SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V11I10P107

Volume 11 Issue 10, 74-84, October 2024
© 2024 Seventh Sense Research Group®

Original Article

Mechanical Characterization of 3D-Printed Banana Fibers Reinforced PLA Biocomposite

Amol Kolhe[1], Sachin Karale[2], Prashant Anerao[3], Yashwant Munde[4]

[1,2]*G H Raisoni University, Amravati, Maharashtra, India.*
[1]*School of Mechanical Engineering, MIT Academy of Engineering, Pune, Maharashtra, India .*
[3]*Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, Pune, Maharashtra State, India.*
[4]*Department of Mechanical Engineering, Cummins College of Engineering for Women, Pune, Maharashtra, India.*

[1]*Corresponding Author : amkolhe3@gmail.com*

Received: 08 August 2024 Revised: 10 September 2024 Accepted: 08 October2024 Published: 30 October 2024

Abstract *- 3D printing uses computer-aided design and layering to create three-dimensional objects. Many researchers are exploring different materials for 3D printing. One of the avenues is reinforcing natural fibers with polymer material due to their biodegradability and better mechanical properties. The primary goal of this study is to explore the use of banana fibers with Polylactic Acid (PLA) for 3D printing using Fused Deposition Modeling (FDM). This paper investigates the effect of natural fibers reinforcement on mechanical characteristics, additionally, the influence of FDM process variables such as nozzle size, infill patterns, layer thickness, and nozzle temperature on mechanical properties are also studied. To determine the significance of these process factors, Variance Analysis (ANOVA) was used, and Taguchi L16 was employed to design the experiments. In this investigation, to perform the mechanical tensile test and flexural test, specimens were printed from banana fibers/PLA biocomposite according to ASTM standards. Items printed with 0.8 mm nozzle size, cubic infill pattern, 0.3 mm thickness of layer, 200°C, showed maximum values for flexural strength, tensile strength, tensile modulus, and flexural strength. Among the 3D-manufactured composite test specimens, 3% banana fibers composition showed a maximum modulus of 985 MPa, a flexural strength maximum of 151 MPa, a maximum of 32 MPa tensile strength, and a maximum of 2452 MPa flexural modulus. The fracture surface's SEM micrograph showed interfacial bonding and fiber pull-out.*

Keywords *- 3D Printing, Biocomposite, Natural fibers, Mechanical properties, Fused deposition.*

1. Introduction

Through the process of adding material in successive layers, additive fabrication, often well known as 3D printing, is a method that creates objects in three dimensions. The ability of 3D printing to quickly and easily build bespoke objects with intricate geometries has made it extremely popular [1]. Fused Deposition Modeling (FDM) is a broadly used and reasonably priced 3D printing technique that produces three-dimensional objects, among other things. Layer upon layer, a 3D item is created in FDM by extruding molten polymer via a nozzle and then cooling it to solidify it. The method provides economical production, short lead times, and substantial design freedom. Thermoplastic polymers, such as Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), Thermoplastic Polyurethanes (TPU), Nylon and Polylactic Acid (PLA) are commonly used in FDM printing technique. These polymers have been utilised in numerous applications, including medical and automotive [2]. The particular needs of the 3D printed object, like strength, stiffness, and durability, determine which polymer material is best. Unfortunately, the mechanical characteristics of the objects that are 3D printed are frequently not up to par, which restricts the use of three dimensional printing in high-performing applications. The filament material process variables, including layer thickness, infill pattern, raster angle, nozzle temperature, infill density, nozzle diameter and bed temperature, have a meaningful footprint on the mechanical and physical characteristics of 3D manufactured items. Layer height, build orientation, and infill influenced the mechanical features of ABS and PLA, which were examined by Rodriguez-Panes et al. [3]. The results of the inquiry revealed that PLA, as opposed to ABS, had a bigger impact on changes in process parameters. A Nugroho et al. [4] revealed The layer thickness influenced the PLA samples' flexural strengths; thicker layers often resulted in stronger samples. With a decrease in printing layer thickness, the specimens' tensile and bending qualities considerably improved. Greater gaps were created by the thicker layers, increasing the cross sectional porosity of the specimen. Poorer mechanical qualities were the outcome of higher porosity [5]. The printed material's tensile modulus elastic modulus, along with elongation at break, increased along with the extruded material's fluidity and bonding strength as The temperature of the nozzle was raised from 195°C to 210°C. The material's tensile strength and elastic modulus both marginally decline when the nozzle temperature rises from 210 to 230 degrees Celsius, while the elongation at break reduces quickly [6]. Tensile and flexural strength values for wood PLA were higher at 200, but at temperatures over 200, flexural and tensile strengths decreased [7]. The findings of the study conducted by Kadhum et al. [8] indicate that the selection of the infill pattern has a meaningful result upon the strength of the FDM printed specimens, specimens printed with gyroid-type infill pattern have maximum tensile strength, whereas the specimen printed with cross infill geometry have better surface roughness measures.

Stefan et al. [9] concluded the feasibility of using a 0.3 mm layer thickness for printing, which reduces printing time without significantly compromising the material's mechanical characteristics. A 3D printer's nozzle hole diameter can be adjusted to produce the desired product quality and shorten manufacturing times. Using a larger diameter could speed up product manufacturing, as evidenced by a study that found a non-linear correlation between nozzle hole diameter and product density and tensile strength [10]. The impact of crucial FDM process variables, such as The effects of extruder temperature, raster angle, the thickness of the layer, infill pattern, and infill on the mechanical features of 3D-manufactured biocomposite, is covered in this work [11]. P.Anerao et al. [12] recommend 0.2 mm for layer thickness, 100% for infill density, and 0° for raster angle as the FDM process settings. Piotr et al. [13] noted that among 0.2 mm, 0.4 mm, 0.8 mm, and 1.2 mm nozzle diameter, printing with 0.8 mm nozzle diameter, 100% infill, 0.2 mm, thickness of layer shown has a high degree of layer and path interconnection with improved mechanical characteristics. [14] Studies have indicated that the tensile and flexural characteristics of printed specimens are greatly influenced by the nozzle diameter selection, with strengths rising with bigger diameters up to a certain point.

Researchers have looked into the utilization of fiber insertion to improve the quality of FDM 3D manufactured items in an effort to get beyond the drawbacks of polymer materials. Fibers, both natural and synthetic, have been researched as possible reinforcements. Synthetic fibers have long dominated the composites industry but face environmental concerns due to their non-biodegradability. Polymer composite materials incorporating synthetic fibers like aramid and carbon are promising for structural applications, enhancing properties like strength and heat resistance in 3D printing [15]. [16] Synthetic fibers enhance polymer matrix composites by providing improved stiffness, strength, and modulus. They must be compatible with the matrix, have superior properties, optimal orientation, and a suitable shape for reinforcement. Surface modifications like saline, plasma, and acid treatments enhance synthetic fibre's properties, improving interphase bonding in epoxy/synthetic fibers composites, which is crucial for automotive, aerospace, and other applications [17]. The addition of GF was shown to improve the composite's modulus and strength but to decrease its flexibility. Conversely, the inclusion of POE-g-MA was found to decrease the composite's modulus and strength and increase its flexibility. When compared to specimens created via 3D printing, those created using the CM approach demonstrated greater values of strength and modulus. Further rheological study results demonstrated that POE-g-MA addition tends to raise viscosity, loss modulus, and storage modulus. The specimens made using the CM approach as opposed to 3D printing had higher crystallinity, according to the results of an X-Ray Diffraction (XRD) examination [18].

