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Mechanical Properties and Flammability Analysis of Wood Fiber Filled Polylactic Acid (PLA) Composites Using Additive Manufacturing

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ABSTRACT

Natural fibers, such as wood fibers, can substitute for synthetic fibers in various applications due to their low environmental impact, cost-effectiveness, and outstanding mechanical properties as rapid-growing materials and renewable resources. This paper aims to investigate the mechanical properties of 20% wood fiber as a reinforcement material in polylactic acid (PLA) using an additive manufacturing approach. The samples were fabricated using 3D printing techniques. The relevant parameters included the orientation of printing in X, Y, and Z directions, with the percentage of infill set to be 100%. The findings indicated that bio-composites and their adopted printing orientations confirmed the significant effects on the mechanical properties. Pure PLA possessed superior properties in all directions compared to wood/PLA. The highest values were 50.33 MPa for tensile strength and 94.36 MPa for flexural strength, both achieved in Y orientations. However, composites showed an improvement in tensile and flexural moduli in X orientation with 1395.40 MPa, and 2937.72 MPa for Young and flexural modulus, respectively. In the flammability test, wood/PLA bio-composites were ignited easily with reduced smoke production compared to the neat PLA. Wood/PLA bio-composites exhibited high stiffness, and their mechanical properties were influenced by many factors, such as percentage of weight fraction, wood type, and printing orientations.

摘要

天然纤维，如木纤维，由于其低环境影响、成本效益和作为快速生长材料和可再生资源的出色机械性能，可以在各种应用中替代合成纤维. 本文旨在采用增材制造方法研究20%木纤维作为聚乳酸（PLA）增强材料的力学性能. 这些样品是使用3D打印技术制造的. 相关参数包括X、Y和Z方向上的打印方向，填充百分比设置为100%. 研究结果表明，生物复合材料及其采用的印刷取向证实了其对力学性能的显著影响. 与木材/PLA相比，纯PLA在各个方面都具有优越的性能.　　拉伸强度和弯曲强度的最高值分别为50.33MPa和94.36MPa，均在Y方向上达到. 然而，复合材料在X方向上的拉伸和弯曲模量有所提高，分别为1395.40MPa和2937.72MPa; 分别. 在可燃性测试中，与纯PLA相比，木材/PLA生物复合材料更容易点燃，产生的烟雾更少. 木材/PLA生物复合材料具有较高的刚度，其力学性能受到许多因素的影响，如重量分数百分比、木材类型和印刷方向.

KEYWORDS

3D printing; additive manufacturing; wood composites; polylactic acid; mechanical properties

关键词

3D打印; 增材制造; 木质复合材料; 聚乳酸; 机械性能

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Introduction

The accumulation of waste composed of plastics and man-made polymers produced from petroleum has led to a considerable exacerbation in environmental pollution challenge (Chen et al. 2021; Evode et al. 2021; Wong et al. 2015; Yusuf et al. 2024). This pollution has reached a critical stage as it is seriously threatening not only the health of mankind but also that of animals and plants. The process of plastics manufacturing began on a commercial scale in 1950s, and since then, the industry has expanded at a rapid rate, with a global annual production rate reached to 330 million metric tons (Mt) in 2016 (Williams and Rangel-Buitrago 2022; Yusuf et al. 2023). Plastics find widespread applications across various varieties of industries, including those dealing with food packaging, medicine, and automobiles. Since the starting point of 1970s decade, researchers have focused their attention on finding a new class of polymers represented by biodegradable polymers as a result of the growing concerns regarding both the availability of material resources and the problems associated with the disposal of plastics (Rahman et al. 2009). According to Mukhtar et al. (2016), the most effective and popular materials used to replace plastics are natural fiber composites. Natural fibers are durable materials found in large quantities in the environment. They have the advantages of cost-effectiveness, lightweight, and biodegradability. Natural fibers can be extracted from many eco-friendly resources such as plants and animal species (Khieng et al. 2021; Peças et al. 2018; Thyavihalli Girijappa et al. 2019). It should be emphasized that these natural fibers are very durable, resilient and can contribute efficiently to the preparation of environmentally friendly materials.

Growing fiber plants produce natural fibers and the best places to get them in large amounts are tropical regions, especially those in South Asia, Africa, and Latin America (Hadi et al. 2022; Satyanarayana, Guimarães, and Wypych 2007).

The term "bio-composites" refers to biopolymers that are reinforced with natural fibers ("Natural Fibre Biocomposites," 2020; Gholampour and Ozbakkaloglu 2020; Khan et al. 2023). These materials have drawn a considerable attention as researched because they are considered as potential substitutes for nonrenewable, refractory, and environmentally harmful materials (Christian 2020). Over time, it has been clear that natural fibers perform better in fiber-based composites (Hao et al. 2018; Saifulazry et al. 2022). Bio-composites were widely used in many industries during the past 10 years such as construction, aerospace, automotive, and circuit board manufacturing sectors.

Agricultural waste can be used to make PLA, which is a flexible polymer that can be fermented to produce carboxylic acid (Ilyas et al. 2021). Since both PLA and natural fibers come from renewable resources, decompose and biodegrade naturally, and may be combined to produce new products, they are considered as recyclable green materials (Zainudin et al. 2023). According to Qureshi (2022), natural fiber reinforced composites can be readily disposed of in a landfill using many methods such as burning, pyrolysis, or any green process. It is reported that among all the biodegradable polymers, PLA has the greatest number of applications to meet industry requirements. This is because PLA's life cycle has shown feasible effectiveness resulted in a supply chain that requires less transportation and produces less greenhouse gas emissions due to its unpretentious decomposition. The main characteristics of PLA-based bio-composites, represented by their biodegradability, renewability, and lower CO_2 emissions, are largely determined by how well they performed in the market (da Silva et al. 2018; Tripathi, Misra, and Mohanty 2021; Trivedi, Gupta, and Singh 2023). Recent years have witnessed a large number of research projects focused on the employment of wood fibers as an efficient reinforcement agent in different polymer matrices. Migneault et al. (2008) studied the applications of wood-plastic composites and found that, when combined in the right amounts, the properties would be improved serving specific applications. It is concluded that greater mechanical qualities are intimately associated with the percentage of fiber loading. According to research conducted by Nazrin et al. (2020), PLA was employed as a biodegradable polymer that was brittle, vulnerable to moisture, and had a low impact resistance. Thus, hybridizing this polymer with natural fibers is one way to promote the mechanical properties of the resulting bio-composites. Using computer-aided design (CAD) data, additive manufacturing creates three-dimensional objects by layering on material. Its capacity to create bespoke items with complex shapes at a lower cost and in a timely manner at production rates has made it consistently reliable in recent years. This sophisticated technique is applied in several industries including construction, aerospace, dental, biomedical, and defense (Mansi et al. 2022). The 3D printing method employed in this work is an additive manufacturing technique, which is licensed by MIT that prints data from CAD drawings using a water-based liquid binder sprayed in a jet onto a powdered starch substrate. When the binder is jetted, the powder particles arranged in a powder bed fuse together. Because it resembles the inkjet printing method used for two-dimensional printing on paper, this procedure is known as 3D printing. This procedure can handle a wide range of polymers (Cooper 2001; Halloran et al. 2011).

