Jurnal Kejuruteraan 36(6) 2024: 2571–2577
https://doi.org/10.17576/jkukm-2024-36(6)-26

A Study on Mechanical Performance of 3D Printed Wood Mimic Materials

Abid Fariduddin Mohd Fauzi, Zaliha Wahid*, Nabilah Afiqah Mohd Radzuan, Nurhasyimah Abd Aziz, Afifah Zakiyyah Juri & Abu Bakar Sulong

Department of Mechanical and Manufacturing Engineering,

Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Malaysia

**Corresponding author: zaliha@ukm.edu.my*

Received 2 February 2024, Received in revised form 15 August 2024
Accepted 15 September 2024, Available online 30 November 2024

ABSTRACT

Wood has played a crucial role in the field of architecture, prototyping, and engineering, owing to its aesthetic appeal and specific mechanical properties tailored for diverse applications. The application 3D printing has facilitated the replication of natural materials like wood, enhancing both their visual and mechanical attributes. This research aims to investigate the mechanical properties of 3D printed PolyWood™ materials and compare them with those of real wood composites. The mechanical property assessments conducted on PolyWood™ samples encompass tensile, flexural, and compression tests. The obtained results are analyzed and compared with data from literature readings on real wood composites. The average tensile strength of PolyWood™ material is 20.31 MPa, the flexural strength is 31.36 MPa, and the compression strength reaches up to 21.70 MPa. In comparison with real wood composites, the PolyWood™ sample exhibits inferior performance in most mechanical properties. Regarding tensile strength, the performance of the material is comparable to other composite but is almost 50% lower than the Pure PLA performance. However, in term of Young's Modulus, a significant difference is observed across all references, indicating more flexibility and larger elastic deformation under a given load for PolyWood™ material. The differences on flexural strength were not obvious, with one research study showing lower strength. Finally, the compressive performance of real wood composites and pure PLA demonstrates superior resistance and strength when contrasted with PolyWood™ materials.

Keywords : Fused Deposition Modeling (FDM); PolyWood™; wood polymer composite

INTRODUCTION

Wood, the most common biological material, is a lightweight cellular composite with strong anisotropic mechanical properties that can compete with modern synthetic materials. Aesthetic criteria and artistic value are essential for some furniture prototypes and architectural models. High-performance bio-inspired materials can be generated through research into the complex structure and exceptional (mechanical) capabilities of biological materials (Tao et al. 2020). Natural materials, particularly biological ones, serve as a great source of inspiration for designing and manufacturing high-performance synthetic materials. The adaptability of wood extends to its transformation into powders, allowing for 3D printing through various additive manufacturing technologies like material extrusion techniques.

(with or without filament), powder bed fusion technology, liquid deposition modeling, and binder jetting (Das et al. 2021). Wood components are consisting of various fibers such as lignin, cellulose, nanocellulose that can be chemically prepared to be usable as printing materials for additive manufacturing techniques (Tomec & Kariz 2022). Cellular composition of wood is as depicted in Figure 1. The use of 3D printing makes it possible to replicate the lightweight structure found in wood (Tao et al. 2020). The investigation of wood-based materials in 3D printing encourages efforts to enhance and address challenges. These challenges include improving mechanical properties, reducing dimensional instability, minimizing part deformation, enhancing aesthetics, offering an eco-friendly substitute for carbon or glass-filled polymer matrices, and cutting down material expenses.

