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Original Article

Mechanical Characterization of Banana Fibers/PLA Biocomposite Samples Produced by Fused Deposition Modeling Based 3D Printing Using Taguchi Method

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Abstract *- In order to explore, evaluate, and maximize the impact strength of Banana Fibers/Polylactic Acid (PLA) Biocomposite created by Fused Deposition Modeling (FDM), this research applies the Taguchi technique and Analysis of Variance (ANOVA). This study investigates how important printing parameters affect impact strength and compression properties, including nozzle size, infill patterns, layer thickness, and nozzle temperature. The settings are changed within predetermined ranges using an experimental design based on a Taguchi L16 orthogonal array. The composite with 3% banana fibers has a maximum impact strength of 41 J/m, 70 % more compared with neat PLA, according to the Analysis of Variance (ANOVA) examination of the data. This is followed by 0.6 mm nozzle size, zig-zag infill pattern, 0.3 mm layer thickness, and 190°C nozzle temperature. The compressive strength and compressive modulus are found to be 44 MPa (69 % more compared with neat PLA) and 1653 MPa (71 % more compared with neat PLA), respectively, for a 3 % banana fibers composite. The most significant variables, according to an ANOVA, are nozzle size and the percentage of banana fibers, which contribute 30.44% and 27.31%, respectively.*

Keywords *- ANOVA, Banana fibers, Biocomposite, Mechanical properties, Fused Deposition Modeling.*

1. Introduction

Nowadays, many manufacturing industries need more affordable, high-quality, bespoke parts with the required mechanical properties. The production of components with complex geometries and desirable properties has significantly advanced thanks to additive manufacturing, or 3D printing [1], [2]. In contrast to traditional machining techniques, Additive Manufacturing (AM) technologies allow the physical object to be manufactured layer by layer using the 3D computer-aided model, utilizing the necessary amount of material [3]. The use of 3D-printed products using various technologies and materials, like Stereolithography (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Laminated Object Manufacturing (LOM), is increasing because of the affordability of assembly and materials. Nowadays, the FDM approach is widely used because of the development of low-cost devices, the elimination of hazardous chemicals and adhesives from sample creation, the low cost associated with printing materials, and the compact device size that can be placed on a tabletop. Several thermoplastic polymers are used in the FDM method to create things with intricate shapes [4]. PLA, or Polylactic acid, is a specific type of thermoplastic material that is sustainable since it can be made from sustainable materials like corn starch or sugarcane. PLA is widely used in food packaging boxes as well as a variety of medical devices, such as implants, dental work, medication containers, and orthopaedic procedures. The simplicity of printing with PLA filaments is the reason for their popularity in 3D printing applications [5-7].

Recent research on the mechanical characteristics and FDM parameter optimization of 3D-printed parts for various composites made from thermoplastics, natural fibers and synthetic fibers are compiled below based on a literature study done prior to the experimental investigations. D. Mahesh et al. [8] stated that the maximum impact strength was found to be 32.15 (J/m) for 50% polypropylene and banana composite.

Oğuz Tunçel. [9] found some interesting things about CF-reinforced PLA 3D-printed samples. Maximum impact strength (113.84 J/m) was attained with optimized parameters. The Taguchi methodology was employed by Atakok et al. [10] to examine the impact of Fused Deposition Modeling parameters towards the characteristics of pure PLA and recycled PLA.

The research outcome showed that parameter layer thickness was the most important component, with better mechanical properties (impact strength of 16.96 kJ/m2) and ideal values. In their investigations, Kam et al. [11] found that the layer height has a major impact on the impact strength of 3D-printed PA12 samples. The excellent impact strength (25.3 kJ/m2) was discovered by a 0.25 mm layer thickness, infill rate of 50 %, infill pattern rectilinear, and 250 °C print temperature.

The study conducted by Lee et al. [12] yielded the following findings: for 3D-printed carbon fibers reinforced PLA composites, impact strengths were found to be influenced by both print orientation and bed temperature, while the table temperature was the highest significant parameter for tensile strength. In their study [13], Sharif et al. discovered that FDM printed 3D products showed thicker layers and faster printing lowered impact strength.

