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Wood 4 Sustainability

Processing, Construction, Products and Design

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Főszerkesztő: Dr. Csiha Csilla

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Tartalom

Wood-based composites for 3D printing filaments to use in technical applications

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ABSTRACT

In recent years, additive manufacturing has gained growing importance in industrial, healthcare, and prototype development. FDM (Fused Deposition Modeling) and resin technologies dominate desktop 3D printing, offering diverse materials, including PLA (polylactic acid) and PETG (polyethylene terephthalate glycol). PLA is biodegradable, compostable, and recyclable, while PETG offers higher impact and heat resistance, making it better suited for industrial applications despite being non-biodegradable. The potential of 3D printing extends beyond polymers, with applications in metalworking and mechanical engineering. While wood-containing PLA filaments are available, the use of additive manufacturing in the woodworking industry remains underexplored. This review, complemented by original research, seeks to develop proprietary wood-based filaments for additive manufacturing.

Key considerations include material strength, weight, surface quality, hygroscopicity, and dimensional stability. The cost-effectiveness and eco-friendliness of FDM technology make it widely accessible, yet demand persists for stronger, lighter, and sustainable materials. Current wood-based materials allow for high-quality, aesthetic products, but limited data on wood species, concentration, and particle size distribution presents opportunities for further research to optimize material performance.

In this paper there were also compared some typical wood-based filaments available on market.

Keywords: 3D printing, FDM printing, wood-based filament, compounding wood and polymer, Industry, innovation and infrastructure

1. Introduction

In recent decades, the industrial, healthcare, and prototype development applications of additive manufacturing technologies have gained increasing significance. FDM (Fused Deposition Modeling) and resin technologies are primarily used in desktop 3D printers, yet a wide variety of materials are available for these technologies. Two common materials are PLA (polylactic acid) and PETG (polyethylene terephthalate glycol). PLA is a plant-based polymer that is fully biodegradable under suitable conditions, compostable, and highly recyclable. PETG, on the other hand, is highly impact-resistant, more heat-resistant than PLA, and therefore better suited for industrial applications, but it is non-biodegradable.

The industrial applications of 3D printing are on the rise, not only in polymer technology but also in metalworking and mechanical engineering. Wood-containing PLA filaments exist, but the use of additive manufacturing technologies in the woodworking industry remains a relatively unexplored area. This review extended with some own research results aims to delve into wood-based 3D printing by developing a proprietary wood-based filament.

As mentioned earlier, the development of additive manufacturing technologies and the emergence of new applications are driving the demand for new printing materials with advanced properties. From a technical perspective, weight and strength properties are among the most important factors. In addition to these, surface quality, hygroscopicity, and dimensional stability are also critical considerations.

Manufacturers of additive manufacturing technologies produce printing materials with various properties depending on their composition. In FDM technology, for example, the primary difference between PLA and PETG is that the latter is more heat-resistant and better withstands dynamic impacts, making it more suitable for industrial applications than PLA. FDM technology, with its relatively low acquisition, operational, and material costs, remains one of the most competitive choices for general users. However, the materials offering better strength and lighter weight tend to be more expensive, making the development of affordable, eco-friendly, and strong materials highly competitive.

For technical and other applications, surface quality and roughness are important factors. In FDM technology, users can choose from high-quality, premium-priced materials, reduced-plastic products, or materials modified with fillers. Using the wood-based printing materials available on the market, it is possible to produce high-quality, aesthetically pleasing products. However, manufacturers typically only provide information about the concentration or type of wood species used. In most cases, the fraction of wood flour determines particle size. Research indicates that incorporating 10% wood content by weight improves strength properties. It would be interesting to compare different particle sizes at the same concentration and examine mixtures with various particle distributions and concentrations for specific printing materials.

2. Wood-based filaments for 3D printing

To understand the properties of wood-based printing materials, they must be compared with traditional printing materials. The basis for comparison can be established through various technical aspects.

2.1. Strength properties

Various studies investigate the properties of bio-fillers in materials, including wood-based filaments, with strength being one of the most important technical aspects. The strength of biocomposite printing materials is heavily influenced by the base matrix material and the type and ratio of the added filler. Different polymers exhibit varied behaviors depending on the amount of filler used. While this research primarily focuses on wood-based filaments, it also briefly examines filaments reinforced with other natural fibers.

Maddah (2016) identifies ABS (acrylonitrile-butadiene-styrene) as a widely used material in FDM 3D printing. With a tensile strength of 30-45 MPa, ABS slightly underperforms compared to PLA but is more heat-resistant, has a lower density (~1.04 g/cm³), and is chemically resistant, making it suitable for food industry applications. Maddah also highlights polypropylene (PP), with a tensile strength of 20-35 MPa, lower than PLA's, but with a much lower density (~0.9 g/cm³). Polyethylene (PE), similar to polypropylene, is rarely used in 3D printing.

