraction on strength properties have been observed by other researchers [46,58,68]. MOE of 3D printed objects have shown degradation when using wood powders as additives in 3D printing mixtures [40]. Bi et al. [44] have found that elongation at the break decreases with an increasing wood powder fraction. In another study, the tensile strength, tensile strain, tensile modulus, impact strength and notched impact strength of wood powderbased 3D printed samples have been characterised before and after soaking in water. There is a clear trend in that higher fractions of wood powder degrade the mechanical properties of the samples [60]. Similarly, Le Guen et al. [39] have observed that flexural strength and strain have decreased with the addition of wood powder, but the flexural modulus increased. The reduction of density of printed object due to incorporating wood powder results in poor strength properties [48,69]. The irregular surface also affects the bonding properties and load transfer among wood powders, leading to poor mechanical properties in the printed object [9]. At higher fractions of wood powders, polymer binders fail to encapsulate wood particles, causing poor bonding and load transfer [9]. In addition, poor interfacial bonding causes poor strength properties. Hydrophilic nature of wood and hydrophobicity of PLA contribute to poor interfacial bonding between wood powder and PLA lead to degrading the strength properties of wood powder/PLA based 3D printed objects [24,39,41]. Poor interfacial bonding because of having higher gaps among filaments with increasing layer thickness results in poor strength properties [47]. The improper mixing of wood powder in the matrix of filament due to clogging of nozzle causes the resistance of heat flow [46] leads to creating the voids and resulting poor strength properties. Researchers have also investigated the effect of binding agent on the mechanical properties of the printed object. Kariz et al. [13] have observed higher MOR (19 MPa) and MOE (2002 MPa) for the 3D printed object obtained from wood powder and binding agent as UF adhesive compared with binding agent as PVAc; the amount of wood powders are more or less similar for both types of binding agents. Nevertheless, researchers have claimed that the bending strength of 3D printed truncated cones are comparable to lightweight building materials fabricated from wood wool and had a bending strength range of 0.5–0.95 MPa [15]. Kumar et al. [55] have observed higher hardness due to the presence of wood powder on the surface of the filament and contributing to the dense structure of the filament.

However, different studies have been conducted to improve the mechanical properties of wood powder based 3D printed objects. For example, the post-processing of SLS printed objects by infiltration of wax has improved the strength properties through improving smoothness and density. However, the intensity of laser had limitation; the intensity above 311 W mm^{-2} lowered the strength properties of both wax infiltrated and non-infiltrated objects [48]. In testing different modifiers, the tensile strength was shown to be higher for MDI samples while elongation at the break was higher for EPDM-g-MAH samples. Weaker intermolecular force between EPDM-g-MAH and matrix may lower the tensile strength for 3D printed specimens when EPDM-g-MAH is used as modifier [44]. On the other hand, MAH can react with OH groups of wood powder and EPDM can cross-link with main chain of TPU [70,71]. Thus, the compatibility between wood powder and TPU is increased with the incorporation of EPDM-g-MAH and the elongation at break has been enhanced for the 3D printed specimens [44]. Bi et al. [45] have found the best stress and strain relation, tear elongation and tensile strength for the 3D printed samples made by the filament containing 4% EPDM-g-MAH and wood powder/TPU 20:80. An appropriate amount of modifier (EPDM-g-MAH) can facilitate a better reaction with wood powder and MAH, which enhances adhesion between the TPU and powder [45,72].

Control of printing parameters may help to improve the mechanical properties of the printed objects [73]. The filling angle has effect on the shape recovery of the sample; Bi et al. [45] have found the best shape recovery of the wood powder based 3D printed human model with 45° filling angle. Kumar et al. [53] have observed better flexural (26.92 MPa) and pull-out (18.11 MPa) performances of the printed object with less void when higher infill density and lower angle are used during printing. Le Guen et al. [39] have observed higher flexural strength and strain of rectangular beams printed in 90° direction. Controlling layer thickness can contribute to the performance of printed objects; the mechanical properties are better for smaller layer thicknesses [47].

The appropriate wood powder proportion and size distribution can affect the mechanical properties of the 3D printed objects. Less wood powder results in less load transfer and a lower tensile strength [74–77]. Bi et al. [44] have found that the tensile strength increased with 30 and 40% wood powder. Meanwhile, Rosenthal et al. [43] have observed that the strength properties of the wood powder based 3D printed objects have been increased with the increasing of the fraction of smaller wood particle. The modification of wood powder using pre-treatment, i.e., thermal can also help to mitigate the mechanical properties [68,78].