It was enhanced by a bigger infill density from 40% to 80%. The ideal parameters were 100 mm/s printing speed (22.12 kJ/m2), 0.1 mm thickness, and 80% infill. Higher impact strength was largely attributed to infill rate and layer thickness.

According to Tanveer et al. [14], PLA specimens with different infill densities had impact strength tests revealed that the Izod strength was 1.7 kJ/m2 and the maximum Charpy strength was 4.72 kJ/m2. By adjusting process settings, Nagendra et al. [15] were able to produce nylon parts that were FDM printed with noticeable improvements. Mechanical qualities were improved by the ideal parameters, which included a rectilinear filling model, infill density of 90%, a raster angle of 90°, a layer thickness of 0.4 mm, and nozzle temperature as 300 °C.

Comparing pure nylon specimen tested at these settings to components pure nylon printed by conventional settings, the specimen showed impact strength through 27.4% (0.637 MJ/m2), and compressive strength by 7.5% (19.42 MPa). Bekraoui et al. investigated that as banana fibers weight % increased with synthetic carbon, the impact strength increased [16].

VP Sajna et al. [17] have found that 30 % Banana fibers with 70 % PLA exhibit an increase in the Impact strength of the composite. [18] Tuan et al. manufactured banana fibers and PLA composite by hot melt mixing, where 20 % banana fibers loading in composite exhibits higher mechanical properties.

Reinforcing natural fibers or biodegradable polymers improves mechanical qualities. Their composites are easy to manufacture and more environmentally friendly. They are popular for their affordability, sustainability, and renewable nature. It has been discovered that polymer composites reinforced with banana fibers have superior mechanical performance. However, Banana Fibers utilization in FDM printed parts has been studied by a few researchers only. One potential application is using banana fiber reinforcement in PLA for FDM-based 3D printing. The biocomposite exhibits enhanced sustainability, less environmental impact, and improved mechanical performance. A notable gap exists in the study of impact and compression properties, particularly in banana fibers reinforced thermoplastic composites using FDM.

The novelty of the current study investigated the effects of incorporating 0, 1, 3, and 5 weight % of banana fibers into PLA and the ways in which particular FDM 3D printing process parameters influenced the mechanical properties of the Biocomposite that were made. Following the addition of varying quantities of banana fibers to PLA, filaments were extruded with 1.75 mm diameter.

The Taguchi L16 array experimental design served as the foundation for the 3D printing of test specimens. In accordance with the standards, impact tests and compressive tests were conducted, and the results were suitably assessed. This study will enlighten the impact of banana fiber addition and printing parameters on the mechanical characteristics of composites. Also, the impact of banana fiber addition on water absorption capacity for the composites is studied.

Four key 3D printing factors were studied: nozzle size, layer thickness, infill pattern, and nozzle temperature. The Taguchi L16 array was utilised in DOE and statistical analysis to arrange the experiments.

In summary, this study has scientific significance since it gives optimum parameter combinations for industrial applications and methodically and thoroughly investigates the impact of 3D printing process parameters on the impact strength and compressive properties of banana fibers/Poly lactic Acid Biocomposite.

2. Materials and Methods

2.1. Material

As an agricultural waste, Banana Fibers (BF) made from banana stems were gathered from the neighbourhood market. The Polylactic Acid (PLA): LX175 granules were provided by Chennai-based NaturTech India Ltd. Table 1 displays the mechanical and physical characteristics of the PLA. By using glycol as a plasticizer, the resulting filament's flexibility and printability were improved. Polyethylene Glycol was supplied by Vadodara-based Shiv Shakti Trading Corporation (PEG).