Mazzanti et al. (2019) found that adding natural fibers improves the strength of polypropylene. Incorporating 30% hemp fibers increased tensile strength by about 50% and stiffness more than doubled. For PLA, adding up to 10% wood flour resulted in a slight strength increase, beyond which strength decreased.

In conclusion, while PLA shows the best strength properties among the materials discussed, higher filler ratios do not yield the same strength improvements as seen with PE, as shown in. Research on the strength of ABS, PLA, and PE biocomposites based on filler ratios reveals that ABS strength decreases significantly up to 10% filler, then increases, while PLA stiffness increases up to 10% filler and stabilizes. ABS stiffness decreases until 10% filler, then slightly increases, while PE stiffness rises significantly.

2.2. Effect of relative humidity on wood-based filaments

When ensuring the strength of a product, its dimensional stability is equally crucial. The dimensional changes in wood and wood-based products are influenced by temperature and relative humidity, which also impact the stability of wood-based printing materials. A study by Kariz et al. (2018) extruded mixtures with 10%, 20%, 30%, 40%, and 50% wood flour and subjected them to bending strength and swelling tests under climate conditions of 20°C at RH33%, RH65%, and RH87%, where RH represents relative humidity. The results showed that adding wood generally decreased the flexural modulus of elasticity. However, higher wood content sometimes increased the modulus, which varied with the climate. For example, increasing wood concentration from 30% to 40% at RH33% and RH65% increased the modulus, but it decreased at RH87%. For 10% wood content, the modulus values were 844 MPa at RH33%, 768 MPa at RH65%, and 791 MPa at RH87%.

In their investigation of dimensional stability, Kariz et al. (2018) measured length changes of conditioned samples in these climates compared to dry conditions. The results showed that length changes increased with wood content and humidity, indicating that lower wood content provides better dimensional stability.

2.3. Surface quality of wood-based filaments

In addition to strength and dimensional stability, surface quality is a key property of a product. For everyday objects, surface roughness is often the most crucial aspect, as it affects the safety and usability by ensuring a firm grip and preventing slipperiness. As wood content in a material increases, surface roughness also changes, a trend that is visually noticeable. In a related study, Ayrilmis et al. (2019) examined the surface roughness of PLA mixed with 10%, 20%, 30%, 40%, and 50% wood content. They analyzed printed specimens in various printing orientations, where orientation refers to the measurement plane being either parallel or perpendicular to the printing direction. In FDM technology, anisotropy occurs due to cohesion within the printing plane and adhesion perpendicular to it, making products more brittle in the direction perpendicular to the print plane. The study measured surface roughness along the y-axis (printing plane) and perpendicular to it, in addition to the average surface roughness. Results revealed that with just 10% wood content, the surface roughness more than doubled in all orientations. Roughness was higher in the printing plane compared to perpendicular measurements, due to the printing direction along the x-axis and measurements along the y-axis. At 50% wood content, the increase in roughness became less pronounced.

Tomec et. al (2024) investigated the impact of wood particle thermal modification on the properties of wood-PLA filaments and 3D-printed components. They compounded wood and PLA in 10% and 20% mass ratios and compared various properties of the control samples with those made from thermally modified wood flour (200°C). It was used beech (*Fagus sylvatica*) in sieved form (below 0.25 mm). Samples were printed by a Creality CR-10-V3 FDM printer in tensile test pieces shape. They experienced the increase of the surface roughness of the filaments with the wood ratio. Filaments containing thermally modified wood elements showed lower roughness (by 14% in case of 10% ratio and by 28% in case of 20% woof ratio).

2.4. Effect of printing orientation on strength

Zandi et al. (2020) studied the effect of FFD printing process on tensile properties of wood-PLA composite parts. They applied wood (beech – *Fagus sylvatica*) ratio of 5–10%, and three printing orientations of X-axis, 45° X-axis and Z-axis. They also used three different filling density by grid infill of 25%, 50% and 75%. For tensile test standard ‘dog bone’ shaped test pieces were printed. It was established that the all-over best combination of printing parameters were Z-axis orientation, 75% fill density and 0.4 mm layer thickness to achieve the highest mechanical properties. Since the direction of the printed layers in the Z-axis orientation is parallel with the test axis, it causes the highest strength values compared to other orientations.

Yao et al. (2019) investigated a method to predict the effect of printing orientation on tensile strength of FDM printed PLA. It was used a 100% fill density and seven orientations as follows: 0°, 15°, 30°, 45°, 60°, 75° and 90°. They applied 0.1 mm, 0.2 mm and 0.3 mm layer thickness. Here also standard ‘dog bone’ shaped test pieces were printed. It was found that by increase of layer thickness the tensile strength was decreased. In case of 0.3 mm layer height the tensile strength resulted the values showed in Table 1.

Table 1. Tensile strength of 3D printed PLA at various printing angles (layer height 0.3 mm) (based on the report by Yao et al. 2019)

Printing angle	0°	15°	30°	45°	60°	75°	90°
Mean tensile strength [MPa]	23.78	~28.8	~29.5	29.19	~34.8	~39.3	45.26

Gordelier et al. (2019) reviewed the optimization of FDM printing to achieve maximal tensile strength. They reported among others the effect of printing orientation on tensile properties.