4.4. *Thermal properties*

Wood powders also affect the thermal stability of 3D printed objects and result in a lower thermal decomposition temperature [24]. The glass transition temperature depends on the compatibility among particles in the composites [79] and fillers reduce the compatibility of the composite resulting in a lower glass transition temperature [80]. Therefore, a lowering of the glass transition temperature occurs due to poor compatibility between wood and PLA [24]. The poor interfacial compatibility is the reason of higher interfacial tension between PLA and wood powder [24]; higher interfacial tension is the result of higher crystallinity of wood powder and PLA composite [81]. The glass transition, cold crystallisation and melting temperature of wood powder based 3D printed samples have shown to be lower than those of PLA [60] and the amount of wood content has no significant effect on thermal properties (Fig. 8d) [24,60]. Bi et al. [45] have observed the optimal thermal stability for the 3D printed samples made by the filament containing 4% EPDM-g-MAH and wood powder/TPU 20:80. An appropriate amount of modifier can enhance the adhesion between the binder and powder [45,72]. Thus, it enhances the thermal stability. Researchers have also found that the fraction of wood powder in the samples has a lower influence on glass transition of 3D printed beams [39]. It has been claimed that incorporation of wood powder in PLA/starch blend can produce suitable filament for 3D printing [52].

5. Implications and potential of wood powder in 3D printing

The potential for 3D printing applications is expanding for large architectural structures and there is growing market interest in products for consumers [82]. Wood powder based filaments for 3D printing are eco-friendly [2,24] as wood is biodegradable and can be recycled [2]. Wood powders can be used in 3D printing processes as additives along with others material, such as lignin, PHA (polyhydroxyalkanoates), nanocellulose, colour masterbatches, and talcum [2]. 3D printing technology can already produce wood-based products [2]. Microtomography and tomography technology are used to characterize 3D-structure of wood materials [83]. Using 3D technology wood cell models with different levels of magnification can be produced using wood powder along with binders [2]. This wood self-replication can be used in teaching through making a 3D wood anatomical atlas. It has potential to contribute to research in biomimetics and bio-inspired materials [2]. Wood powder based 3D printed masks can be produced using 3D printing technology [84]. 3D printing has made it easier to produce products with complex structures [1,31,85–89]. This finds benefits in the production of furniture for realising any desired shape [85,86,88].

Furthermore, wood powders obtained from thinning wood or other sources of waste can be used for 3D printing to produce wood products. In addition, making of complex structure with in a short time through this technique may help to produce the products at home. Therefore, 3D printing with wood powders has the potential for new dimensions in wood-based industries. The renewability of wood is an attractive criterion in modern manufacturing and the technology is sure to spread to other areas. This may be driven by the low cost of wood as a resource, political incentives for sustainable manufacturing or specialised applications.

The problem of nozzle blocking of 3D printer during printing by wood powder based filament can be possible to overcome by using ultrafine powder as additive for wood-based filament [2]. The control of nozzle diameter by magnetostrictive material can help to avoid blocking and provide good printing quality with high efficiency [90]. On the other hand, the use of thermosetting binder can improve the water absorption properties and the incorporation of glass fibre can improve the strength properties [91]. Wax infiltration may improve surface and strength properties of wood powder based 3D printed objects [48]. Incorporation of coupling agent and lignin can also enhance the strength properties of wood powder based filaments [92].

What is clear is that there is a lack of studies on the effect of printing parameters on wood particle quality, including the influence of wood species, in order to identify suitable compositions for filaments in 3D printing [9]. Structural differences among different wood species, i.e., softwood and hardwood may affect the quality of printed composite [93]. Hence, more research is needed to better characterise wood powder based 3D printed objects.

6. Conclusions

Renewable woody materials have great potential as a raw material in 3D printing applications due to low cost and abundance of supply. The use of wood powders can partially address cost, environmental and sustainability issues in manufacturing. Furthermore, the use of bio adhesives as binders combined with wood powders can further increase environmental benefits. The use of wood powder in 3D printing does have disadvantages such as reduced physical and mechanical performance. However, controlling printing parameters, using modifiers, incorporating appropriate particle sizes, and applying post-curing techniques can address some of the challenges with filaments and product quality. Technical challenges also exist in the printing operation, such as nozzle blocking with wood powder based filaments. However, the field is relatively new and more investigations into the effect of powder quality (e.g. particle geometry and tree species) is needed in this developing area of research. Additionally, bio adhesives constituents and their material source require greater attention in order to safeguard environmental concerns and promote sustainability utilisation of 3D printing technology. Nevertheless, the use of wood powders in 3D printing will extend the benefits of the bio economy and aid the global shift from fossil-based resources.