Alternative reinforcement solutions are being investigated, like natural fibers or biodegradable materials, having similar strength qualities and being easier to get. They are also more environmentally friendly. Natural fibers have gained popularity because of their affordability, sustainability, renewable nature, rigidity, high specific strength, and low equipment abrasiveness [19–23]. Natural fibers-reinforced composites have benefits over synthetic fibers composites [24]. Scientists and researchers are interested in using them as a substitute material for automotive and aerospace applications [25]. Various degrees of success have been achieved by reinforcing natural fibers like flax [26], jute [27], and hemp [28] in FDM printed parts. After 3D printing, the thermal and mechanical characteristics of the resultant composite have significantly improved when agricultural wastes are used as reinforcement in Polylactic Acid (PLA) [29].

In order to produce bioavailable materials and improve mechanical and thermal properties, research has been done on natural fibers like banana fibers [30, 31]. Banana fibers composites are eco-friendly with good mechanical properties [31]. Polylactic Acid (PLA) and Banana Fibers (BF) were combined to create a composite using the melt blending process, as reported by Shih Y F et al. [32]. Banana fibers were added to PLA, which improved its mechanical and thermal qualities. The composites' tensile and flexural strengths increased by two and 1.66 times, respectively, in comparison to virgin PLA, with 40% fibers reinforcement. Conversely, impact strength decreases as fiber concentration rises. Additionally, Virgin PLA's HDT improved by 122%, rising from 62°C to 139°C with a 40% fibers fraction. Jandas P. J. et al., [33] Melt blending was used to create a bio composite made of Banana Fibers (BF) and Polylactic Acid (PLA). Following that, compression molding was completed. Comparing treated fibers composite to untreated green composite, mechanical testing revealed meaningful improvements in both impact strength and tensile strength. The rise in melting transitions has been shown in DSC and TGA testing to indicate the presence of effective adhesion at the fibers and matrix interfaces. The impact of ultrasonic treatment on water and mechanical absorption composite properties made from banana weave fibers, was investigated by Ghosh Rajesh et al. [34]. For sonicated dry specimens, according to the findings, the tensile strength is about 122 MPa, and the flexural strength is approximately 136 MPa. Banana fibers-added polymer composites have been found to have better mechanical performance. A few explorations have been done on the use of banana fibers in FDM printed parts. Banana fibers as reinforcement in PLA for FDM printing are one possible use. The biocomposite that is produced has the potential to provide increased sustainability, less environmental impact, and improved mechanical performance. The Novelty of the present study is to examine the impact of adding banana fibers to PLA and the ways in which specific FDM 3D printing process parameters affected the mechanical characteristics of the resultant biocomposite. After adding different amounts of banana fibers to PLA, the lots were forced out to filaments having a 1.75 mm diameter for FDM. Test specimens were 3D printed using the Taguchi L16 experimental design as a basis. Various mechanical tests were brought out in harmony with the norms, and the outcomes were evaluated appropriately.

2. Materials and Methods

2.1. Material

Banana Fibers (BF), produced from banana stems, were collected from the local market as agricultural waste. The Polylactic Acid (PLA): LX175 granules were supplied by NaturTech India Ltd., located in Chennai. The physical and mechanical features of the PLA are shown in Table 1. The resulting filament's flexibility and printability were enhanced by the use of glycol as a plasticizer. Shiv Shakti Trading Corporation, Vadodara, provided Polyethylene Glycol (PEG).

2.2. Biocomposite Filament Production for FDM

Four groups of filaments were produced. A batch mixer was used, in which the first group of 98 wt% PLA granules was combined with 2wt% polyethylene glycol. In the second group, 1wt% banana fibers and 2wt % glycol were combined with 97wt %PLA granules. Third group, 95wt % PLA granules mixed with 3wt % banana fibers and 2wt % glycol. Fourth group, 93wt % PLA granules were mixed with 5wt % banana fibers and 2wt % glycol.

In the batch mixer, each batch was meticulously blended to produce a consistent composition. After each batch was ready, it was put into a single-screw extruder. The temperature set in each zone is displayed in Table 2. For processing BF/PLA composite filament, the extruder was adjusted to the proper settings, which included temperature at 170°C to 210°C based on the barrel's zone, speed of the screw was at 20–30 rpm, with 2500–3000 PSI die pressure. After that, the batches inside the extruder barrel were heated, melted, and completely combined. The melted PLA composites were formed into a continuous filament with a diameter of 1.75 mm by extruding them through a die. A schematic representation of the FDM technique for producing banana fibers/PLA bio-composite filaments.

2.3. FDM Process Parameters

The printing process parameters utilized in the FDM method showed a considerable effect on the mechanical qualities of 3D manufactured specimens, according to the literature [3–10, 13, 14]. Certain factors can be crucial, but others, such as printing speed, could not have much of an impact on mechanical quantities [35]. Therefore, while maintaining the other process variables at their standard values. This investigation seeks to examine the effects of four important process variables: nozzle temperature, printing pattern, nozzle size, and layer thickness. Table 3 displays the constant process variables.

Table 1. Mechanical properties of PLA

Matrix	Melt flow index (g/10 min)	Density (g/cc)	Tensile modulus (MPa)	Tensile Strength (MPa)	Elongation at yield (%)
PLA: X175	6.0	1.24	3500	45	5

Table 2. Extrusion process temperature for filament making

Barrel zone	Feed zone [°C]	Compression zone [°C]	Mixing zone [°C]	Die zone [°C]	Screw speed [RPM]
PLA	195	195	220	210	30
PLA + BF + PEG	180	185	195	195	20

Table 3. Printing process parameters are used as constants

FDM 3D printing process parameters	Settings
Temperature of Bed	60°C
Speed of Printing	60 mm/s
Build orientation	Flat

This study intends to obtain a profound understanding of each parameter's unique control on the mechanical properties of the FDM items by concentrating on these chosen ones. The precise path the extrusion nozzle takes during printing is referred to as the printing pattern, and it can affect elements like strength and surface polish. Each printed layer's thickness is determined by the layer thickness, which also influences the final object's strength and resolution. The nozzle size has the potential to impact mechanical attributes such as product density and tensile strength. Lastly, nozzle temperature can significantly impact its elastic properties, elongation at break, fluidity and bonding strength. Through a methodical variation and analysis of chosen process parameters, the investigation aims to offer an essential understanding of optimizing the FDM 3D printing process to achieve improved mechanical qualities in FDM printed objects.