Song et al. (2017) printed PLA blocks with 0°, 45° and 90° orientation (90° considered parallel) with 100% infill density. They found that the material exhibits a significant disparity between tension and compression behavior, with the compressive flow stress significantly surpassing the tensile flow stress in all directions. This difference arises from the early onset of cohesion loss during the tensile response.

Letcher & Waytashek (2014) evaluated the mechanical properties of PLA filament and 3D-printed PLA specimens. Tensile testing revealed that specimens with a 45° raster orientation exhibited the highest strength. Conversely, fatigue testing demonstrated that specimens with a 90° orientation (90° considered perpendicular) were the most susceptible to fatigue-induced failure.

Afrosa et al. (2016) also tested the three main orientation (X-orientation: 0°, 45° and Y-oriantation: 90°, where 0° was considered parallel) of PLA for tensile properties. The PLA samples constructed with parallel deposison exhibited the highest tensile strength, reaching 38.7 MPa, which corresponded to approximately 60–64% of the strength of the raw PLA material.

Tymark et al. (2014) analyzed 0°/90 and +45°/-45° orientations. They experienced that between the 0°/90° and + 45°/ 45° orientations, the latter was the strongest, but 0°/90° had the larger MOE.

3. Comparison of wood-based filaments available on the market

We examined the key characteristics of commercially available filaments, rather than those specially developed for laboratory conditions.

Many manufacturers' products are sold by various online stores, with a separate category specifically for wood-based PLAs among the printing materials. Here, the offering is divided, as there are products that genuinely contain wood and others that are labeled as "wood filament" purely for marketing purposes. The latter often falls into a lower price category. In addition to quality and brand, manufacturers frequently emphasize environmental consciousness, such as using recycled wood or blending the wood chips with reduced plastic content or bio-PLA, which in some cases justifies a higher price.

Some manufacturers provide information about the wood content ratio. There are printing materials with 10%, 20%, 30%, and 40% wood content available in online shops. Others provide no such information, only stating that the material is wood-based. Some even specify the wood species used, but this should be approached with caution, as often only a dye is added to the mixture. To determine whether there is a real difference between mixtures containing different types of wood from the same manufacturer, we conducted a few comparative tests.

3.1. Materials and methods

3.1.1. Strength tests

In the study, it was examined the tensile strength of PLA filaments with different wood contents available on the market (Table 2.), both in the printing direction and perpendicular to it, while also determining their density with density samples to gain insight into the effects of wood content on the printing materials. The test includes measuring the tensile strength of four different filaments in the printing direction, and three of the materials are tested perpendicular to the printing direction, with three samples for each material. For determining the density of the materials, 10x10x10 mm cubes were printed with 100% infill. The test in the printing direction provides a general understanding of the material, while the perpendicular test shows the adhesion of the printing layers.

For the tests, a control PLA (100%), 40% pine, 40% bamboo, and 30% wood PLA filaments were used, each with three samples. It is worth noting that although bamboo is a grass, the manufacturer markets it as a wood-based material, which is why it is included in the study. The pine and bamboo-based filaments are from the same manufacturer and product line, allowing us to examine the properties of different wood species in the filament, such as density and strength. The manufacturer of the 30% wood PLA does not disclose the type of wood used. None of the manufacturers provide information on particle size or distribution on the technical data sheet.

The following parameters were used for printing the samples:

- nozzle material, diameter: hardened, steel, 0.6 mm,
- layer height: 0.2 mm,
- printing temperature: 200 °c,
- bed temperature: 60 ºc,
- printing speed: 50 mm/s,
- toolpath angle: 90°,
- infill factor: 100%,
- position: laying flat on the bed.

A MakerBot Method X desktop 3D printer was used for printing the samples.

With the given parameters, the following test specimens shown in Figure 1. were printed based on EN ISO 527-2 standard.

Table 2. Density of the tested filaments

Material	Producer	Species	Filler content (mass%)	Size (cm³)	Mass (g)	Density (g/cm³)
PLA	Eryone	-	0%	1.04	1.22	1.18
Wood PLA (30%)	R3D	wood (non specified)	30%	1.04	1.28	1.23
Bamboo PLA (40%)	AzureFilm	bamboo	40%	1.01	1.15	1.14
Pine PLA (40%)	AzureFilm	pine	40%	0.99	1.15	1.16

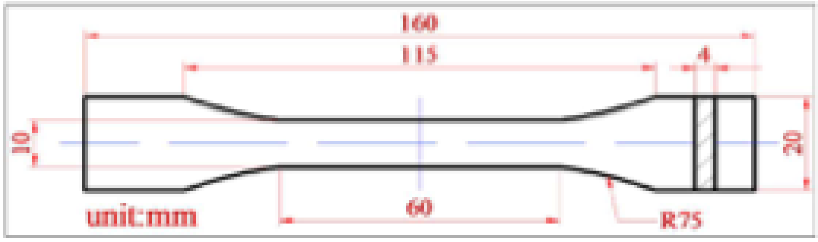

Figure 1. Design of the test specimen used

The tensile strength test was carried out at the University of Sopron in the KVL laboratory, using an Instron 5566s material testing machine.