Credit author statement

Atanu Kumar Das: Conceptualization, Methodology, Literature review, Writing – original draft, Writing - Review & Editing, Visualization **David A. Agar:** Conceptualization, Writing - Review & Editing, **Magnus Rudolfsson:** Writing - Review & Editing **Sylvia H. Larsson:** Conceptualization, Writing - Review & Editing.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Funding from the Department of Forest Biomaterials and Technology at SLU and the Swedish Bio4Energy Strategic Research Environment is acknowledged.

Nomenclature

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
AMF	Additive manufacturing file
CAD	Computer aided design
CAM	Computer aided manufacturing
DMLS	Direct metal laser sintering
DOD	Deposited following drop on demand
EBM	Electron beam melting
FDM	Fused deposition modelling
FFF	Fused filament fabrication
FLM	Fused layer modelling
LOM	Laminated object manufacturing
LVR	Linear viscoelastic region
MAH	Maleic anhydride
MDI	Diphenylmethyl propane diisocyanate
MOE	Modulus of elasticity
MOR	Modulus of rupture
PEG	Polyethylene glycol
PHA	Polyhydroxyalkanoates
PLA	Polyactic acid
PVAc	Polyvinyl alcohol
PVC	Polyvinyl chloride
RH	Relative humidity
SHS	Selective heat sintering
SLM	Selective laser melting
SLS	Selective laser sintering
STL	StereoLithography
TPU	Thermoplastic polyurethane elastomer
UF	Urea formaldehyde
UV	Ultra violet
3D	Three-dimensional

REFERENCES

[1] Kariz M, Kuzman MK, Sernek M. Adhesive bonding of 3D-printed ABS parts and wood. J Adhes Sci Technol 2017;31(15):1683–90.

[2] Wimmer RSB, Woess J, Koddenberg T, Mundigler N. 3D Printing and wood. Pro Ligno 2015;11(4):144–9.

[3] Parandoush P, Lin D. A review on additive manufacturing of polymer-fiber composites. Compos Struct 2017;182:36–53.

[4] 3D printing. The merriam-webster.com dictionary. Merriam-Webster Inc.; 2019. https://www.merriam-webster.com/dictionary/3-D%20printing. [Accessed January 2020].

[5] Conner BP, Manogharan GP, Martof AN, Rodomsky LM, Rodomsky CM, Jordan DC, et al. Making sense of 3-D printing: creating a map of additive manufacturing products and services. Addit Manuf 2014;1:64–76.