A previous study was conducted as a crucial preliminary step toward the utilization of a blend of modified natural fibers including wood, coconut, and bamboo fibers as reinforcing materials in PLA matrix as an outset part related to an extensive investigation of PLA/natural fiber composites conducted by Zhang et al. (2012). According to the achieved findings, the efficient inclusion of three different kinds of natural fibers into PLA led to obtaining bio-composites that possessed the ability to promote both the mechanical and thermal characteristics. Natural fibers following modification may further enhance the durability of composites. In addition, the composite made of PLA and coconut fiber had the best thermal features and lasted longer compared to the other bio-composites.

Wood flours extracted from softwood species are preferred for their ease of processing as well as their mechanical qualities. In wood-plastic composites (WPCs), the size of the wood fiber has a significant impact on mechanical properties. Larger-sized particles contribute to higher notched impact energy, while finer particles enhance tensile strength and modulus (L. Matuana and Stark 2015). Within the field of natural fibers, the Coefficient of Variation (CV) % is an indicator of statistical significance utilized to quantify the relative variability exhibited by a given dataset. The measurement related to this coefficient is indicated as a percentage and is computed by dividing the standard deviation of a dataset by its means. In the context of natural fibers, a higher CV (%) signifies the presence of noticeable fluctuations in the quality or properties of the fibers within the given sample. CV is frequently employed by researchers and engineers in materials science and engineering in order to evaluate the dependability and uniformity of fiber properties. The proportion of wood flour incorporated in WPCs has a major impact on the processing qualities as well as the end-use properties. Since wood flour obstructed the movement of polymer chains when the composites degraded in the melting stage, increasing the amount of wood flour resulted in an improvement in composites viscosity (Guo et al. 2008; Li and Wolcott 2005; Shah and Matuana 2004). A drop was placed in the MFI device to confirm that when the amount of wood flour in the composites was increased, the composite would melt more viscously. Research work has indicated that the presence of solid wood flour particles within the polymer matrix caused an increase in friction against the melt's flow, ultimately leading to a higher viscosity. The ascription related to this behavior stated that these particles enhanced the resistance to the melt's movement (L. M. Matuana and Diaz 2013). The current study uses additive manufacturing to focus on the mechanical characteristics of PLA composites loaded with sugar palms. The novelty of this work is represented by its diverse approach toward a comprehensive assessment of mechanical and morphological attributes in wood/PLA bio-composites, specifically, those fabricated composites at varying printing orientations through additive manufacturing. In addition, a few studies were devoted to explaining the flammability characteristics of wood fiber-reinforced PLA composites. This work aimed to highlight the flammability characteristics of the aforementioned bio-composites, which is another novel objective related to this work. The study's scope involved the preparation of dog bone structure sample specimens, specifically bio-composites comprising wood fiber-reinforced PLA and neat PLA, employing additive manufacturing, the 3D printing method.

Materials and methods

Materials

The materials used in this work were bought from a commercial source [3D Gadgets Malaysia (3D printer), Malaysia]. The tests were carried out following the ASTM standards. For the flexural test, the referenced standard was D790 (2015). For tensile test, the followed specifications were in line with D638–10 (2015) (Ahn et al. 2002). The dimensions of flexural testing are indicated in Figure 1.

The printing parameters included orientation of printing which was *X*, *Y*, and *Z* orientation. The percentage of infill was set to be 100% for the wood/PLA bio-composites, and neat PLA material (Figure 2). Additionally, the difference in orientation and percentage of the used infill had a considerable effect on the design's overall strength. Table 1 shows the parameters for each filament with line types of pattern design. Five specimens were prepared for the tensile and flexural tests and three specimens for the flammability test.

Tensile test

The tensile test was carried out using the universal tensile testing machine (UTM Instron 3366, USA) with a load cell of 10 KN, and a speed of the crosshead was adjusted on 1.0 mm min^{-1}. Five prepared samples have the dimensions of $165 \times 19 \times 3.2$ mm underwent the test, and the average value was calculated. Equation 1 is the employed formula to compute the theoretical tensile strength using the maximum tensile stress:

$$\sigma = \frac{w}{A} \tag{1}$$

where w represents the maximum load, and A represents the cross-sectional area of the tensile specimen's narrowest part.

Equation 2 can be exploited to evaluate the tensile modulus:

$$E = \frac{\sigma}{\varepsilon} \tag{2}$$

where σ represents the uniaxial stress, and ε represents the strain or proportional deformation.

Flexural test

By following the guidelines established by ASTM D790 (2003) for 3-point bending, flexural testing was carried out with the assistance of an Instron 3365 machine, USA. The span length was determined to be 16 times the thickness of the material. Using five specimens of each orientation that had dimensions of $127 \times 12.7 \times 3.2$ mm, the resulting span length was 50 mm.

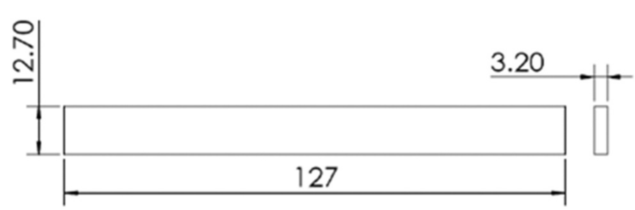

Figure 1. Standard specimens for flexural testing (unit mm).