2.4. Specimen Production and Testing

The four degrees of variation and the five parameters under research are shown in Table 4. The Taguchi design is used to provide robust and dependable results, reduce time and money invested in experiments, and obtain critical insights into the variables that most significantly affect the response variable.

In this work, the L16 Taguchi orthogonal array was utilized for statistical analysis with Minitab to investigate the impact of particular components and levels. Samples of the banana fibers/PLA biocomposite were printed in the arrangements indicated in Table 5. The CAD model was imported into Ultimaker Cura Software for G-code generation. Using a Reality CR 10 Max 3D Printer, an FDM-based 3D printer, the banana fibers/PLA based biocomposite specimens were created. The parameters listed in Table 4 were established, and for each experiment run, the other variables were adjusted in accordance with Table 5. For each experiment run, three specimens were printed. In line with ASTM D638 guidelines, specimens were printed to perform mechanical tensile testing (refer to Figure 1) at room temperature.

Tensile modulus and tensile strength were noted. An experiment was conducted three separate times independently to guarantee the precision and repeatability of the results. At a distance of 115 mm, specimens with dimensions 165 mm in length, 19 mm in width, 13 mm in width, and 3.2 mm in thickness were securely held. A universal testing machine with a 10 kN load cell capacity and a crosshead speed of 2 mm/min was subjected to a continuous tensile load. Kalpak Instruments and Controls manufactured the machine in Pune, India. The flexural test (see Figure 2) was conducted using a bending arrangement in line with ASTM D790 guidelines at room temperature. Rectangular cases with 127 mm length×, 12.7 mm width × 3.2 mm thickness and a 16:1 span-to-depth ratio were utilized in compliance with ASTM regulations. By using a cell capacity of 10 kN, the crosshead speed through the bending test was 1.3 mm/min. Equations provided in the ASTM guidelines and recorded load vs. displacement data were used to evaluate the flexural properties.

Table 4. Selected parameters and their levels in experiments

Parameters	Level 1	Level 2	Level 3	Level 4
Weight % of banana fiber in composite (%WBFC)	0	1	3	5
Nozzle size (mm)	0.4	0.6	0.8	1.0
Infill pattern	Grid	Gyroid	Cubic	Zig-zag
Layer thickness (mm)	0.1	0.2	0.3	0.4
Temperature of Nozzle (°C)	190	195	200	205

Table 5. Design of experiment Taguchi L16 orthogonal array

Experiment run	% weight of Banana fibers	Nozzle size (mm)	Infill pattern	Layer thickness (mm)	Nozzle temperature (°C)
1	0	0.4	Grid	0.1	190
2	0	0.6	Gyroid	0.2	195
3	0	0.8	Cubic	0.3	200
4	0	1.0	Zig-zag	0.4	205
5	1	0.4	Gyroid	0.3	205
6	1	0.6	Grid	0.4	200
7	1	0.8	Zig-zag	0.1	195
8	1	1.0	Cubic	0.2	190
9	3	0.4	Cubic	0.4	195
10	3	0.6	Zig-zag	0.3	190
11	3	0.8	Grid	0.2	205
12	3	1.0	Gyroid	0.1	200
13	5	0.4	Zig-zag	0.2	200
14	5	0.6	Cubic	0.1	205
15	5	0.8	Gyroid	0.4	190
16	5	1.0	Grid	0.3	195

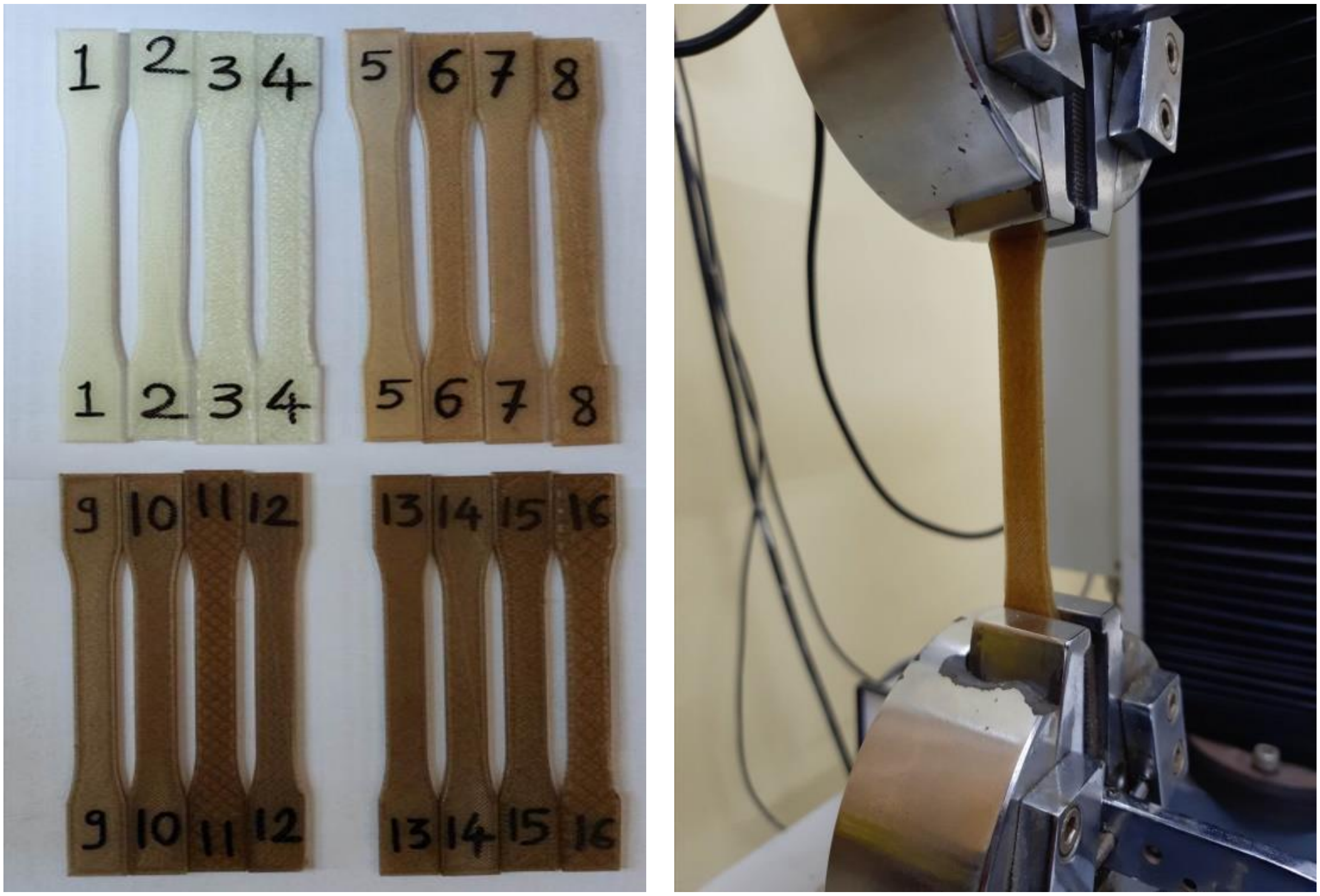


Fig. 1 3D printed specimen and mechanical tensile testing

3. Result and Discussion

3.1. Effect on Tensile Properties

The highest modulus (1101 MPa) and tensile strength (38 MPa) are obtained with a cubic pattern, 0.8 mm nozzle size, 0.3 mm layer thickness and nozzle temperature of 200°C with 0% Banana Fibers (see Table 6). The second highest values are found for experiment number 11, where tensile strength (32 MPa) and modulus (985 MPa) are found with 0.8 mm nozzle size, grid infill pattern, 0.2 mm layer thickness, and 205°C nozzle temperature with 3% banana fibers.