[6] Tofail SAM, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C. Additive manufacturing: scientific and technological challenges, market uptake and opportunities. Mater Today 2018;21(1):22–37.
[7] Tymrak BM, Kreiger M, Pearce JM. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. Mater Des 2014;58:242–6.
[8] Berman B. 3-D printing: the new industrial revolution. Bus Horiz 2012;55(2):155–62.
[9] Kariz M, Sernek M, Obucina M, Kuzman MK. Effect of wood content in FDM filament on properties of 3D printed parts. Mater Today Commun 2018;14:135–40.
[10] Silva FJG, Campilho R, Gouveia RM, Pinto G, Baptista A. A novel approach to optimize the design of parts for additive manufacturing. In: Sormaz D, Suer G, Chen FF, editors. 28th international conference on flexible automation and intelligent manufacturing; 2018. p. 53–61.
[11] Carausu C, Mazurchevici SN, Mazurchevici AD, Andrusca L, Comaneci R, Popa RI, et al. Mechanical characterization of additive manufactured samples from biodegradable materials. In: Modtech international conference - modern technologies in industrial engineering, Viii; 2020.
[12] Beniak J, Krizan P, Matus M. Conductive material properties for FDM additive manufacturing. Sci J 2020;2020:3846–51.
[13] Kariz M, Sernek M, Kuzman MK. Use of wood powder and adhesive as a mixture for 3D printing. Eur J Wood Wood Prod 2016;74(1):123–6.
[14] Bulanda K, Oleksy M, Oliwa R, Budzik G, Gontarz M. Biodegradable polymer composites based on polylactide used in selected 3D technologies (Rapid communication). Polimery 2020;65(7–8):557–62.
[15] Henke K, Treml S. Wood based bulk material in 3D printing processes for applications in construction. Eur J Wood Wood Prod 2013;71(1):139–41.
[16] Demirbas MF, Balat M, Balat H. Potential contribution of biomass to the sustainable energy development. Energy Convers Manag 2009;50(7):1746–60.
[17] Sharma V, Roozbahani H, Alizadeh M, Handroos H. 3D printing of plant-derived compounds and a proposed nozzle design for the more effective 3D FDM printing. IEEE Access 2021;9:57107–19.
[18] Kudahettige-Nilsson RL, Ullsten H, Henriksson G. Plastic composites made from glycerol, citric acid, and forest components. BioResources 2019;13(3):6600–12.
[19] Campbell TA, Ivanova OS. 3D printing of multifunctional nanocomposites. Nano Today 2013;8(2):119–20.
[20] Gardan J, Nguyen DC, Roucoules L, Montay G. Characterization of wood filament in additive deposition to study the mechanical behavior of reconstituted wood products. J Eng Fibers Fabr 2016;11(4):56–63.
[21] Jiang Q, Xu Y, Chen M, Meng Q, Zhang C. Modification of the wood-plastic composite for enhancement of formaldehyde clearance and the 3D printing application. J Appl Polym Sci 2021;138(3):49683.
[22] Tao YB, Pan L, Liu DX, Li P. A case study: mechanical modeling optimization of cellular structure fabricated using wood flour-filled polylactic acid composites with fused deposition modeling. Compos Struct 2019;216:360–5.
[23] Ayrilmis N. Effect of layer thickness on surface properties of 3D printed materials produced from wood flour/PLA filament. Polym Test 2018;71:163–6.
[24] Tao YB, Wang HL, Li ZL, Li P, Shi SQ. Development and application of wood flour-filled polylactic acid composite filament for 3D printing. Materials 2017;10(4).
[25] Gibson I, Rosen D, Stucker B. Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Second Edition. 2nd ed 2015. p. 1–498.
[26] AMRG Group. About additive manufacturing. Loughborough University; 2020. https://www.lboro.ac.uk/research/amrg/about/. [Accessed January 2020].
[27] Chua CK, Leong KF, Lim CS. Rapid prototyping: principles and applications. Rapid Prototyping: Principles and Applications, Third Edition. 3rd ed 2010. p. 1–512.
[28] Process-Make. Introduction to 3D printing - additive processes. 2018. https://make.3dexperience.3ds.com/processes/binder-jetting. [Accessed July 2021].
[29] Chua CK, Leong KF. 3D printing and additive manufacturing: Principles and applications: the 5th edition of rapid prototyping. *Principles and applications*. 3D Printing and Additive Manufacturing: Principles and Applications: The 5th Edition of Rapid Prototyping: Principles and Applications. 2017. p. 1–426.
[30] Walker JL, Santoro M. Processing and production of bioresorbable polymer scaffolds for tissue engineering. In: Perale G, Hilborn J, editors. Bioresorbable polymers for biomedical applications: from fundamentals to translational medicine; 2017. p. 181–203.
[31] Wang X, Jiang M, Zhou ZW, Gou JH, Hui D. 3D printing of polymer matrix composites: a review and prospective. Compos B Eng 2017;110:442–58.
[32] Turner BN, Strong R, Gold SA. A review of melt extrusion additive manufacturing processes: I. Process design and modeling. Rapid Prototyp J 2014;20(3):192–204.
[33] Reineke LH, Wood Flour. USDA forest service. Madison, WI, USA: Forest Products Laboratory; 1966. p. 13.
[34] Clemons CM, Caulfield DF. Wood flour. In: Xanthos M, editor. Functional fillers for plastics. USA: WILEY-VCH Verlag GmbH & Co KGaA; 2005.
[35] Wang Y, Forssberg E. Enhancement of energy efficiency for mechanical production of fine and ultra-fine particles in comminution. China Particuol 2007;5(3):193–201.
[36] Zhao XY, Ao Q, Yang LW, Yang YF, Sun JC, Gai GS. Application of superfine pulverization technology in Biomaterial Industry. J Taiwan Inst Chem Eng 2009;40(3):337–43.
[37] Barakat A, de Vries H, Rouau X. Dry fractionation process as an important step in current and future lignocellulose biorefineries: a review. Bioresour Technol 2013;134:362–73.
[38] Mayer-Laigle C, Rajaonarivony RK, Blanc N, Rouau X. Comminution of dry lignocellulosic biomass: Part II. Technologies, improvement of milling performances, and security issues. Bioengineering 2018;5(3):50.
[39] Le Guen MJ, Hill S, Smith D, Theobald B, Gaugler E, Barakat A, et al. Influence of rice husk and wood biomass properties on the manufacture of filaments for fused deposition modeling. Front Chem 2019;7.
[40] Kariz M, Sernek M, Kuzman MK. Effect of humidity on 3d-printed specimens from wood-pla filaments. Wood Res 2018;63(5):917–22.
[41] T.B.L.Z.F.V.L.B.O.S.R. L. 3D printing biocomposites. Society of plastics Engineers. Plastics Research Online; 2015. p. 1–3.
[42] Ayrilmis N, Kariz M, Kuzman MK. Effect of wood flour content on surface properties of 3D printed materials produced from wood flour/PLA filament. Int J Polym Anal Char 2019;24(7):659–66.
[43] Rosenthal M, Henneberger C, Gutkes A, Bues CT. Liquid Deposition Modeling: a promising approach for 3D printing of wood. Eur J Wood Wood Prod 2018;76(2):797–9.
[44] Bi HH, Ren ZC, Guo R, Xu M, Song YM. Fabrication of flexible wood flour/thermoplastic polyurethane elastomer composites using fused deposition molding. Ind Crop Prod 2018;122:76–84.