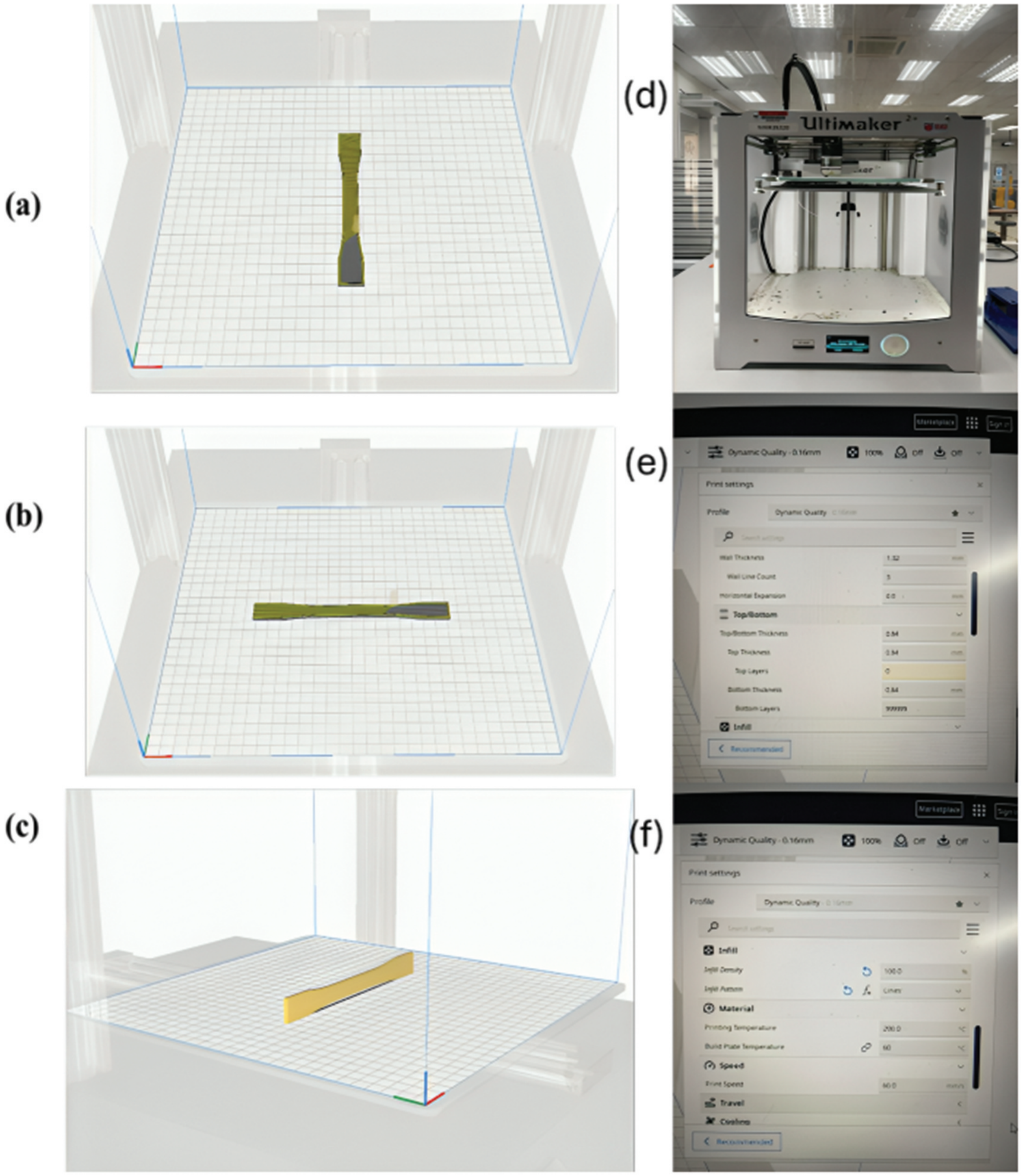

Figure 2. The *X*, *Y* and *Z* orientations of the specimens in the printing process (a–c), (d) 3D printing Ultimaker 2+ machine, and (e–f) print settings for each filament design.

Flammability test

The flammability test was performed to determine how resistant the composites were to fire when they heated up. The test was conducted with five samples of each orientation by using a horizontal burning method for the pure PLA and wood/PLA bio-composites according to ASTM D635 (2006) (Suriani et al. 2021). The fire was stopped when it reached the 100 mm mark of the samples, which was the second point mark. The application time was set to 15 s. In case of improper performance, the

Table 1. The parameters for each design based on orientation of printing and infill percentages.

Type of filament	Orientation	Infill percentage	Type of pattern
Pure PLA	X		
	Y		
	Z	100	Lines
Wood PLA composites	X		
	Y		
	Z		

experiment was aborted. In other words, if the flame reached the first mark of 25 mm within 15 s, the flame application was discontinued.

When the fire reached the second mark, the time was recorded as having passed the first mark. The aim of the first mark was to explore whether the specimen was flammable or not. To determine the burning rate in millimeters per minute (mm/min), this distance was divided by the total number of minutes that the specimen was exposed to burn. Equation 3 is included in order to find the burning rate.

$$Burning\ rate = \frac{Length\ of\ the\ burnt\ part(mm)}{Total\ time\ (min)} \tag{3}$$

Morphology test

To determine the degree to which natural fibers adhered to the polymer matrix, morphological research was carried out in order to investigate treated and untreated fiber composites. A Scanning Electron Microscope (SEM) was utilized to make observations regarding morphology. Field-Emission Scanning Electron Microscopy (FESEM) was exploited to analyze the microstructural analysis for the samples. The specifications of the machine were (Nova NANOSEM 230 FESEM, Netherlands) of 5.0 kV power. The microscope was used at discrete magnifications, and the samples were coated with platinum for 50 s using a high vacuum sputtering unit. The employed sputter coater (Model: K575X, UK) specified to coat the samples in order to achieve conducting surfaces, prevent the charge buildup, and consequently, avoid the possible contamination inside the chamber of the microscope that would affect the quality of the captured images.