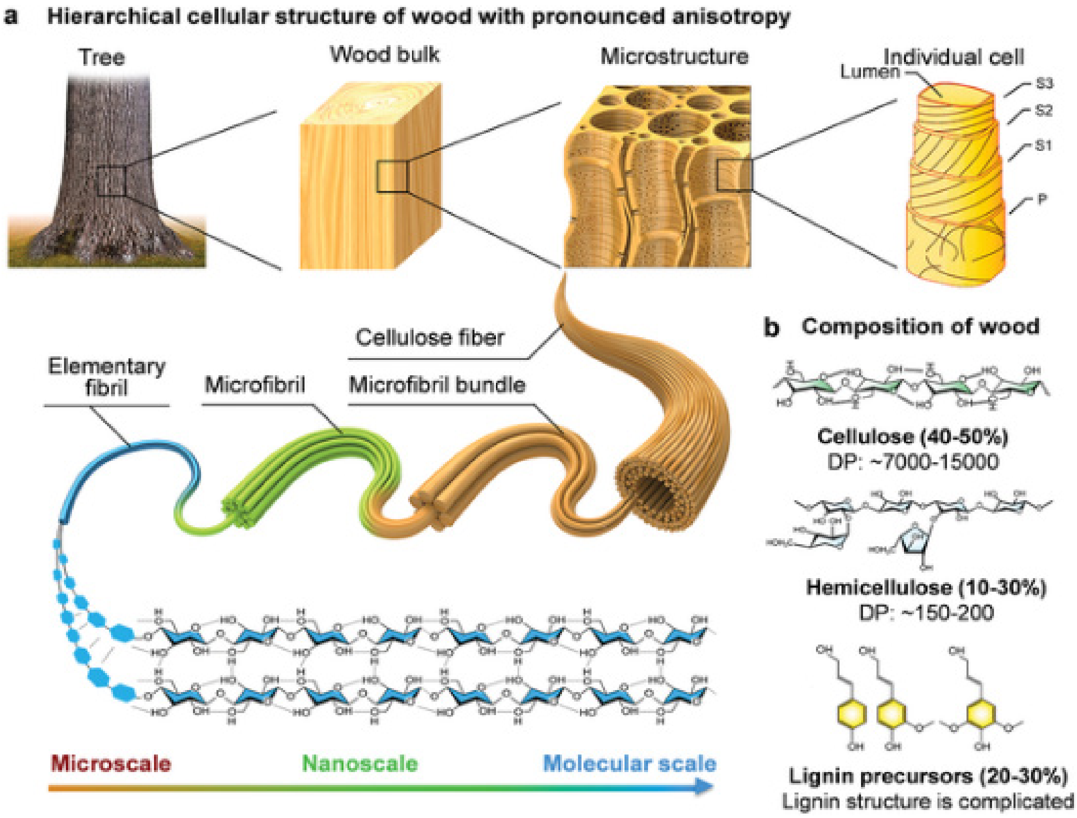

FIGURE 1. Hierarchical structure and compositions of woods
Source: Chaoji & Hu (2020)

To keep up with the rapid expansion of 3D printing, it is increasingly important to explore new materials, such as advanced composites, aesthetically refined choices, and high-performance materials designed for specific applications. (Norazyan et al. 2023). The raw material used in this study for the 3D printing process is PolyWood™, a commercially available filament by Polymaker. Parts fabricated with PolyWood™ material will have a wood-like appearance. Although the final parts mimic wood, the material is entirely made from PLA, without actual wood powder, and is claimed to resemble wood in terms of density and appearance. The material is innovated using Jam-Free™ technology, eliminating the risk of nozzle clogging normally associated with wood fiber in wood composite 3D printing (Zhu et al. 2020).

Apart from appearance, PolyWood™ was aimed to have the same density as real wood. Based on the material specification data provided by the manufacturer, the density of the material is only 0.8 g/cm^3. While real wood density usually falls between 0.35 and 0.85 g/cm^3, and the density of pure PLA, on the other hand, is 1.25 g/cm^3. The material is made with Stabilized Foaming™ technology to have very low density compared to its base material, PLA density.

Building on this information, the motivation behind this study is to assess whether the properties and appearance of printed PolyWood™ resemble those of wood or PLA. The study objectives are twofold: first, to evaluate the mechanical properties of 3D printed samples made from PolyWood™; and second, to compare the mechanical performance of PolyWood™ with that of 3D printed wood-polymer composites. The goal is to establish a clear classification and application for the material based on these properties.