3.1.2. Effect of anisotropy and layer adhesion

To assess the adhesion between the layers of the filament, the tensile strength perpendicular to the printing orientation is a useful indicator, as it reflects how well the layers are held together. To quantify the degree of anisotropy, it was considered the ratio of the tensile strength measured perpendicular to the printing orientation to the tensile strength measured along the printing orientation. This ratio provides insight into the proportion of the tensile strength achieved perpendicular to the layers compared to within the layers, which can be useful during design. In this investigation, it was examined the tensile strength perpendicular to the printing orientation of traditional PLA, 30% wood-filled PLA, and 40% pine-filled PLA. At the time of the study, there was insufficient material available for printing test specimens of Bamboo-PLA, but an estimation of its value can be made by comparing it to Pine-PLA.

For the study, three test specimens were printed for each material with the following parameters:

- nozzle material: hardened steel,
- nozzle diameter: 0.6 mm,
- layer height: 0.2 mm,
- printing temperature: 200 °C,
- bed temperature: 60 °C,
- printing speed: 50 mm/s,
- tool path angle: 90°,
- infill density: 100%,
- position: standing on the bed (not lying flat).

The only change made to the geometry of the test specimens compared to the previous ones was in their length. The modified test specimen dimensions are shown in Figure 2.

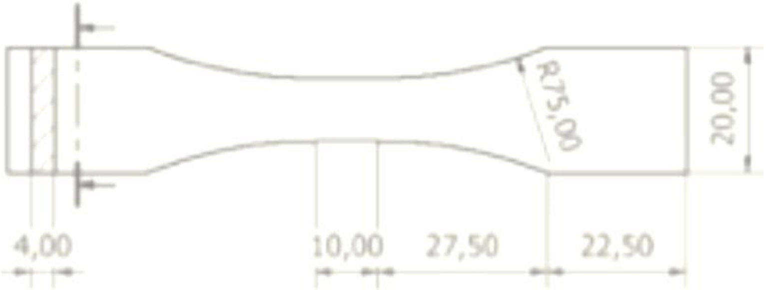

Figure 2. Modified test specimen design

The tensile strength testing perpendicular to the printing orientation took place at Sopron University in the KVL laboratory, using an Instron 5566s material testing machine.

3.2. Strength testing of wood-based printing materials available on the market

In the case of regular PLA, there was shrinkage in the first layers, and the upper layers were strongly bulged and smeared. The surface felt entirely plastic-like, with a glossy finish. For the 30% wood PLA, the upper layers were smoother, and the lower layers adhered nicely to the build plate. This material felt matte due to the wood content. For the pine and bamboo-based filaments, the lower layers smoothed out nicely, and the upper layers were also smooth.

The surface was matte, and the wood content was more noticeable in both texture and color compared to the previous sample. The strength test results are shown in Table 3.

Table 3. Mean tensile strength comparison of samples

Material	Cross-sectional Area (mm²)	Tensile Load (N)	Tensile Strength (MPa)	Elongation (%)
PLA	42.28	1866.00	44.14	37.46
Wood PLA (30%)	42.40	1362.00	32.12	26.13
Bamboo PLA (40%)	39.86	887.00	18.95	19.58
Pine PLA (40%)	40.01	994.33	24.85	21.42

The load-deformation diagrams can provide insights into the failure characteristics.