Results and discussion

Tensile properties

In Figure 3, the bar graph illustrates the ultimate tensile strength, which is determined by evaluating the maximum stress of PLA and wood/PLA composite specimens. It is important to note that specimens vary in their orientations. The determination of the specimens' strength was derived from analyzing the load-deflection data obtained from the extensometer. The PLA specimen oriented along the Y-axis (red bar) exhibits the highest tensile strength, 50.33 MPa. Subsequently, the PLA specimens oriented along the *Z*-axis and *X*-axis demonstrate tensile strengths of 45.44 and 31.80 MPa, respectively. In the case of ultimate tensile strength, it is generally observed that pure PLA exhibits superior performance compared to wood/PLA composites (Agaliotis et al. 2022). The percentage of wood/PLA composites for tensile strength decreases by 22.1% which demonstrates tensile stress values of 24.77 MPa for *X* orientations, 22.21 MPa for *Y* orientations, and 18.89 MPa for Z orientations. According to research conducted by Vayshbeyn et al. (2023), it was observed that pure PLA exhibited a comparatively elevated tensile strength owing to its molecular arrangement. This molecular structure facilitated robust intermolecular bonding and enhanced the strength between polymer chains. Furthermore, it is worth noting that PLA possesses a crystalline arrangement that may contribute to enhancing its mechanical durability.

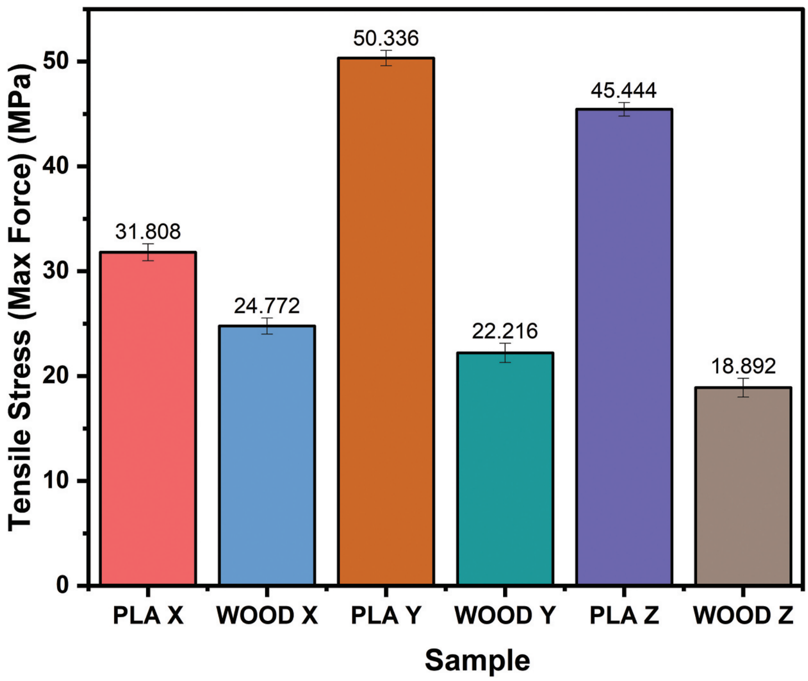

Figure 3. Maximum tensile stress for PLA and wood/PLA composites in different types of orientations.

Young's modulus, which is also defined as the modulus of elasticity, serves as a quantitative indicator of a material's rigidity. It is also a pointer for the material's ability to withstand deformation when subjected to either tensile or compressive forces. The highest Young's modulus is observed in PLA in *Z* orientation, recording 1481.95 MPa, while PLA in *Y* orientation exhibits a slightly lower value of 1459.04 MPa. The observed outcomes display variations in Young's modulus values for wood/PLA composites in *X* and *Y* orientations, which are significantly greater at 1385.4 MPa and 1208.52 MPa, respectively, in comparison to PLA in *X* orientation, which read 1114.71 MPa (Figure 4). The specimen composed of wood/PLA in *Z* orientation exhibits a minimal value of tensile modulus (1099.09 MPa) compared to the other specimens. In a general context, the incorporation of wood particles or fibers into the PLA matrix leads to a reduction in the composite's Young's modulus compared to pure PLA. Nevertheless, it is conceivable that wood/PLA bio-composites, when arranged in a particular orientation, such as *X* and *Y*-axes, may demonstrate an enhanced Young's modulus in comparison to pure PLA. This phenomenon is ascribed to the process of fiber reinforcement linked to composites' preparation.

Flexural properties

According to the data presented in Figure 5, the flexural strength of PLA with *Y* orientation is the highest, measuring 94.362 MPa. PLA with *Z* orientation reads a flexural strength of 83.782 MPa, while PLA with *X* orientation exhibits a flexural strength of 81.504 MPa. The achieved outcome is attributed to the inherent characteristics of pure PLA. Significantly, pure PLA exhibits similar behavior in relation to tensile strength (Vakharia et al. 2021). In a conclusive statement, it is apparent that pure PLA possesses superior properties in terms of strength compared to wood/PLA bio-composites. In parallel with the incorporation of natural wood fibers, flexural strength properties are experienced with a minimization of approximately (30–40) % in all directions. Specifically, the values of flexural strength for wood are 52.056 MPa in *X* orientation, 47.246 MPa in *Z* orientation, and the lowest

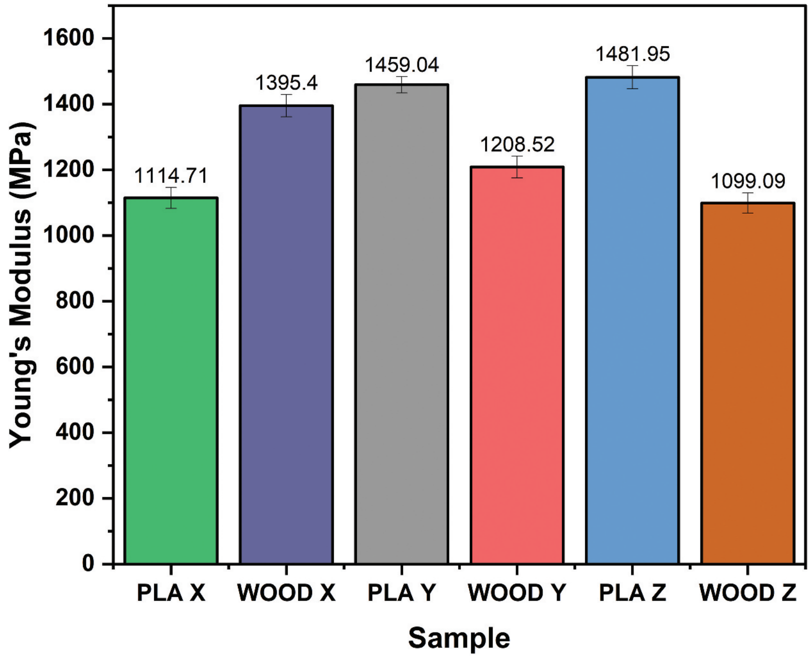

Figure 4. Tensile modulus for PLA and wood/PLA composites in different types of orientations.