To gain a better understanding of the influence of process factors on tensile strength and tensile modulus, main effect plots were developed (refer to Figures 3 & 4). Figure 7 illustrates the stress-strain curve of sixteen FDM-printed test cases under tensile testing. Figure 8 displays the behavior of load-displacement sixteen tensile test trials. Experiment number 6 showed least values of Ultimate Tensile Strength (22 MPa) and Tensile Modulus (608 MPa) with 0.6 mm nozzle size, grid infill pattern, 0.4 mm layer height, and 200°C nozzle temperature with 1% banana fibers. Because the fibers contain substances like wax and other materials that act as ductile material, increasing the fibers loading in composites improves the percentage elongation [36]. All five factors were discovered to have a significant effect on the Ultimate Tensile Strength of specimens by looking at the Analysis of Variance (ANOVA) (refer to Table 7). However, the composition of banana fibers was found to be dominant, with a 43.58% contribution. This could be because of the fibres' superior interfacial connection with the matrix and their uniform distribution [37]. Meanwhile, for the Tensile Modulus, nozzle size was found to be dominant, with a 42.67% contribution (refer to Table 8).

Because of the enhanced particle-to-particle load transmission, stress distribution and load-bearing capability are more effective. The primary effect plot also showed that the nozzle size should be 0.8 mm, the thickness of the layer should be 0.3 mm, the nozzle temperature should be 200°C, and the Gyroid or Cubic infill pattern should be used for pure PLA. A higher nozzle size results in enhanced density and tensile strength.

This makes the printed product stronger overall. Thicker layers often improve the unity and soundness of the printed object since they tend to offer interlayer adhesion [31]. The composite material's tensile modulus and stiffness have grown as a result. Numerous research has shown that an increase in banana fibers corresponds to a rise in tensile strength [32–34].

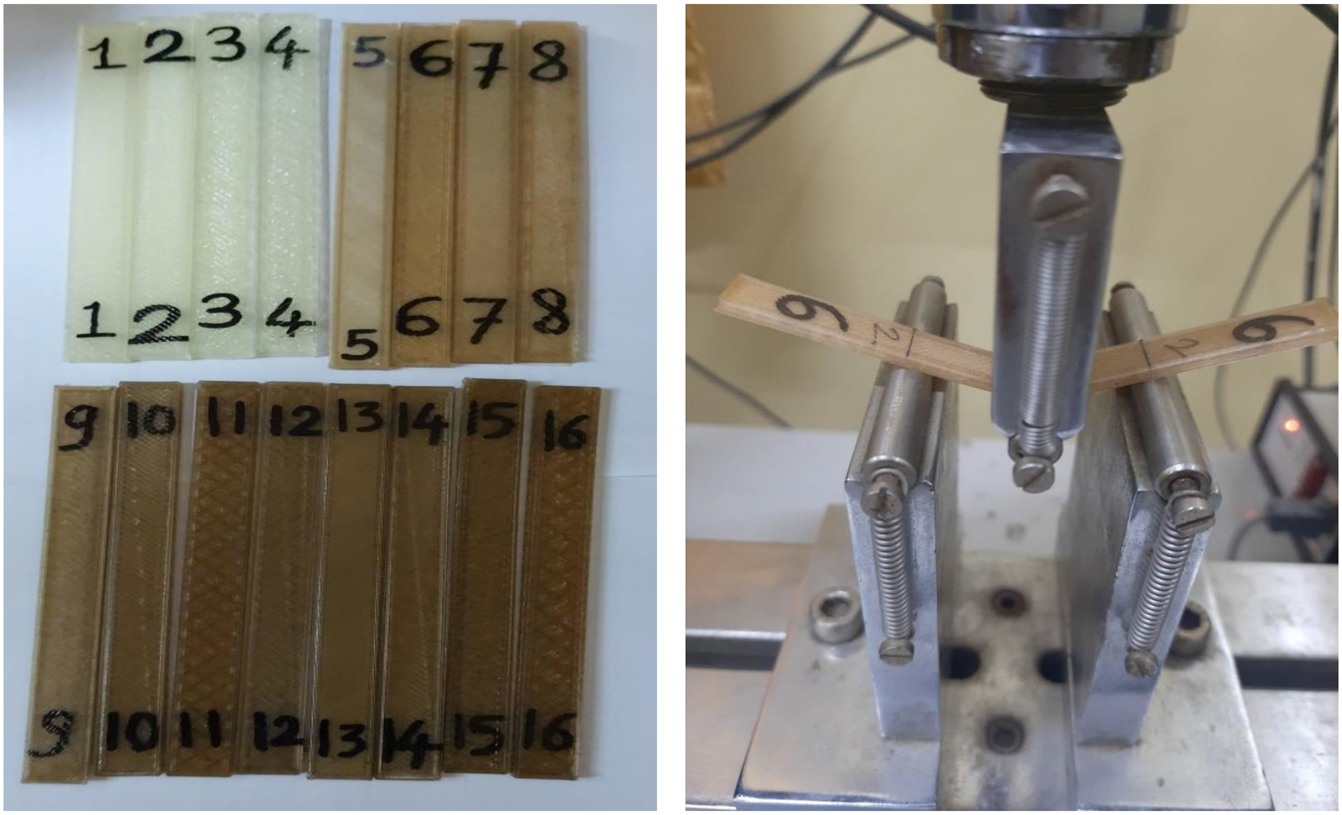


Fig. 2 3D printed specimen and mechanical flexural testing

Table 6. Mechanical Tensile test observations for 16 experiments.