[45] Bi HJ, Xu M, Ye GY, Guo R, Cai LP, Ren ZC. Mechanical, thermal, and shape memory properties of three-dimensional printing biomass composites. Polymers 2018;10(11).
[46] Chawla K, Singh J, Singh R. On recyclability of thermosetting polymer and wood dust as reinforcement in secondary recycled ABS for nonstructural engineering applications. J Thermoplast Compos Mater 2020.
[47] Ayrilmis N, Kariz M, Kwon JH, Kuzman MK. Effect of printing layer thickness on water absorption and mechanical properties of 3D-printed wood/PLA composite materials. Int J Adv Manuf Technol 2019;102(5–8):2195–200.
[48] Zeng WL, Guo YL, Jiang KY, Yu ZX, Liu Y, Shen YD, et al. Laser intensity effect on mechanical properties of wood-plastic composite parts fabricated by selective laser sintering. J Thermoplast Compos Mater 2013;26(1):125–36.
[49] Plarre R, Zocca A, Spitzer A, Benemann S, Gorbushina AA, Li YX, et al. Searching for biological feedstock material: 3D printing of wood particles from house borer and drywood termite frass. PloS One 2021;16(2).
[50] Hamzah HH, Shafiee SA, Abdalla A, Patel BA. 3D printable conductive materials for the fabrication of electrochemical sensors: a mini review. Electrochem Commun 2018;96:27–31.
[51] Spoerk M, Gonzalez-Gutierrez J, Lichal C, Cajner H, Berger GR, Schuschnigg S, et al. Optimisation of the adhesion of polypropylene-based materials during extrusion-based additive manufacturing. Polymers 2018;10(5).
[52] Sun YF, Lee D, Wang YP, Li SL, Ying JL, Liu XP, et al. Thermal decomposition behavior of 3D printing filaments made of wood-filled polylactic acid/starch blend. J Appl Polym Sci 2021;138(9).
[53] Kumar S, Singh R, Singh TP, Batish A. Flexural, pull-out, and fractured surface characterization for multi-material 3D printed functionally graded prototype. J Compos Mater 2020;54(16):2087–99.
[54] Kumar S, Singh R, Singh TP, Batish A. Investigations of polylactic acid reinforced composite feedstock filaments for multimaterial three-dimensional printing applications. Proc IME C J Mech Eng Sci 2019;233(17):5953–65.
[55] Kumar S, Singh R, Singh TP, Batish A. On process capability comparison of hybrid and multi blend PLA matrix composite: magnetic and surface properties view point. Mater Today Proc 2020;28:521–5.
[56] Kumar S, Singh R, Singh TP, Batish A. 3D printed tensile and flexural prototypes of thermoplastic matrix reinforced with multimaterials: a statistical analysis. Mater Today Proc 2021;44:79–85.
[57] Kumar S, Singh R, Singh TP, Batish A. Multimaterial printing and characterization for mechanical and surface properties of functionally graded prototype. Proc IME C J Mech Eng Sci 2019;233(19–20):6741–53.
[58] Chansoda K, Suwanjamrat C, Chookaew W. Study on processability and mechanical properties of parawood-powder filled PLA for 3D printing material. In: IOP conference series: materials science and engineering; 2020.
[59] Sanders JE, Wang L, Gardner DJ. Comparing mechanical properties of impact modified polypropylene-copolymer (IMPP) from injection molding (IM) and fused layer modeling (FLM) processes. Rapid Prototyp J 2020;26(6):993–1003.
[60] Ecker JV, Haider A, Burzic I, Huber A, Eder G, Hild S. Mechanical properties and water absorption behaviour of PLA and PLA/wood composites prepared by 3D printing and injection moulding. Rapid Prototyp J 2019;25(4):672–8.
[61] Yu Y, Guo Y, Jiang K. Temperature field simulation of wood powder/PES composite powder material. In: Key engineering materials; 2016. p. 218–23.