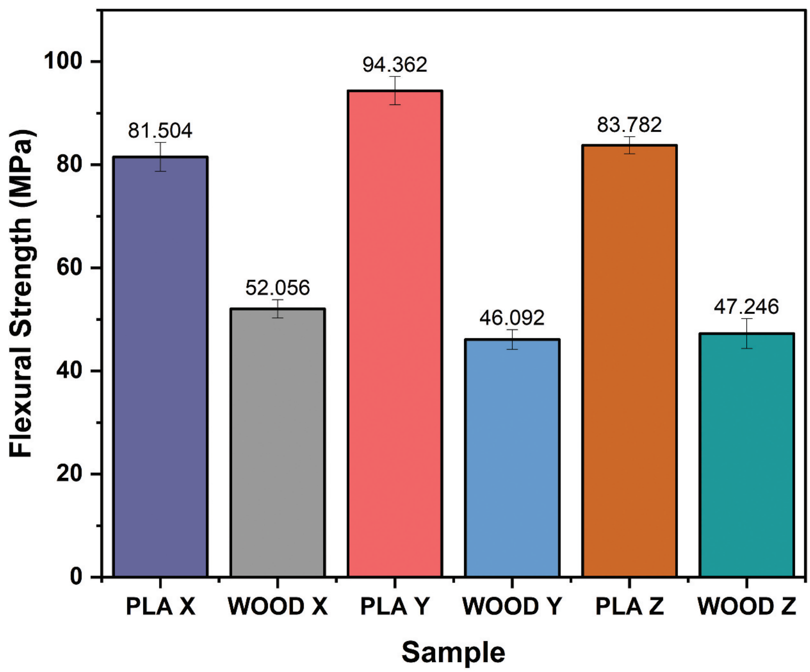

Figure 5. Flexural strength for PLA and wood/PLA composites in different type of orientations.

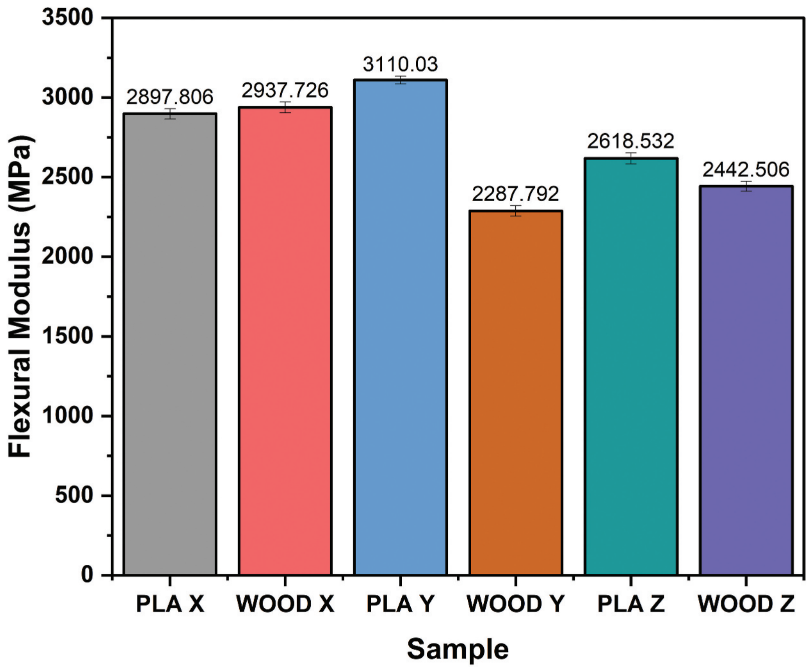

Figure 6. Flexural modulus for PLA and wood/PLA composites in different types of orientations.

flexural strength appears in *Y* direction, which is 46.092 MPa. It is observed that wood/PLA bio-composites exhibit a reduced flexural strength compared to pure PLA. According to Dubey, Purohit, and Hemanth Kumar (2021) who reported similar observations, this outcome can be attributed to the presence of wood fibers in the heterogeneous system of composite materials, and these fibers function as stress concentrators.

From the bar chart shown in Figure 6, the flexural modulus for PLA in *Y* direction had the highest value with 3110.03 MPa. The flexural modulus of a material is a physical characteristic that indicates the substance's capacity to bend. However, the flexural modulus for wood/PLA bio-composites in *X* direction, which read 2937.72 MPa, have slightly higher flexural modulus compared to PLA in *X* and *Z* orientation, 2897.80 MPa and 2618.53 MPa, respectively. This is due to better interfacial adhesion between the matrix and the fibers in *X* orientation that leads to a more uniform distribution of the applied stress.

In contrast, pure PLA in *X* and *Z* orientation is not as strong in the direction of its length. According to Christie (2023), this is because the molecules in PLA are arranged randomly, and there is no long-range order. As a result, pure PLA has a lower flexural modulus in the *X* and *Z* direction than wood/PLA bio-composites in *X* direction.

The above-mentioned findings are followed by other findings, which are wood/PLA bio-composites in *Z* direction with 2442.50 MPa, and the lowest flexural modulus, which is wood/PLA composites in *Y* direction with 2287.79 MPa. In 3D printing, *X* is the direction in which the layers of material are deposited. This means that the wood fibers in wood/PLA composites oriented in *X* direction are more efficient compared to those composites that their wood fibers are oriented in *Y* and *Z* orientations.

Flammability test

Based on Table 2, the average time taken for the specimens to finish burning for three samples was recorded with the behavior of each sample.

Table 2. The time recorded for the sample to be burnt and the burning behavior of pure PLA and wood/PLA composites.

Sample	Time taken to burn (minute)	Burning rate (mm/min)	Behaviour
PLA	1.68	44.64	Fully burnt with high, light-colored smoke
Wood/PLA	1.42	52.81	Fully burnt with low, light-colored smoke.