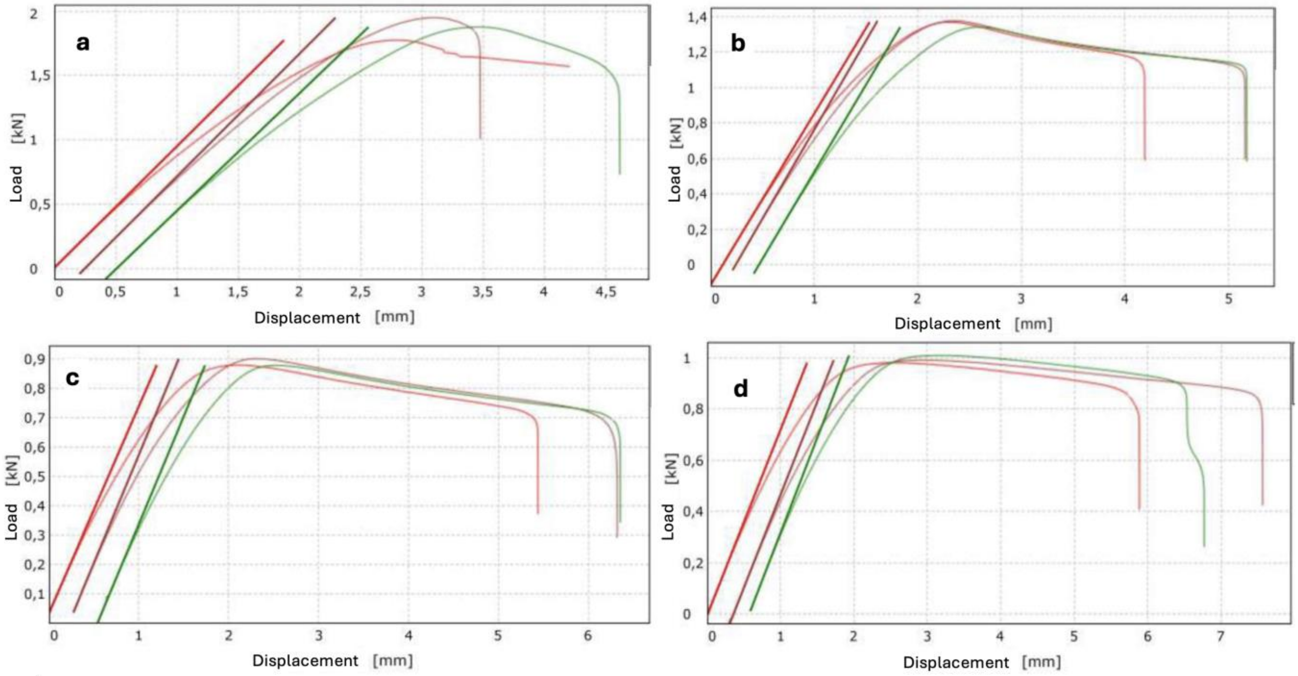

Figure 3. The load-deformation diagram of the test samples

Figure 3.a. shows the load-deformation diagram of PLA with 0% wood content. From this, it is visible that the breaking elongation was approximately 3.5-4.6 mm, and the tensile force exceeded 1700 N in all cases.

Figure 3.b. displays the load-deformation diagram of PLA with 30% wood content. It is clear that with increasing wood content, the tensile force decreased and did not exceed 1400 N, while the breaking elongation increased to approximately 4.2-5.3 mm.

Figure 3.c. shows the load-deformation diagram of PLA with 40% bamboo content. As the wood content increased, the tensile force further decreased, and the elongation increased.

Figure 3.d. illustrates the load-deformation diagram of PLA with 40% pine content. A noticeable difference compared to the bamboo-PLA is that despite being from the same manufacturer and having the same concentration, the pine-based material exhibited greater elongation and a "flatter" contraction phase before failure. In light of this, we will examine the different products from the manufacturer to determine whether the wood species affect the filament properties.

By plotting the averages of the measurement results on a graph, we can better compare the properties of the materials. The tensile strength values for the printing orientation are presented in Figure 4.

As shown in the diagram, the presence of wood content reduces the tensile strength. Among the wood-based printing materials, the Wood-PLA with 30% wood content achieved the best result, with a tensile strength of 32.12 MPa. The results for bamboo-PLA and pine-PLA also confirm the effect of the wood species on the filaments. It is also interesting to observe the relationship between wood content and measurement error, as the largest variation in results occurred for the traditional PLA.

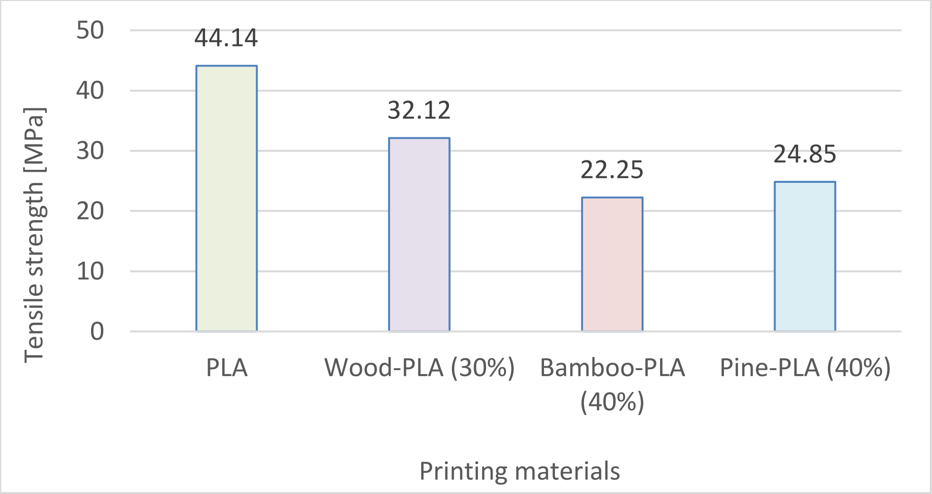

Figure 4. Tensile strength of printing materials in printing orientation

In addition to strength values, an important consideration is the strength-to-density ratio of a material. This ratio allows us to infer the mass of a product that can be used to solve a task with a given material. If we choose a material with lower strength for a specific load, we must increase the cross-sectional area to achieve the required resistance, thereby increasing the product's mass as well. Thus, a material with a lower strength-to-density ratio would result in a heavier product to fulfill the same task.