[62] Rana MN, Islam MN, Nath SK, Das AK, Ashaduzzaman M, Shams MI. Influence of chemical additive on the physical and mechanical properties of cement-bonded composite panels made from jute stick. J Build Eng 2020;31.
[63] Masek A, Latos-Brozio M. The effect of substances of plant origin on the thermal and thermo-oxidative ageing of aliphatic polyesters (PLA, PHA). Polymers 2018;10(11).
[64] Miklecic J, Jirous-Rajkovic V. Influence of thermal modification on surface properties and chemical composition of beech wood (Fagus sylvatica L.). Drv Ind 2016;67(1):65–71.
[65] Correa D, Papadopoulou A, Guberan C, Jhaveri N, Reichert S, Menges A, et al. 3D-Printed wood: programming hygroscopic material transformations. 3D Print Addit Manuf 2015;2(3):106–16.
[66] Du J, Wang YY, Xie XF, Xu M, Song YM. Styrene-assisted maleic anhydride grafted poly(lactic acid) as an effective compatibilizer for wood flour/poly(lactic acid) bio-composites. Polymers 2017;9(11).
[67] Ding Y, Zhang M, Gong F, Xu J. Effect of in-situ compatibilization technique on the mechanical properties and dynamic rheological behaviors of PS/EPDM blends. Polym Mater Sci Eng 2013;29(2):78–81.
[68] Sabirova GA, Safin RR, Galyavetdinov NR, Shaikhutdinova AR, Khayrullin RZ. Studying the rheological properties of a polylactide melt mixed with wood filler. Lesnoy Zhurnal-Forest J 2021;(1):173–9.
[69] Girdis J, Gaudion L, Proust G, Loschke S, Dong A. Rethinking timber: investigation into the use of waste macadamia nut shells for additive manufacturing. JOM (J Occup Med) 2017;69(3):575–9.
[70] Akbarian M, Hassanzadeh S, Moghri M. Short Twaron aramid fiber reinforced thermoplastic polyurethane. Polym Adv Technol 2008;19(12):1894–900.
[71] Yao XL, Qi XD, He YL, Tan DS, Chen F, Fu Q. Simultaneous reinforcing and toughening of polyurethane via grafting on the surface of microfibrillated cellulose. ACS Appl Mater Interfaces 2014;6(4):2497–507.
[72] Wang JHZ, B.K., Zhu LP, You-Yi XU. Fabrication of maco-nano hierarchical structure hybrid surfaces based on ultrahigh molecular poly(styrene-alt-maleic). J Funct Mater 2014;45(5):5041–4.
[73] Goh GD, Yap YL, Tan HKJ, Sing SL, Goh GL, Yeong WY. Process-structure-properties in polymer additive manufacturing via material extrusion: a review. Crit Rev Solid State Mater Sci 2020;45(2):113–33.
[74] El-Shekeil YA, Sapuan SM, Abdan K, Zainudin ES. Influence of fiber content on the mechanical and thermal properties of Kenaf fiber reinforced thermoplastic polyurethane composites. Mater Des 2012;40:299–303.
[75] El-Shekeil YA, Sapuan SM, Jawaid M, Al-Shuja'a OM. Influence of fiber content on mechanical, morphological and thermal properties of kenaf fibers reinforced poly(vinyl chloride)/thermoplastic polyurethane poly-blend composites. Mater Des 2014;58:130–5.
[76] Vajrasthira C, Amornsakchai T, Bualek-Limcharoen S. Fiber-matrix interactions in aramid-short-fiber-reinforced thermoplastic polyurethane composites. J Appl Polym Sci 2003;87(7):1059–67.
[77] Zo HJ, Joo SH, Kim T, Seo PS, Kim JH, Park JS. Enhanced mechanical and thermal properties of carbon fiber composites with polyamide and thermoplastic polyurethane blends. Fibers Polym 2014;15(5):1071–7.
[78] Zhang JS, Yang YT, Qin ZK, Luo JJ, Gao W, Wei SL. Research progress of the modified wood powder for 3D printing. In: Zhu SH, editor. Proceedings of the 2016 4th international conference on mechanical materials and manufacturing engineering; 2016. p. 574–7.