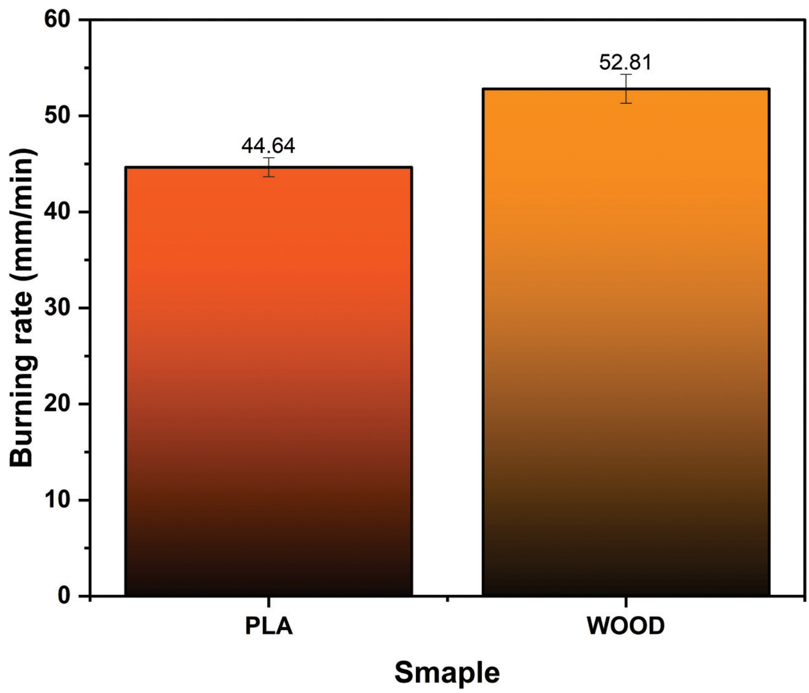

Figure 7. The average burning rate of the samples.

Horizontal burning test properties

Three samples are tested with the burning test in accordance with the standard of UL-94 horizontal burning test (Akash et al. 2017). Figure 7 shows the average burning rate of PLA and wood/PLA bio-composites. The findings show that adding wood fibers might increase the burning rate of the sample by an average of 52.81 mm/min compared to pure PLA, which is burned at a rate of 44.64 mm/min. The result may contribute to the density of the material, which means that pure PLA is a denser material than wood fibers (Neagu et al. 2012). This means that PLA requires more heat to melt than wood/PLA composites, which leads to a slowing down of the combustion process. In addition, by observing the burning behavior of all samples, it is understood that all the samples were being burnt, and the difference is where the pure PLA dripped fast compared to wood/PLA composites.

Since PLA is a thermoplastic material, it can dissolve and flow when heated. When PLA liquefies, it becomes more fluid and compliant for dripping. Wood fibers are fibrous substances composed of long and thin filaments. These strands can function as a barrier against the flow of molten PLA, which makes the dripping process for PLA very difficult. The reduced smoke production observed in wood/PLA composites is attributed to the higher burning rate exhibited by this material compared to PLA (see Figure 8). This could prove advantageous in scenarios where enhanced visibility is of crucial significance, such as firefighting operations or confined environments.

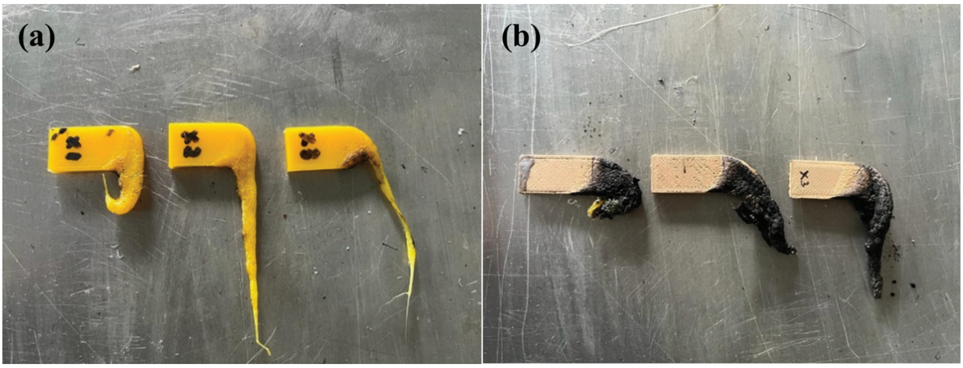

Figure 8. Samples after burning test; (a) pure PLA (b) wood/PLA composites.

SEM analysis

Figure 9 displays the morphological analysis, revealing the fractured surface of the tensile test of both pure PLA and wood/PLA bio-composites. A total of six specimens are observed with respect to *X, Y*, and *Z* orientations for PLA and wood/PLA bio-composites. In the given diagram, when the magnification is set to 50X, it becomes feasible to observe the complex components of the FDM orientation layer.

In the case of pure PLA, nearly symmetric voids are typically formed between the deposited print shells. These voids are observed in any direction. The crossed deposition directions of the printed material lines of pure PLA in *X* direction can be observed in Figure 9(a). These lines show voids, which are formed by the gaps between the rasters. According to the observations presented in Figure 9(b), PLA material oriented in the *Y* direction possesses a significant amount of crystallinity.

This is evidenced by the characteristics of brittle fracture behavior, which is commonly observed in amorphous polymers. Additionally, the interface between the layers appears smooth, indicating a uniform and cohesive structure (Qiao, Maazouz, and Lamnawar 2022). The observed voids explicitly indicate a triangular shape, reflecting the fact that their formation has occurred in conjunction with the printing procedure. In contrast, Figure 9(c) shows the complex periodic microstructure of PLA in *Z* orientation, which resembles a bone with voids in the shape of triangles resulting from the manufacturing process. Figure 9(d-f) proves the change in fracture nature from ductile to fragile due to the role played by wood fiber incorporated within the neat polymer. Furthermore, the presence of numerous pores in wood/PLA bio-composites impacts the layer structure of each orientation (Bahar et al. 2023).

Figure 10 displays the fractured surface of the wood/PLA bio-composites, which is magnified by a factor of 500 to enable a closer examination of the profound details related to the wood fiber structures.