METHODOLOGY

The research study followed the process outlined in Figure 2. Sample preparation adhered to the ASTM D638, ASTM D790, and ASTM D695 standards for tensile, flexural, and compressive testing, respectively. The compressive sample was 4 cm in height and 1 cm in diameter, maintaining the recommended 1:4 ratio as specified by the standard. All tests were conducted using a Universal Testing Machine. As shown in Figure 3, five samples were printed for each test to determine the average value. Additionally, the standard deviation was calculated to highlight the variance in the test results

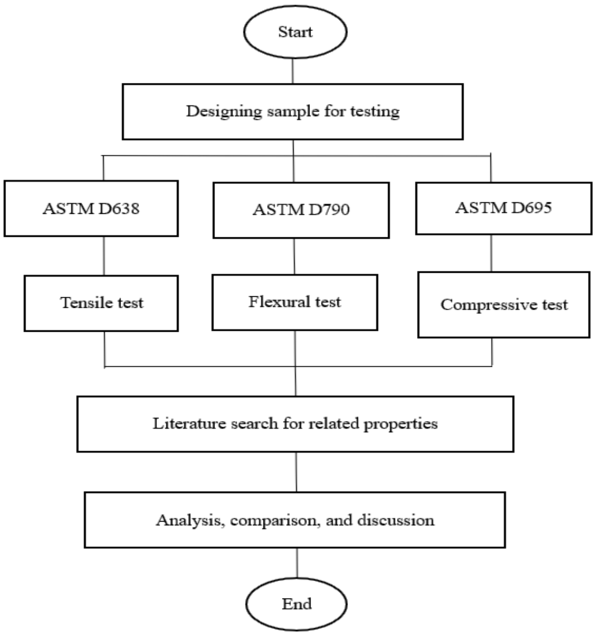

FIGURE 2. Flowchart of study

PolyWood™ by Polymaker, shown in Figure 3 is the material used in this study. The filament was printed using a Raise3D printer with settings that included a nozzle temperature of 210°C, a plate temperature of 60°C, and a printing speed of 45 mm/s. To reduce the risk of clogging, a larger nozzle size of 0.4 mm was employed in this study.

FIGURE 3. PolyWood™ filament

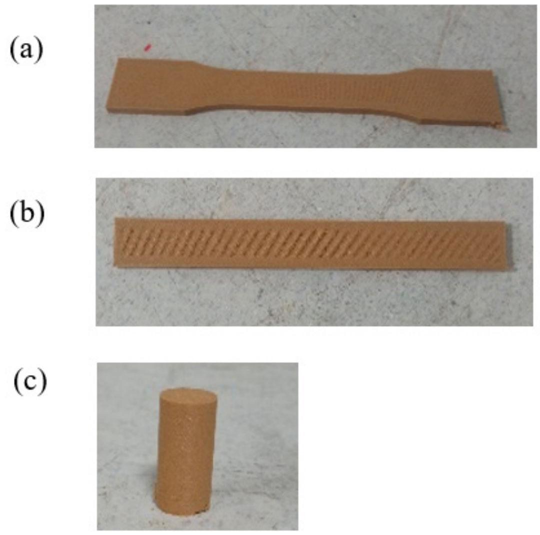

FIGURE 3. Printed sample for (a) tensile, (b) flexural, and (c) compressive tests

After conducting the tests, the obtained results undergo thorough analysis. Additionally, a comprehensive comparison is made to assess the performance of PolyWood™ in relation to other 3D printed wood composites documented in previous research. During the literature review, values are extracted from studies with diverse objectives, some of which examine the effects of wood composition rather than solely concentrating on the parameter of interest. In such cases, preference is given to values closely aligning with the parameter considered in this study.

RESULTS AND DISCUSSION

The post-test condition of the samples is illustrated in Figure 4. Notably, all tensile samples experienced fractures within the gauge length. Out of the five specimens, only two underwent complete fracture, while the remaining three exhibited high ductility by bending rather than breaking. In the compression test, the specimen was compressed until the maximum force, revealing the low-density behavior of the printed material.