Experiment Number	Ultimate Tensile Strength (MPa)	Tensile Modulus (MPa)	% Elongation at Break
1	28+-6	819+-170	6+-2
2	32+-6	874+-176	4+-2
3	38+-5	1101+-173	4+-2
4	29+-3	776+-133	4+-2
5	28+-4	898+-137	4+-2
6	22+-4	608+-128	5+-2
7	28+-1	927+-62	4+-2
8	26+-2	732+-30	4+-2
9	29+-3	845+-94	4+-2
10	30+-3	808+-97	5+-2
11	32+-3	985+-135	4+-2
12	31+-3	939+-172	4+-2
13	30+-3	947+-172	3+-2
14	29+-3	828+-144	4+-2
15	31+-16	850+-474	4+-4
16	28+-23	802+-669	4+-5

Table 7. Analysis of variance of means for ultimate tensile strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	73.188	73.1875	24.3958	*	*	43.58%
Nozzle Size	3	42.687	42.6875	14.2292	*	*	25.42%
Infill Pattern	3	24.188	24.1875	8.0625	*	*	14.40%
Layer Thickness	3	23.188	23.1875	7.7292	*	*	13.81%
Nozzle Temperature	3	4.688	4.6875	1.5625	*	*	2.79%
Residual Error	0	*	*	*			
Total	15	167.938					100.00%

Table 8. Analysis of variance of means for tensile modulus

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	27838	27838.2	9279.4	*	*	14.68%
Nozzle Size	3	80936	80936.2	26978.7	*	*	42.67%
Infill Pattern	3	17572	17571.7	5857.2	*	*	9.27%
Layer Thickness	3	43426	43426.2	14475.4	*	*	22.90%
Nozzle Temperature	3	19887	19887.2	6629.1	*	*	10.49%
Residual Error	0	*	*	*			
Total	15	189659					100.00%

3.2. Flexural Properties

For each experimental number, three specimens were printed and tested using an FDM printer. Table 9 shows mean readings for each specimen for all performed tests. The maximum rate of Flexural Strength (180 MPa) and Flexural Modulus (2720 MPa) is found with a 0.8 mm size of nozzle, a cubic pattern, 0.3 mm layer thickness, and nozzle temperature of 200°C with 0% Banana Fibers (see Table 9). The second highest values are found for experiment number 11, where Flexural Strength (151 MPa) and modulus (2452 MPa) are found with a 0.8 mm size of nozzle, grid infill pattern, 0.2 mm layer thickness, and 205°C nozzle temperature with 3% banana fibers. To see a good behavior of the control of process ingredients on Flexural properties, main effect plots were developed (refer to Figures 5 and 6). Experiment number 8 showed least rate of Flexural Strength (105 MPa) and Flexural Modulus (1417 MPa) with 0.4 mm nozzle size, cubic infill pattern, 0.2 mm layer height, and 190°C temperature of nozzle with 1% banana fibers. It was found that each of the five process variables significantly affected the 3D printed material's flexural strength. Specimens by looking at the Analysis of Variance (ANOVA) (refer to Table 10); however, the composition of banana fibers was found to be dominant with a 43.69% contribution. For Flexural Modulus, the composition of banana fibers was found to be dominant, with a 33.03% contribution (refer to Table 11).

Table 9. Mechanical flexural tests observations for 16 experiments.

Experiment Numbers	Flexural Strength (MPa)	Flexural Modulus (MPa)
1	148+-19	2221+-394
2	144+-26	1832+-571
3	180+-26	2720+-528
4	133+-28	1850+-499
5	135+-24	2062+-278
6	109+-33	1677+-519
7	134+-29	2110+-460
8	105+-28	1417+-464
9	125+-14	1985+-202
10	138+-6	2366+-176
11	151+-3	2452+-190
12	148+-8	2322+-233
13	144+-9	2358+-227
14	132+-10	1994+-207
15	141+-86	2273+-1283
16	140+-121	2247+-1814

Table 10. Analysis of variance of means for flexural strength.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	1923.69	1923.69	641.229	*	*	43.69%
Nozzle Size	3	1108.19	1108.19	369.396	*	*	25.17%
Infill Pattern	3	95.19	95.19	31.729	*	*	2.16%
Layer Thickness	3	945.19	945.19	315.063	*	*	21.47%
Nozzle Temperature	3	330.69	330.69	110.229	*	*	7.51%
Residual Error	0	*	*	*			
Total	15	4402.94					100.00%

Table 11. Analysis of variance of means for flexural modulus

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	515911	515911	171970	*	*	33.03%
Nozzle Size	3	491177	491177	163726	*	*	31.45%
Infill Pattern	3	46898	46898	15633	*	*	3.00%
Layer Thickness	3	381273	381273	127091	*	*	24.41%
Nozzle Temperature	3	126462	126462	42154	*	*	8.10%
Residual Error	0	*	*	*			
Total	15	1561722					100.00%