According to Mazur et al. (2022), the deterioration in mechanical properties of wood/PLA bio-composites is attributed to the absence of material continuity, and the presence of gaps between the applied filaments, which leads to porosity improvement for the materials. It is evident that wood fibers possess the greatest width due to inadequate adhesion between the matrix and the fibers that leads to a decrement in mechanical properties. Based on Figure 10(a), it is observed that wood fiber in the *X* orientation demonstrates a superior Young's modulus in comparison to *Y* and *Z* orientations. The printed part shows clear evidence of longitudinal compression along *X*-axis printing orientation. Despite the presence of voids, the structure demonstrates a promoted solidity, and arrangement compared to *Y* and *Z* structures. In Figure 10(b), *Y* orientation of wood/PLA bio-composites is distinguished. The layer structure appears to be random, full of voids everywhere, and resembling a torn material. In addition, the main characteristic is noted to be fragile (Wang et al. 2023). In Figure 10(c), the size of the voids is apparently increased in a random manner and distributed

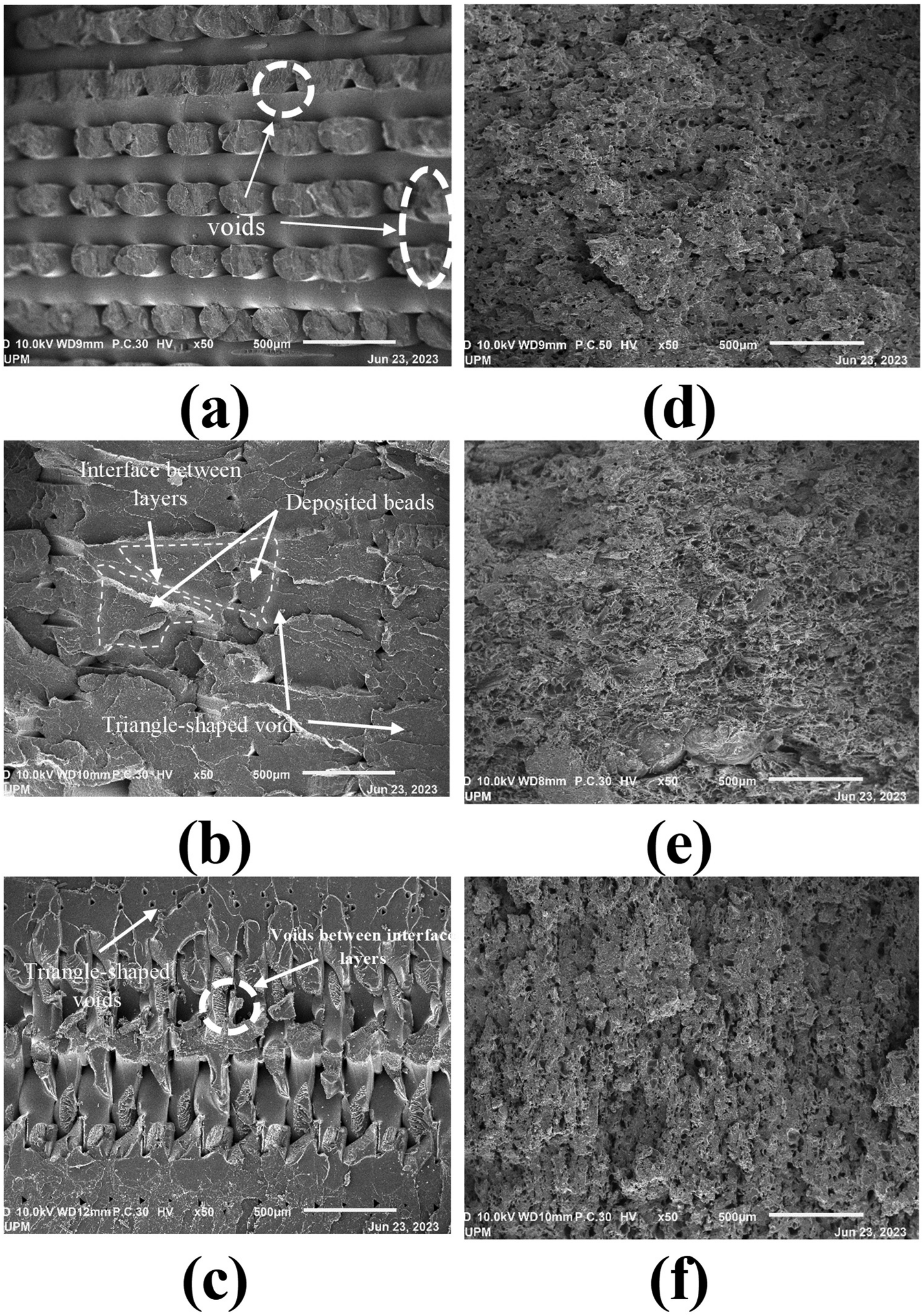

Figure 9. SEM images of fracture morphology for tested samples; for PLA and for wood/PLA composites (a) PX, (b) PY, (c) PZ, (d) WX, (e) WY, (f) WZ.

throughout the entire space. The insufficient bonding during the FDM process is the justification related to the debonding that is noticed between the adjacent layers. As a result, weak bonding between the adjacent beads may be produced. The occurrence of debonding is intimately associated with applying load to the specimens.