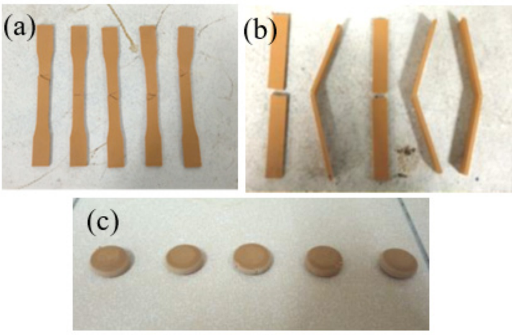

FIGURE 4. The specimen after (a) tensile, (b) flexural and (c) compression test

Concerning the stress-strain curve, as depicted in the plots for the three tests in Figures 5(a), 5(b), and 5(c), the tensile and compressive results exhibited consistency across all samples. With the exception of the flexural result, where slight variations in behavior align with the distinctions between bent and fully broken samples as can be referred in Figure 4(b). Nevertheless, the ultimate strength is comparable among all five samples.

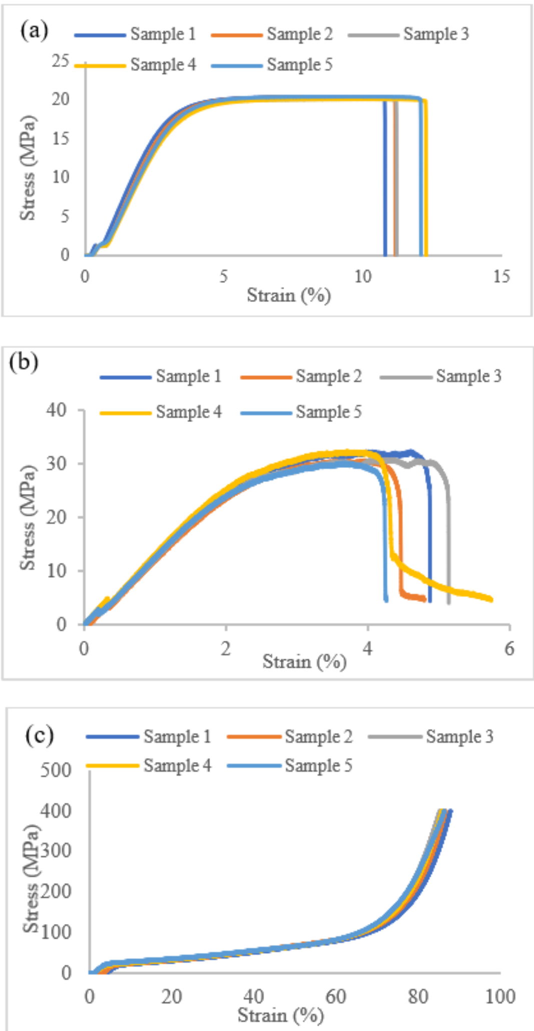

FIGURE 5. The stress-strain curve for (a) Tensile test, (b) Flexural test and (c) Compressive test.

The results of the tensile, flexural, and compressive tests are summarized in Table 1. The higher standard deviation observed in the flexural breaking point can be attributed to the varying outcomes experienced by the flexural samples. The data in Table 1 reflects the results obtained from the printed and tested PolyWood™ material. The ultimate strengths, or peak strengths, recorded were 20.31 MPa for tensile, 31.36 MPa for flexural, and 21.70 MPa for compressive tests. However, these values are based on experimental data from specific printing conditions. To properly evaluate the performance of this material, it is essential to compare it with values from other past studies of similar condition; 3D printed, wood-polymer composites and pure PLA, which is the focus of this study.