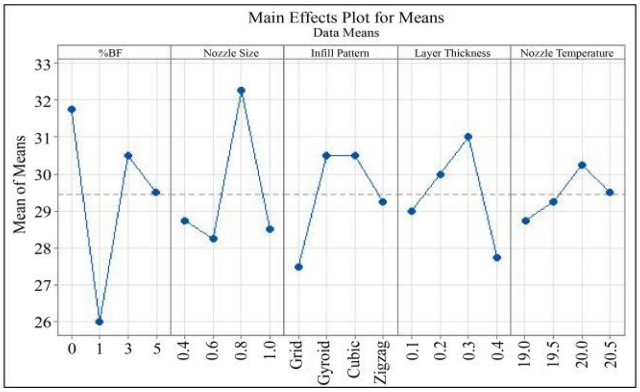


Fig. 3 Main effects plot for UTS

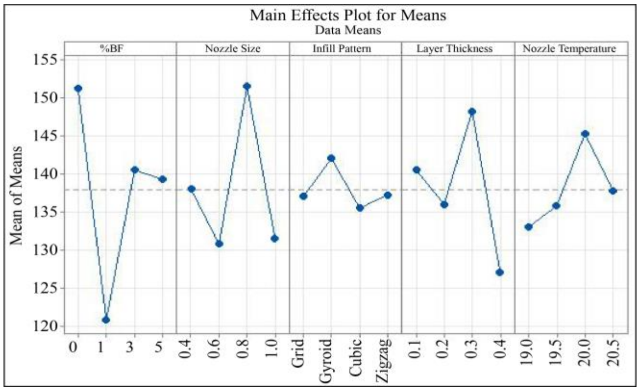


Fig. 5 Main effects plot for FS

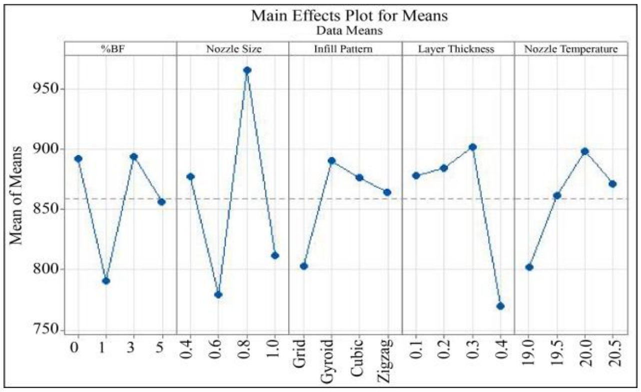


Fig. 4 Main effects plot for TM

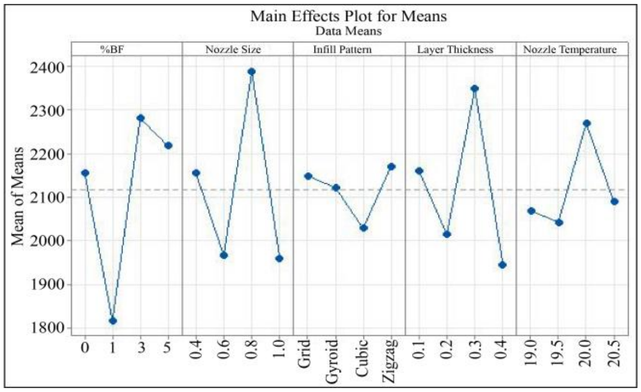


Fig. 6 Main effects plot for FM

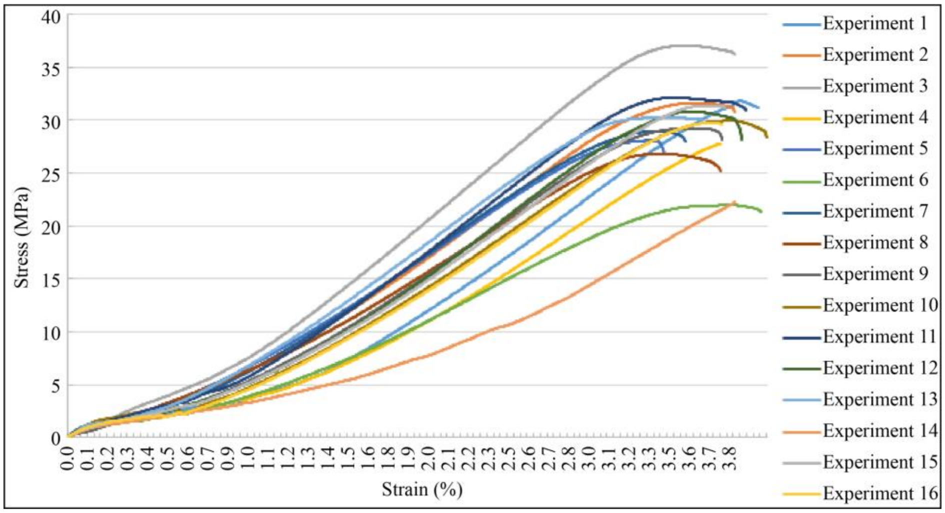


Fig. 7 16 FDM-manufactured test specimens' stress-strain behavior under tensile loading

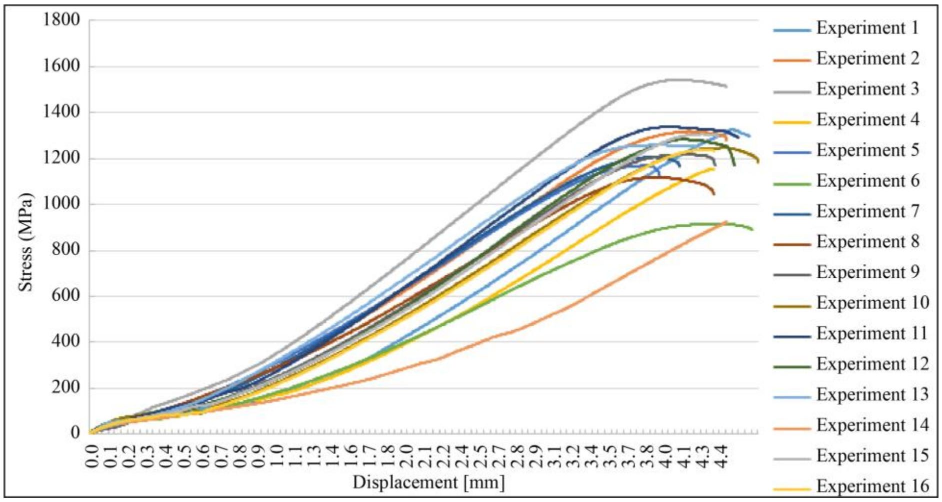
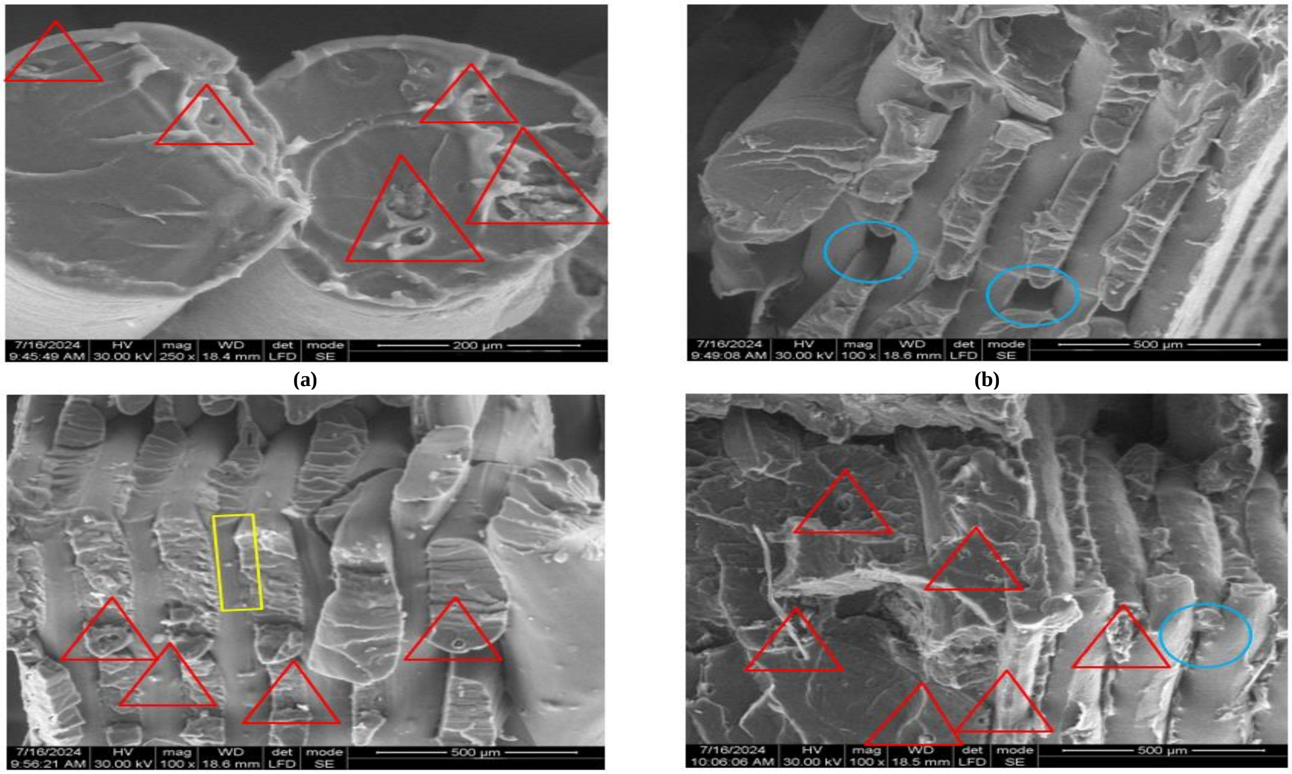