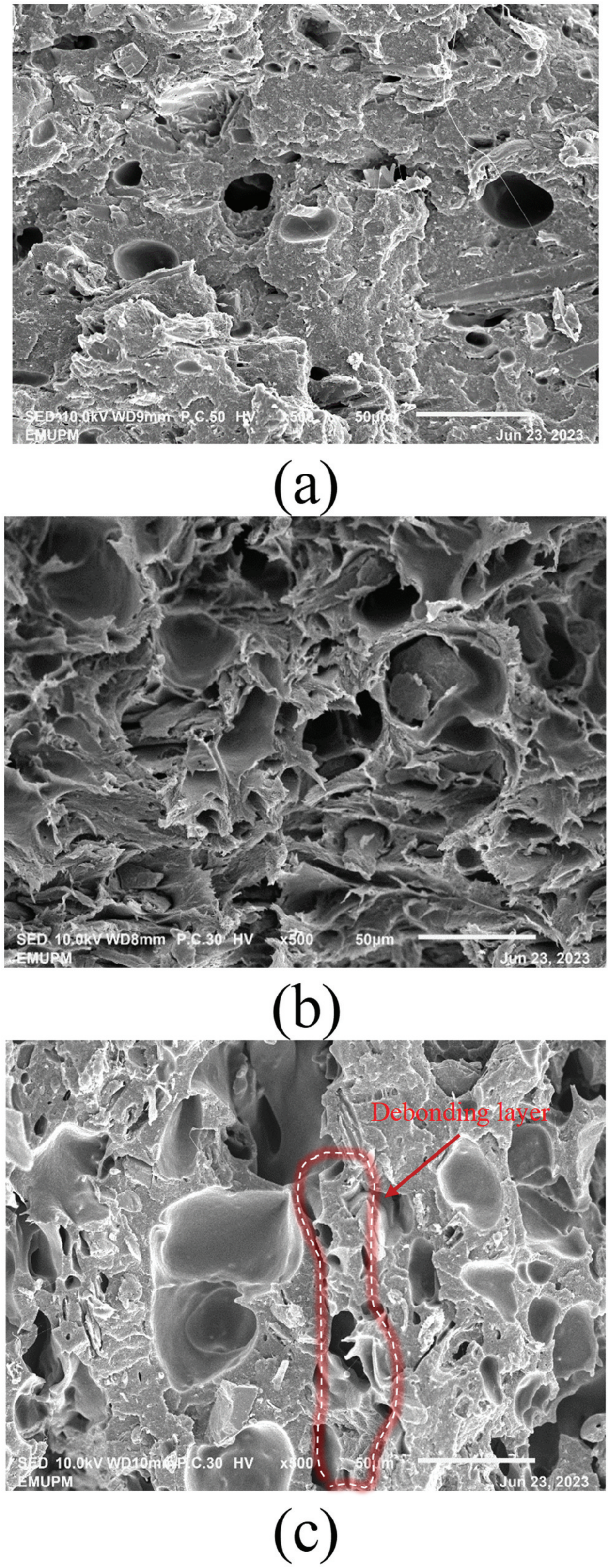

Figure 10. SEM images of fracture morphology for wood/PLA composites tested materials; (a) WX, (b) WY, (c) WZ.

Comparison of pure PLA and wood/PLA composites

Wood/PLA bio-composites, also known as PLA composites or PLA with wood fibers, are hybrid materials that combine PLA with wood particles or fibers. 3D printing is a technique, which is often employed in order to achieve a wood-like appearance or texture. However, the addition of wood particles or fibers to the PLA matrix can affect the mechanical properties of the material.

As for tensile properties, basically, wood fibers are generally weaker than pure PLA and can act as stress concentrators, reducing the overall strength of the host materials. Moreover, the presence of wood particles can disrupt the intermolecular bonding in the PLA matrix, leading to reduced tensile strength. Besides, the addition of wood particles or fibers to PLA can decrease the overall Young's modulus of the composite compared to the pure PLA.

According to the research disseminated by Mazur et al. (2022), it was observed that wood/PLA composites exhibited a reduced flexural strength compared to pure PLA. This can be attributed to the presence of wood fibers as a reinforcing agent in the prepared composites, which function as stress concentrators. This outcome indicated that they generate regions of elevated stress within the material, thereby potentially resulting in premature failure. Furthermore, it should be noted that the wood fibers showed a relatively lower strength compared to PLA, thereby rendering them more susceptible to fracture when subjected to external forces. However, the wood fibers provide an occasionally additional support and resistance to deformation along the aligned direction, resulting in improved stiffness compared to pure PLA. The fibers help distribute and resist applied forces, thereby increasing the overall rigidity of the composite material. The amount of wood fibers in composite material also affects their flexural strength. As the amount of wood fiber increases, the flexural strength decreases. This is because wood fibers become more numerous and create more stress concentration in the material. However, referring to Vigneshwaran and Venkateshwaran (2019), the mechanical properties of wood/PLA composites can be affected by various factors, including percentage of weight or volume loading, length, size of distribution, and type of wood fibers utilized, along with the processing conditions.

Effect of orientation on mechanical properties in 3D printing

The orientation in 3D printing plays a significant role as it directly influences the strength and elasticity of composites. The obtained findings in this research have demonstrated the significant influence of orientation on the investigated mechanical properties of the bio-composites. The results of the tests indicate that pure PLA exhibited the highest values, particularly in terms of tensile and flexural strength. However, it is possible for wood/PLA bio-composites in a specific orientation to exhibit a higher Young's modulus compared to pure PLA in the same orientation. According to Huang et al. (2021), when wood fibers are aligned in a specific direction within the PLA, they can act as reinforcement elements, enhancing the mechanical properties of composites in that particular direction. This alignment of fibers can create a stiffer and more rigid structure, leading to an increase in Young's modulus as shown in X and Y orientations. It is important to emphasize the impact of X orientation of wood/PLA bio-composites on the tensile and flexural modulus. The reason for this phenomenon is attributed to the presence of wood fibers in X plane, which serves to enhance resistance against both tensile and flexural forces. In the context of 3D printing, it is important to note that X direction refers to a specific orientation in which the layers of the material are systematically deposited. The wood fibers in wood/PLA bio-composites exhibit orientation along X direction. Wood fibers show high Young's modulus along their longitudinal axes. This implies that they possess the capability to offer a substantial support against bending and stretching in X direction. The mechanical properties of wood/PLA bio-composites in X orientation were recognized to yield favorable outcomes.

Conclusions

This work highlighted valuable insights into the mechanical properties and environmental considerations of PLA and wood/PLA bio-composites. The examination of pure PLA revealed its superior mechanical characteristics, particularly in tensile and flexural strength, attributed to its higher homogeneity compared to PLA reinforced with wood particles. The absence of wood particles in pure PLA prevented any potential disruption to the molecular structure and contributed to its enhanced mechanical performance. Furthermore, the investigation into the effect of orientations in 3D printing highlighted the possible improvement in the mechanical properties, exemplified by the superior outcomes observed in *X* orientation for wood/PLA composites. Importantly, both pure PLA and wood/PLA composites demonstrated a favorable environmental aspect by producing lighter-colored smoke and exhibiting a lower tendency to release toxic chemicals. This comprehensive analysis underscored the importance of material composition and printing orientation in optimizing both mechanical performance and environmental impact in the area of PLA and wood/PLA bio-composites.

Highlights

- Wood fibers have the potential to replace synthetic fibers in various applications.
- Mechanical properties of PLA composites are influenced by 20% wood fiber.
- Pure PLA exhibits superior strength in all directions compared to wood/PLA.
- Wood/PLA composites demonstrate high stiffness and reduced smoke production.

List of abbreviations

AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer-aided Design Software
CV	Coefficient of Variation
FDM	Fused Deposition Modelling
LA	Lactic Acid
MFI	Melt Flow Index
PE	Polythene
PP	Polyethylene
PS	Polystyrene
PMC	Polymer Matrix Composites
PP/PLA	Polyethylene reinforced Polylactic Acid
SEM	Scanning Electron Microscope
SLA	Stereolithography
STL	Standard Tessellation Language
TMP	Thermomechanical Pulp Fibers
WFs	Wood Fiber
WF/PLA	Wood fiber reinforced Polylactic Acid
WPCs	Wood-plastic Composites

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