TABLE 1. Results from stress-strain tests

	Points on curve	Average value of stress (MPa)	Standard deviation
Tensile Strength	Breaking Point	17.70	0.340
	Peak Strength	20.31	0.148
	Young’s Modulus	709.00	
Flexural Strength	Breaking Point	9.90	6.582
	Peak Strength	31.36	0.898
Compression Strength	Ultimate Strength	21.70	0.002

Table 2 presents a comparison of results obtained in the current study with findings from previous research on 3D printed wood material, along with the general values of PLA. All the referred value from Researcher 1, Researcher 2 and Researcher 3 are generally on 3D printed WPC, except one that is still based on WPC but not 3D printed. The study of tensile strength usually represented by two parameters, ultimate strength and Young’s Modulus, therefore both parameters were included in the study and from the past research of some literatures on the same interest. As the point of this study, other parameters are flexural strength and compressive strength. As can be seen from Table 2, there are only two researchers has studied two or three parameters in the same study. Researcher 1,2 and 3 are not related and was referred independently to show range of wood composite properties. Since some researchers focus solely on specific parameters in their studies, comparisons for other parameters necessitate referencing different researchers.

TABLE 2. Comparison of result with various past studies

		Current Study	Researcher 1	Researcher 2	Researcher 3	Pure PLA
Tensile Strength	Peak Strength	20.31 MPa	19.2 MPa (Guessasma et al. 2019)	19.8 ± 0.8 MPa (Yang & Yeh, 2020)	16.26MPa (Zhang et al. 2022)	40.23 MPa (Atakok et al. 2022)
	Young’s Modulus	709 MPa	438 ± 10 MPa (Guessasma et al. 2019)	1731 ± 60 MPa (Yang & Yeh, 2020)	3.65 GPa (Bhagia et al. 2020)	4.17 GPa
Flexural Strength		31.36 MPa	47.26 MPa (Zandi et al. 2020)	34.0 ± 1.5 MPa (Yang & Yeh, 2020)	27.47 MPa (Chen et al. 2020)	43.6 MPa (A Nugroho et al. 2018)
Compression Strength		21.70 MPa	*12.27 MPa (Li et al. 2022) *not 3D printed	31.8 ± 0.6 MPa (Yang & Yeh, 2020)	33.7 MPa (Xi & Zhao, 2022)	43 MPa (Abeykoon et al. 2020)

The tensile ultimate strength of the PolyWood™ material utilized in this study is comparable to findings from other studies, with discrepancies ranging from only 0.29 to 4.05 MPa. In comparison to 3D printed pure PLA, the ultimate strength of the material in our current study is only 50%. The determination of the Young’s Modulus value involves the strain rate of the material during loading, explaining the significant difference in Young’s Modulus despite the comparable ultimate strengths. The three researchers in the comparison utilized real wood fiber in their studies, but the final results depend on the composition of the polymer in the composite. For instance, Bhagia et al. (2020) reported a Young's Modulus of 3.65 GPa, compared to 709 MPa in this study. A comparison with pure PLA also yielded a substantial difference, possibly influenced by the lower density of PolyWood™.

In terms of flexural performance, the average value determined in this study falls within the range observed in other studies, ranging from 27.47 MPa to 47.26 MPa. Notably, Zandi et al. (2020) achieved the highest value of 47.26 MPa, focusing on the influence of experimental parameters such as layer height, nozzle diameter, fill density, and printing velocity on flexural strength. The material used was 3D printed Timberfill, a PLA material reinforced with real wood fiber. In comparison, pure PLA without reinforcement yielded a flexural strength of 43.6 MPa. Generally, a material's density can significantly impact its flexural strength. However, the relationship between the two is not straightforward and can depend on various factors, as discussed in a study on the effect of density profile on the flexural modulus of polymer foams (Rodrigue, 2007).

Regarding compressive strength, the material employed in this study exhibits lower values. Wood composites are not commonly used in compression applications, as observed in non-3D printed wood composites. Other 3D printed materials demonstrated comparable values, ranging around 32.4 to 33.7 MPa. Ultimately, pure PLA exhibits higher strength in terms of compression performance.