During the tests, this aspect was also taken into account, and the strength-to-density ratio for the printing orientation is shown in Figure 5. As seen in the diagram, this test aspect follows a similar trend to the previous results.

The 40% pine and 40% bamboo-based printing materials come from the same manufacturer but contain different fillers. It is important to note that although bamboo is a grass, the manufacturer refers to it as a wood-based material, and bamboo is also a common raw material in many everyday products.

To understand the effect of wood species on filament properties, we compared the results of the different materials. The data are presented in Table 4.

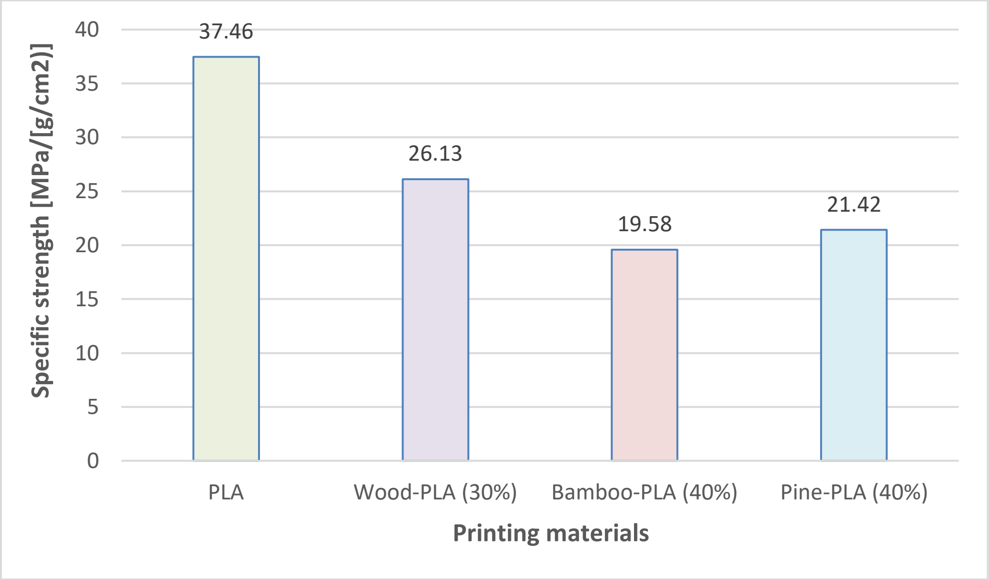

Figure 5. Strength-to-density ratio of printing materials in printing orientation

Table 4. Comparison of Different Materials from the Same Manufacturer

Property	Bamboo-PLA	Pine-PLA
Density (g/cm³)	1.14	1.16
Tensile Strength Average (MPa)	22.25	24.85
Standard Deviation (%)	1.52%	0.68%
Strength-to-Density Ratio Average (MPa/(g/cm³))	19.58	21.42
Standard Deviation (%)	1.53%	0.7%

3.3. Comparison of various printing materials from the same manufacturer

The test specimens were created using identical printing parameters. The sizes of the finished specimens can provide insights into how accurately a product can be manufactured using a given material. The data for this is shown in Table 5.

The most significant results are also illustrated in diagrams, and the comparison of technical properties is shown in Figure 6.

From the chart, it can be observed that although Pine-PLA is only about 2% denser than Bamboo-PLA, it offers almost a 12% improvement in tensile strength. As a result, the strength-to-density ratio is also higher for Pine-PLA, with a difference of almost 11%.

In addition to these properties, the accuracy of the printed product's dimensions is also an important factor. From the data presented in Table 4, it is clear that the average cross-sectional area of Pine-PLA is closer to the nominal cross-sectional area of the test specimen. However, due to the relatively larger variation in the width dimension, the standard deviation of these measurements is also higher than that of Bamboo-PLA.

Figure 6. Comparison of pine-PLA and bamboo-PLA

Table 5. Manufacturing Precision of Printing Materials from the Same Manufacturer

Material	Width (mm)	Thickness (mm)	Cross-sectional Area (mm²)
Bamboo-PLA	10.06	3.96	39.86
	±0.02	±0.02	±0.09
Pine-PLA	10.08	3.97	40.00
	±0.06	±0.01	±0.32

3.4. Investigation of anisotropy and layer adhesion in printing materials available on the market

The tensile strength test results perpendicular to the printing orientation are shown in Table 6.

Table 6. Tensile strength test results perpendicular to the printing orientation

Material	Cross-sectional Area (mm²)	Tensile Load (N)	Tensile Strength (MPa)	Strength/ Density (MPa/(g/cm^3))
PLA	42.13	466.00	10.95	9.30
Wood PLA (30%)	43.14	513.00	11.89	9.67
Pine PLA (40%)	40.15	357.67	8.91	7.67

The load-deformation diagrams here are quite different from those measured in the printing orientation (Figure 7.).