Fig. 8 Load vs displacement behaviour of 16 tensile test experiments

3.3. Tensile Fracture Specimen Morphology

At a resolution of 200–500 µm, Figure 9 shows the cracked surface morphology in a cross-section of tensile testing specimens from four tests: 5, 7, 11, and 14. The 3D manufactured specimens' surface shape, as shown in Figure 9, provides unambiguous visible confirmation of the chosen process parameters, including layer thickness, listed in Table 5. In Figures 9(a), (c), and (d), the fibers pulled out are depicted by red triangles. There was a clear space between the layers in Figures 9(b) and (d), as shown by the blue circles. The banana fibers/PLA composite saw a decrease in TS, TM, FS, and FM as a result of this variation. With Experiment 11 obtaining the second-highest Tensile Strength (TS) at 32 MPa and a maximum Tensile Modulus (TM) of 985 MPa, the results show the influence of these factors. The combination of the experiment's greater weight percentage (3%) of banana fibers and the minimum thickness of the layer of 0.2 mm is probably responsible for the high value of TM. The carefully aligned layers of a 3D-printed item show distortion indicators such as swelling, bending, or separation in Figure 9(c).



(a) **(b)**

(c) **(d)**

Fig. 9 SEM morphology of the experiment run number's tensile cracked specimen (a) 5, (b) 7, (c) 11, and (d) 14.

4. Conclusion

The extrusion of a banana fibers/PLA biocomposite 3D printing filament has been accomplished, allowing it to be used in Fused Deposition Modeling (FDM). The addition of banana fibers resulted in a rise in tensile strength and tensile modulus. This indicates that applications requiring higher stiffness can benefit greatly from the use of the 3D-printed banana fibers/PLA biocomposite. Tensile values decreased as a result of the inadequate interfacial bonding. Parameters like nozzle size, infill pattern, layer thickness, and nozzle temperature greatly influence the mechanical characteristics of biocomposite. Ultimate Tensile Strength and Tensile Modulus, with 3% banana fiber composition, showed the second highest values. Items printed with 0.8 mm size of the nozzle, cubic infill pattern, 0.3 mm thickness of the layer, 200°C, and 0% banana fibers composition showed the highest values for tensile modulus and second highest value for tensile modulus with 3% banana fibers. Since wax and other substances are present in the fibers and function as ductile material, increasing the fibers loading in composites improves the percentage elongation. Flexural Strength and Flexural Modulus, with 3% banana fiber composition, showed the second highest values. Items printed with 0.8 mm size of the nozzle, grid infill pattern, 0.2 mm thickness of the layer, 205°C, 0% banana fibers composition showed the highest values for flexural strength, flexural modulus, and second highest value for flexural strength and flexural modulus with 3% banana fibers. Lastly, there could be a big improvement in the mechanical performance and sustainability of FDM printed objects if banana fibers are used. To achieve the desired qualities, more study is needed to optimize the printing conditions and the amount of banana fibers. The creation of FDM printed items reinforced with banana fibers may open up new possibilities for high-performance, ecologically friendly engineering applications. Considering the outcomes of the experimental study, it is possible to combine 3% banana fiber composition with PLA biocomposite material as an alternative to traditional fibers-reinforced polymer composites, as it can bear higher loads than the combination.

References

[1] Anoop Kumar Sood, Rajkumar Ohdar, and Siba Sankar Mahapatra, “Parametric Appraisal of Mechanical Property of Fused Deposition Modelling Processed Parts,” *Materials & Design*, vol. 31, no. 1, pp. 287-295, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[2] Samarthya Bhagia et al., “Critical Review of FDM 3D Printing of PLA Biocomposites Filled with Biomass Resources, Characterization, Biodegradability, Upcycling and Opportunities for Biorefineries,” *Applied Materials Today*, vol. 24, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] Adrián Rodríguez-Panes, Juan Claver and Ana María Camacho, “The Influence of Manufacturing Parameters on the Mechanical Behaviour of PLA and ABS Pieces Manufactured by FDM: A Comparative Analysis,” *Materials*, vol. 11, no. 8, pp. 1-21, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[4] A Nugroho et al., “Effect of Layer Thickness on Flexural Properties of PLA (PolyLactid Acid) by 3D printing,” *6th International Seminar of Aerospace Science and Technology*, Jakarta, Indonesia, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[5] Nadir Ayrilmis et al., “Effect of Printing Layer Thickness on Water Absorption and Mechanical Properties of 3D-Printed Wood/PLA Composite Materials,” *The International Journal of Advanced Manufacturing Technology*, vol. 102, pp. 2195–2200, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Shuheng Wang et al., “Effects of Fused Deposition Modeling Process Parameters on Tensile, Dynamic Mechanical Properties of 3D Printed Polylactic Acid Materials,” *Polymer Testing*, vol. 86, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Teng-Chun Yang, “Effect of Extrusion Temperature on the Physico-Mechanical Properties of Unidirectional Wood Fiber-Reinforced Polylactic Acid Composite (WFRPC) Components using Fused Deposition Modeling,” *Polymers*, vol. 10, no. 9, pp. 1-11, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[8] A. H. Kadhum, Salah Al-Zubaidi, and Salah S. Abdulkareem, “Effect of the Infill Patterns on the Mechanical and Surface Characteristics of 3D Printing of PLA, PLA+ and PETG Materials,” *ChemEngineering*, vol. 7, no. 3, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[9] Stefan Szczepanik, and Piotr Nikiel, “Influence of Structural Characteristics on the Mechanical Properties of FDM Printed PLA Material,” *Journal of Casting & Materials Engineering*, vol. 4, no. 1, pp. 1-8, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[10] Joko Triyono et al., “The Effect of Nozzle Hole Diameter of 3D Printing on Porosity and Tensile Strength Parts Using Polylactic Acid Material,” *Open Engineering*, vol. 10, no. 1, pp. 762-768, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Prashant Anerao, Atul Kulkarni, and Yashwant Munde, “A Review on Exploration of the Mechanical Characteristics of 3D-Printed Biocomposites Fabricated by Fused Deposition Modelling (FDM),” *Rapid Prototyping Journal*, vol. 30, no. 3, pp. 430-440, 2024, [CrossRef] [Google Scholar] [Publisher Link]