Among the referenced studies, Yang and Yeh (2020) conducted comprehensive mechanical testing, mirroring the approach adopted in this current study. Their study utilized a commercial wood-polymer-composite filament, comprising 40 wt % wood fiber and 60 wt % PLA, sourced from Formfutura BV in Gelderland, The Netherlands. The material's density is 1.20 g/cm^3, closely resembling pure PLA with a density of 1.25 g/cm^3, while PolyWood™ has a lower density at 0.8 g/cm^3. In the study by Yang and Yeh (2020), the primary focus was on exploring the effect of printing speed on various properties, including three fundamental mechanical performance aspects. However, the variation in printing speed affected the volume and weight of the printed specimens, consequently modifying the density. The newly calculated values ranged from 0.96 to 1.07 g/cm^3, positioning the density between PolyWood™ and pure PLA. Notably, the tensile strength of PolyWood™ and Wood-Polymer Composite (WPC) in that study appeared almost identical. In the quest for the tensile modulus, the combination of wood fiber and PLA in the WPC material increased the strain rate, although lower than that of pure PLA without wood fiber. The trends observed in Table 2 indicate a similar pattern in the flexural results, with PolyWood™ and WPC in Yang and Yeh's (2020) study demonstrating comparable strength, while the elasticity of PLA was reduced by the presence of wood fiber. Another study indicated that the filaments exhibited an increase in tensile strength from 55 MPa to 57 MPa with the addition of 10% wood, yet a decline occurred at higher wood content levels, reaching 30 MPa for filaments with 50% wood content (Kariz et al. 2018).

Variance emerged in the compression results, potentially attributed to the orientation difference. Yang and Yeh's (2020) study subjected the printed part to longitudinal compression along the printing X-axis, whereas in the current study, the compression loading are on the printing building orientation. The vertical layers, coupled with the strength between adjacent layers, contributed support, resulting in higher compressive strength. In contrast, the loading on PolyWood™ materials led to compaction, which is more favorable for less dense structures. A study highlighted varying effects of wood sawdust incorporation, revealing a reduction in the tensile strength of the composites, while a notable increase in flexural strength values was observed with the addition of wood sawdust (Narlıoğlu et al. 2021).

CONCLUSION

This study has successfully conducted a comprehensive analysis of the mechanical properties of PolyWood™ materials, specifically focusing on tensile, flexural, and compressive properties in the context of 3D printing. The obtained findings were subsequently compared to results from other studies, leading to the following main conclusions: PolyWood™ stands out as the optimal choice for applications where aesthetic appeal and a wood-like appearance are crucial. However, in terms of overall performance, the mechanical behavior of PolyWood™ falls short when compared to other materials utilizing 3D printed wood-polymer composites. Despite being made from PLA and employing special techniques to reduce density, the performance of PolyWood™ is also inferior compared to pure PLA materials.

Looking ahead, future explorations can involve investigating the impact of different orientations on the mechanical properties of PolyWood™. Furthermore, considering that wood materials are often used in wet conditions, exploring the hydrophobic properties of PolyWood™ can be a potential application. This additional research can provide insights into the material's performance and usability in environments characterized by moisture exposure.

ACKNOWLEDGEMENT

The authors express their gratitude for the support extended by the Mechanical and Manufacturing Engineering Department Laboratory, Universiti Kebangsaan Malaysia which provided access to equipment and printing facilities and research grant FRGS/1/2020/TK0/UKM/02/18 for supporting the research work.

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Abeykoon, C., Sri-Amphorn, P., Fernando, A. 2020. Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures. *International Journal of Lightweight Materials and Manufacture* 3(3): 284-297.

Atakok, G., Kam, M., Bukre Koc, H. 2022. Tensile, three-point bending and impact strength of 3D printed parts using PLA and recycled PLA filaments: A statistical investigation. *Journal of Materials Research and Technology* 18: 1542-1554.

Bhagia, S., Lowden, R. R., Erdman, D., Rodriguez, M., Bethany A. Haga, Ines Roxanne M. Solano, Nidia C. G., Yunqiao Pu, Muchero, W., Vlastimil Kunc, Arthur J. Ragauskas. 2020. Tensile properties of 3D-printed wood-filled PLA materials using poplar trees. *Applied Materials Today* 21:100832.