Figure 7.a. shows that the tensile strength measured perpendicular to the printing orientation falls significantly short compared to that measured in the printing orientation. Additionally, the contraction phase is absent, and the specimen fractured in a brittle manner. It is worth noting that one of the traditional PLA specimens broke during placement in the testing machine, leaving only two measurement results available.

Figure 7.b. shows that the wood content increases the fracture elongation even when measured perpendicular to the printing orientation. Interestingly, the results exhibit significantly lower variation, with each specimen breaking at approximately 500 N of tensile force. In contrast, for traditional PLA, there was a difference of several hundred Newtons between the two specimens.

Based on the force-displacement diagram of the pine-PLA (Figure 7.c.), it is further confirmed that the wood content increases the fracture elongation while reducing the tensile strength. In this case, the variation in results is larger compared to the material containing less wood. For clearer comparisons, the averages of the results are also organized into diagrams.

The neat PLA not only exhibited lower tensile strength values but also significantly higher error was observed, with a relative standard deviation of nearly 50%.

As previously mentioned, let us examine the ratio of the tensile strength perpendicular to the printing orientation ($\sigma_{\perp}/\sigma_{\parallel}$) to the tensile strength measured in the printing orientation.

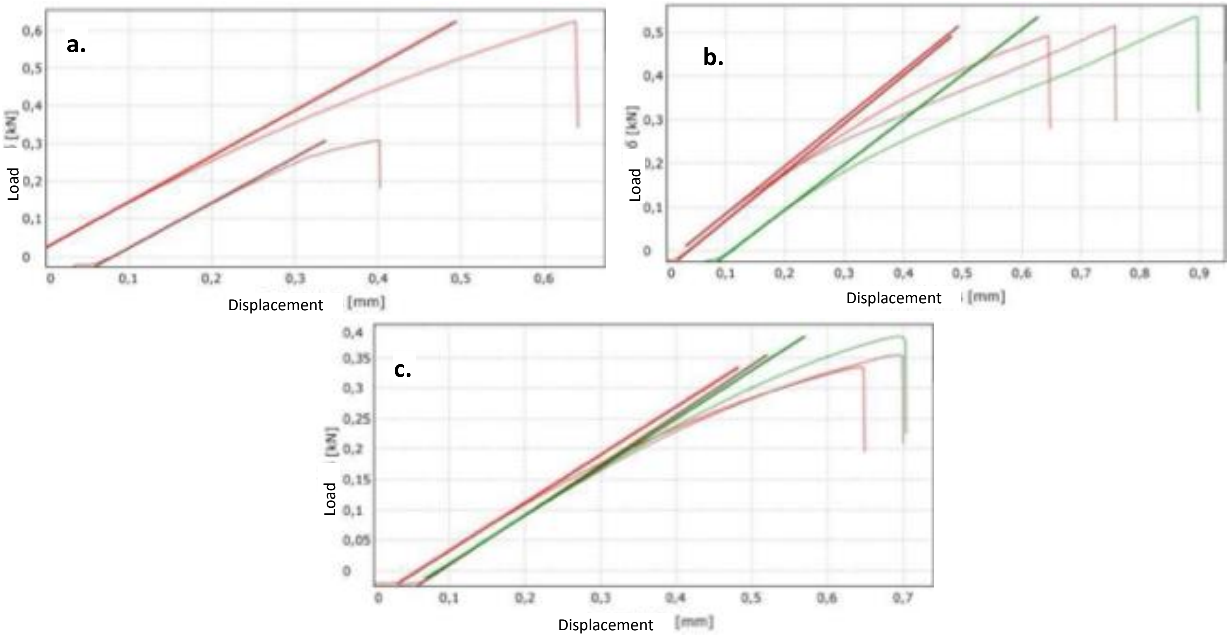

Figure 7. Force-displacement diagrams perpendicular to the printing orientation

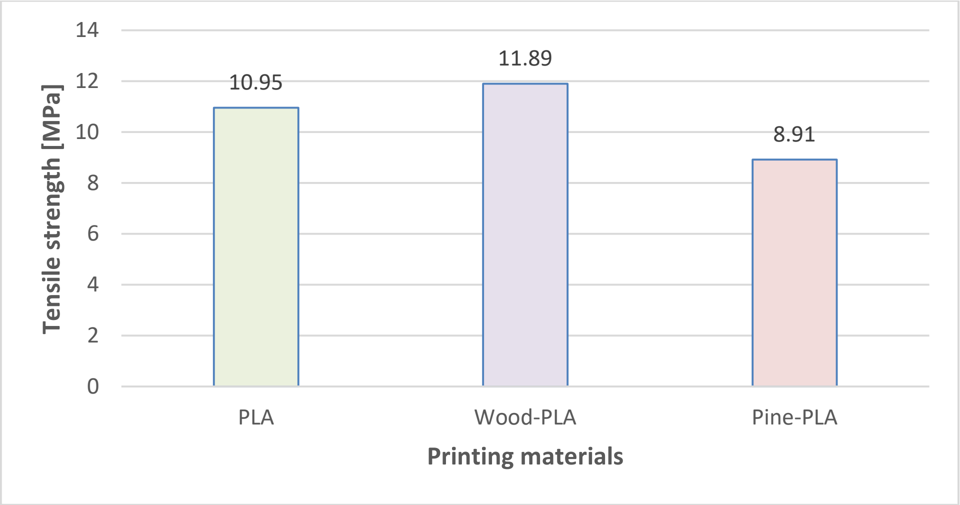

Figure 8. Tensile strength of printing materials perpendicular to printing orientation

The influence of wood content demonstrates the most significant improvement in this property evaluation. As seen in Figure 9, traditional PLA achieves less than 25% of its tensile strength measured in the printing orientation when tested perpendicular to the printing orientation. In contrast, for wood-PLA and pine-PLA, this ratio exceeds 35%, making them less anisotropic materials. The wood-containing printing materials exhibit a nearly 50% higher $\sigma_{\perp}/\sigma_{\parallel}$ ratio, which is a particularly striking result.