[12] Prashant Anerao et al., “Biochar Reinforced PLA Composite for Fused Deposition Modelling (FDM): A Parametric Study on Mechanical Performance,” *Composites Part C: Open Access*, vol. 12, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Piotr Czyżewski et al., “Influence of Extruder’s Nozzle Diameter on the Improvement of Functional Properties of 3D-Printed PLA Products,” *Polymers*, vol. 14, no. 2, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Ioan Tamașag et al., “Experimental Study of In-Process Heat Treatment on the Mechanical Properties of 3D Printed Thermoplastic Polymer PLA,” *Polymers*, vol. 15, no. 10, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Evgeniy Lobov et al., “Effect of Short Carbon Fiber Reinforcement on Mechanical Properties of 3D-Printed Acrylonitrile Butadiene Styrene,” *Polymers*, vol. 15, no. 9, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Dipen Kumar Rajak, Pratiksha H. Wagh, and Emanoil Linul, “A Review on Synthetic Fibers for Polymer Matrix Composites: Performance, Failure Modes and Applications,” *Materials*, vol. 15, no. 14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Raed B. Alsuwait et al., “Recent Development in the Processing, Properties, and Applications of Epoxy-Based Natural Fiber Polymer Biocomposites,” *Polymers*, vol. 15, no. 1, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[18] Satish V Joshi et al., “Are Natural Fiber Composites Environmentally Superior to Glass Fiber Reinforced Composites?,” *Composites Part A: Applied Science and Manufacturing*, vol. 35, no. 3, pp. 371–376, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ke-Chang Hung et al., “Assessing the Effect of Wood Acetylation on Mechanical Properties and Extended Creep Behavior of Wood/Recycled-Polypropylene Composites,” *Construction and Building Materials*, vol. 108, pp. 139–145, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[20] D. García-García et al., “Green Composites Based on Polypropylene Matrix and Hydrophobized Spend Coffee Ground (SCG) Powder,” *Composites Part B: Engineering*, vol. 78, pp. 256–265, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[21] Praveen Kumar, Megumi Kawasaki, and Terence G. Langdon, “Review: Overcoming the Paradox of Strength and Ductility in Ultrafine-Grained Materials at Low Temperatures,” *Journal of Materials Science*, vol. 51, pp. 7–18, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[22] Estefanía Lidón Sánchez-Safont et al., “Biocomposites of Different Lignocellulosic Wastes for Sustainable Food Packaging Applications,” *Composites Part B: Engineering*, vol. 145, pp. 215–225, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[23] M.N.M. Azlin et al., *Natural Polylactic Acid-Based Fiber Composites : A Review*, Advanced Processing, Properties, and Applications of Starch and Other Bio-Based Polymers, Elsevier, pp. 21-34, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[24] S. Singh et al., “A Comprehensive Review of Banana Fiber-Reinforced Composites: Properties, Processing and Applications,” Journal of Computers, Mechanical and Management, vol. 1, no. 2, pp. 36–49, 2022, [CrossRef] [Google Scholar] [Publisher Link]

[25] Gholamhossein Sodeifian, Saghar Ghaseminejad, and Ali Akbar Yousefi, “Preparation of Polypropylene/Short Glass Fiber Composite as Fused Deposition Modeling (FDM) Filament,” *Results in Physics*, vol. 12, pp. 205–222, 2019, [CrossRef] [Google Scholar] [Publisher Link]

[26] Ana Paulo ET AL., “Mechanical Properties of PLA Specimens Obtained by Additive Manufacturing Process Reinforced with Flax Fibers,” *Journal of Composites Science*, vol. 7, no. 1, 2023, [CrossRef] [Google Scholar] [Publisher Link]

[27] Sean A. Hinchcliffe, Kristen M. Hess, and Wil V. Srubar, “Experimental and Theoretical Investigation of Prestressed Natural Fiber-Reinforced Polylactic Acid (PLA) Composite Materials,” *Composites Part B: Engineering*, vol. 95, pp. 346-354, 2016, [CrossRef] [Google Scholar] [Publisher Link]

[28] Sheedev Antony, Abel Cherouat, and Guillaume Montay, “Fabrication and Characterization of Hemp Fibre Based 3D Printed Honeycomb Sandwich Structure by FDM Process,” *Applied Composite Materials*, vol. 27, pp. 935-953, 2020, [CrossRef] [Google Scholar] [Publisher Link]

[29] Vito Gigante et al., “Improvement of Interfacial Adhesion and Thermomechanical Properties of PLA Based Composites with Wheat / Rice Bran,” *Polymers*, vol. 14, no. 16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[30] Siva Ramasamy et al., “Comprehensive Characterization of Novel Robusta (AAA) Banana Bracts Fibers Reinforced Polylactic Acid Based Biocomposites for Lightweight Applications,” *Polymer Composites*, vol. 43, no. 11, pp. 8569-8580, 2022, [CrossRef] [Google Scholar] [Publisher Link]

[31] Tuan Anh Nguyen, and Thi Huong Nguyen, “Study on Mechanical Properties of Banana Fiber-Reinforced Materials Poly (Lactic Acid) Composites,” *International Journal of Chemical Engineering*, vol. 2022, no. 1, pp. 1-7, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[32] Y. F. Shih and C. C. Huang, “Polylactic Acid (PLA)/Banana Fiber (BF) Biodegradable Green Composites,” *Journal of Polymer Research*, vol. 18, pp. 2335–2340, 2011, [CrossRef] [Google Scholar] [Publisher Link]

[33] P.J. Jandas et al., “Effect of Surface Treatments of Banana Fiber on Mechanical, Thermal, and Biodegradability Properties of PLA/Banana Fiber Biocomposites,” *Polymer Composites*, vol. 32, no. 11, pp. 1689-1700, 2011, [CrossRef] [Google Scholar] [Publisher Link]

[34] Rajesh Ghosh et al., “Water Absorption Kinetics and Mechanical Properties of Ultrasonic Treated Banana Fiber Reinforced-Vinyl Ester Composites,” *Procedia Materials Science*, vol. 5, pp. 311–315, 2014, [CrossRef] [Google Scholar] [Publisher Link]

[35] John D. Kechagias et al., “Parameter Design of PLA/Wood Fused Filament Fabrication Using Taguchi Optimization Methodology,” *Research Square*, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[36] Raghavendra Subramanya, D. N. Subba Reddy, and Prabhakara Shimoga Sathyanarayana, “Tensile, Impact and Fracture Toughness Properties of Banana Fibre-Reinforced Polymer Composites,” *Advances in Materials and Processing Technologies*, vol. 6, no. 4, pp. 661-668, 2020, [CrossRef] [Google Scholar] [Publisher Link]

[37] Budrun Neher et al., “Study of the Physical, Mechanical and Thermal Properties of Banana Fiber Reinforced HDPE Composites,” *Materials Sciences and Applications*, vol. 11, pp. 245–262, 2020, [CrossRef] [Google Scholar] [Publisher Link]