Chaoji, Chen & Hu, Liangbing. 2020. Nanoscale ion regulation in wood-based structures and their device applications. *Advanced Materials* 33(28): 2002890.

Chen, H., Meng G., Yinghei C. & Felisa C. 2020. Mechanical behaviour of wood compressed in radial direction-part I. New method of determining the yield stress of wood on the stress-strain curve. *Journal of Bioresources and Bioproducts* 5(3): 186-195.

Das A. K., David A. Agar, Magnus Rudolfsson, Sylvia H. Larsson. 2021. A review on wood powders in 3D printing: Processes, properties and potential applications. *Journal of Materials Research and Technology* 15: 241-255.

Guessasma, S., Belhabib, S. & Nouri, H. 2019. Microstructure and mechanical performance of 3D printed wood-PLA/PHA using fused deposition modelling: Effect of printing temperature. *Polymers* 11(11): 1778.

Kariz, M., Sernek, M., Obućina, M., & Kuzman, M. K. 2018. Effect of wood content in FDM filament on properties of 3D printed parts. *Materials Today Communications* 14: 135–140. doi:10.1016/j.mtcomm.2017.12.016

Krapež Tomec, D. & Kariž, M. 2022. Use of wood in additive manufacturing: Review and future prospects. *Polymers* 14(6): 1174.

Li J., Huo R., Liu W., Fang H., Jiang L. & Zhou D. 2022. Mechanical properties of PVC-based wood–plastic composites effected by temperature. *Frontiers in Materials* 9: 1018902.

Narlıoğlu, N., Salan, T. & Alma, M. H. 2021. Properties of 3D-printed wood sawdust-reinforced PLA composites. *BioResources* 16(3): 5467–5480. doi:10.15376/biores.16.3.5467-5480.

Norazyan R. H., Nabilah A. M. R., Nisa N. K. & Abu B. S. 2023. 3D printed carbon fibre reinforced polyamides in high temperature. *Jurnal Kejuruteraan* 35(6): 1351-1361.

Nugroho, A., Ardiansyah, R., Rusita L. & Larasati I. L. 2018. Effect of layer thickness on flexural properties of PLA (PolyLactid Acid) by 3D printing. *Journal of Physics: Conference Series* 1130: 012017.

Rodrigue, D. 2007. The effect of density profile on the flexural modulus of polymer foams. *Antec-Conference Proceedings* 5: 2992.

Tao, Y., Li, Z. & Li, P. 2020. A design and fabrication method for wood-inspired composites by micro x-ray computed tomography and 3D printing. *Applied Sciences* 10(1400).

Xi, F. & Zhao, L. 2022. Experimental study of the compressive properties of a wood–plastic composite at different temperatures. *Polymer Composite* 43(10): 7372.

Yang, T.-C. & Yeh, C.-H. 2020. Morphology and mechanical properties of 3D printed wood fiber/polylactic acid composite parts using fused deposition modeling (FDM): The effects of printing speed. *Polymers* 12 : 1334.

Zandi, M. D., Jerez-Mesa, R., Lluma-Fuentes, J., Roa, J. J., & Travieso-Rodriguez, J. A. 2020. Experimental analysis of manufacturing parameters' effect on the flexural properties of wood-PLA composite parts built through FFF. *The International Journal of Advanced Manufacturing Technology* 106: 3985-3998.

Zhang, Q., Ma, L. Zhang, X., Zhang, L. & Wang, Z. 2022. Lignocellulose nanofiber/polylactic acid (LCNF/PLA) composite with internal lignin for enhanced performance as 3D printable filament. *Industrial Crops and Products* 178: 114590.

Zhu Q., Yao Q., Liu J., Sun J. & Wang Q. 2020. Emissions from the fused filament fabrication 3D printing with lignocellulose/polylactic acid filament. *BioResources* 15: 7560–7572.