In Table 6. the results of our tests are compared to other similar published results.

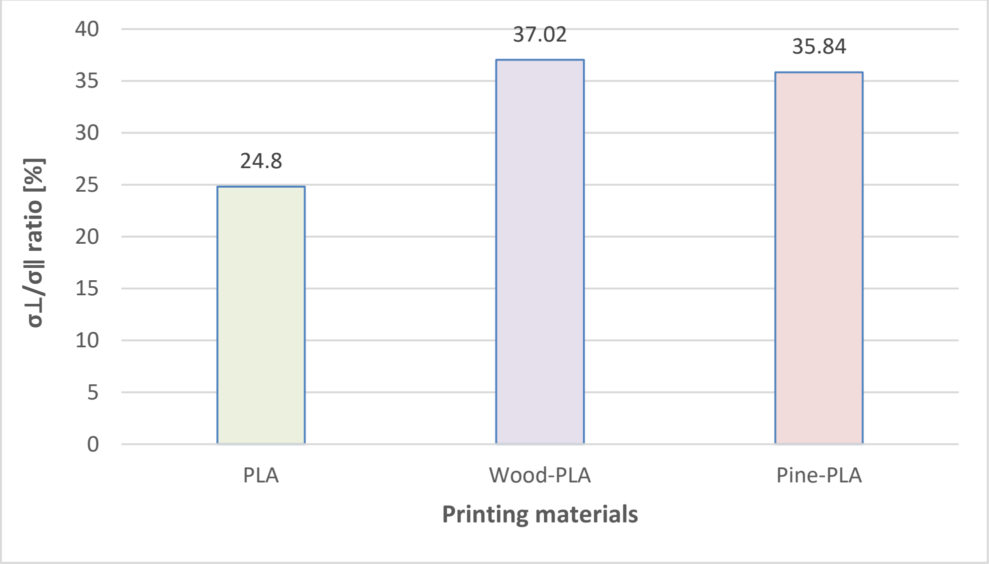

Figure 9. The $\sigma_{\perp}/\sigma_{\parallel}$ ratio of printing materials

Table 6. Comparison of effect of printing angle on the tensile strength

Material	Tensile strength parallel [MPa]	Tensile strength perpendicular [MPa]	Source
PLA	44.14	10.95	this report
Wood-PLA (30%)	11.95	11.89	
Pine PLA (40%)	24.85	8.91	
PLA	45.26	23.78	Yao et al. 2019
PLA	58.45	55.01	Letcher & Waytashek (2014)
PLA	38.7	31.1	Afrosa et al. (2016)

4. Summary and conclusion

Comparing on market available wood-based printing filaments the followings can be concluded. The application of wood-based printing materials can be an effective way to manufacture high-quality products. With increasing wood content, the product's texture becomes more matte and pleasant compared to traditional PLA, though its strength values decrease significantly. The examination of bamboo and pine PLA from the same manufacturer offers several insights regarding potential blends. Firstly, the choice of wood species is a critical factor, as in this case, pine-based materials yielded better results than bamboo-based ones, assuming identical particle sizes. Secondly, selecting the appropriate particle size and shape is equally important. Although bamboo has a higher tensile strength than pine species, the pine-based samples demonstrated greater overall strength due to the size of the fractions within the samples. The choice of wood species also affects dimensional precision during manufacturing, as bamboo-based samples exhibited smaller dimensional deviations compared to pine-based ones. While traditional PLA samples generally exhibited higher strength than wood-based ones, their strength properties were far more variable. From the final comparison and previous analyses, it is evident that a wood-based printing material can offer greater consistency and predictability as a design material, provided that optimal mixing parameters are used.

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Author statements

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