[79] Chung HJ, Lee EJ, Lim ST. Comparison in glass transition and enthalpy relaxation between native and gelatinized rice starches. Carbohydr Polym 2002;48(3):287–98.
[80] Lee SY, Kang IA, Doh GH, Yoon HG, Park BD, Wu QL. Thermal and mechanical properties of wood flour/talc-filled polylactic acid composites: effect of filler content and coupling treatment. J Thermoplast Compos Mater 2008;21(3):209–23.
[81] Mathew AP, Oksman K, Sain M. The effect of morphology and chemical characteristics of cellulose reinforcements on the crystallinity of polylactic acid. J Appl Polym Sci 2006;101(1):300–10.
[82] Li TJ, Aspler J, Kingsland A, Cormier LM, Zou XJ. 3D printing - a review of technologies, markets, and opportunities for the forest industry. J Sci Technol Forest Prod Proces 2015;5(2):60–7.
[83] Mayo SC, Chen F, Evans R. Micron-scale 3D imaging of wood and plant microstructure using high-resolution X-ray phase-contrast microtomography. J Struct Biol 2010;171(2):182–8.
[84] Joris 3D printing in wood flour. 2011. http://i.materialise.com/blog/entry/3d-printing-in-woodflour [Accessed January 2020].
[85] Aydin M. Use of 3D printing in furniture production. Akademik Platform; 2019. https://pdfs.semanticscholar.org/fe9d/9285977034760236e4fdd827deb5860e942c.pdf [Accessed January 2020].
[86] Ayrilmis N, Kuzman MK, Sernek M, Kariz M. Use of wood in 3d printing technology - case Studies. In: Glavonjic B, editor. Increasing the use of wood in the global bio-economy; 2018. p. 283–9.
[87] Grujovic N, Zivic F, Zivkovic M, Sljivic M, Radovanovic A, Bukvic L, et al. Custom design of furniture elements by fused filament fabrication. Proc IME C J Mech Eng Sci 2017;231(1):88–95.
[88] Murmura F, Bravi L. Additive manufacturing in the wood-furniture sector: sustainability of the technology, benefits and limitations of adoption. J Manuf Technol Manag 2018;29(2):350–71.
[89] Pop MA, Croitoru C, Bedo T, Geaman V, Radomir I, Cosnita M, et al. Structural changes during 3D printing of bioderived and synthetic thermoplastic materials. J Appl Polym Sci 2019;136(17).
[90] Xu P, Hu M, Li N, Gao X. Magnetic controlled variable diameter Nozzle for Wood powder 3D printer. Rev Técnica Fac Ing Univ del Zulia 2016;39(8):77–84.
[91] Pitt K, Lopez-Botello O, Lafferty AD, Todd I, Mumtaz K. Investigation into the material properties of wooden composite structures with in-situ fibre reinforcement using additive manufacturing. Compos Sci Technol 2017;138:32–9.
[92] Liu L, Lin M, Xu Z, Lin M. Polylactic acid-based wood-plastic 3D printing composite and its properties. BioResources 2019;14(4):8484–98.
[93] Stokke DD, Gardner DJ. Fundamental aspects of wood as a component of thermoplastic composites. J Vinyl Addit Technol 2003;9(2):96–104.