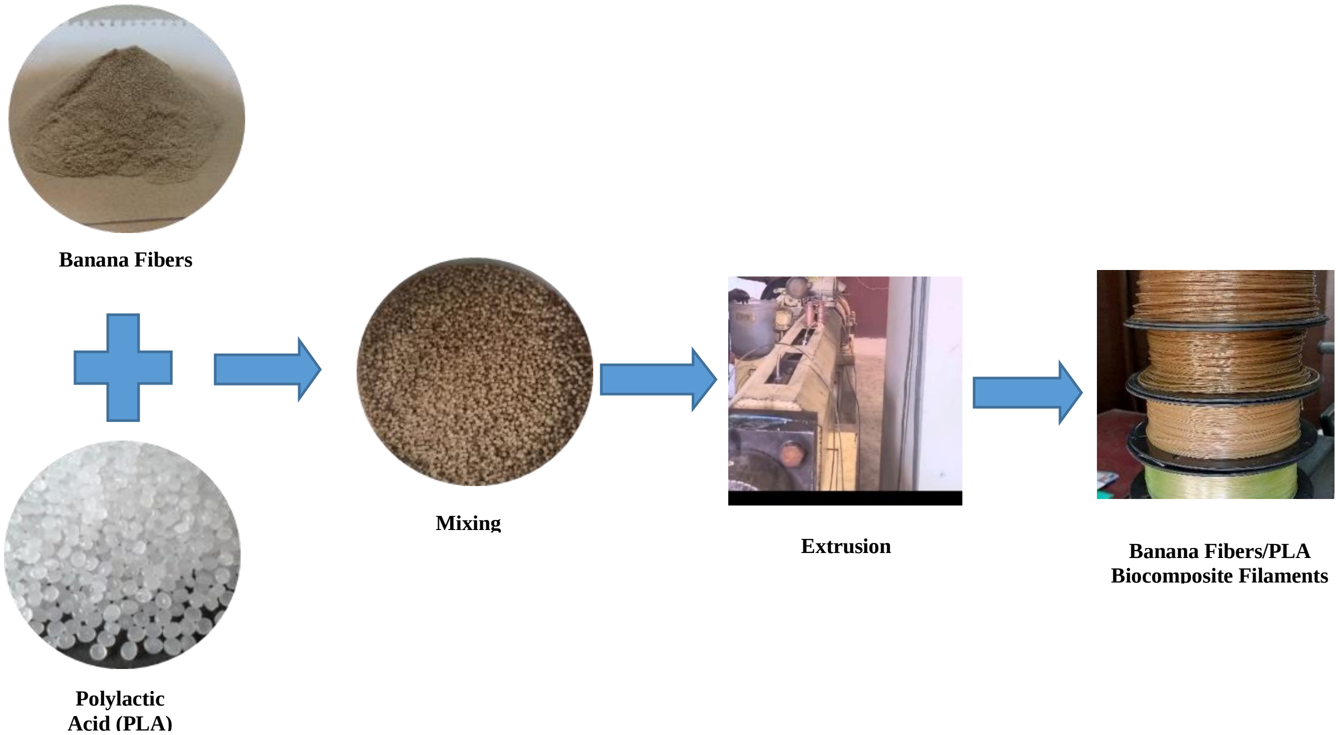

Fig. 1 Representation of producing banana fibers/PLA biocomposite filament for the FDM 3D printing process.

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. Selected process parameters and levels

Parameters	Levels			
	1	2	3	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
Nozzle temperature (°C)	190	195	200	205

2.2. Biocomposite Filament Production for FDM

Four types of filaments were manufactured. The first type was manufactured using 98 % PLA and 2 % glycol. The second type was manufactured using 1 % banana fibers, 97 % PLA and 2 % glycol. The third type was manufactured with 3 % banana fibers, 95 % PLA and 2 % glycol. The fourth type was manufactured using 5 % banana fibers, 97 % PLA and 2 % glycol. The filaments with 1.75 mm diameter were produced. During the extrusion of filaments, the feed zone was at a temperature of 195 °C for PLA and 180 °C for PLA/BF/PEG. In the compression zone, the temperature was 195 °C for PLA and 185 °C for PLA/BF/PEG. In the mixing zone, the temperature was 220 °C for PLA and 195 for PLA/BF/PEG. In the die zone, 210 °C for PLA and 195 °C for PLA/BF/PEG. The water at room temperature was used to cool the filaments. Figure 1 shows the representation of the production of banana fibers/PLA biocomposite filament for the FDM 3D printing process.

The literature indicates that the printing process settings used in the FDM method had a meaningful influence on the 3D-printed objects' mechanical characteristics. All along, some features, like print speed, might not have much of an influence on mechanical quantities, while others may be very important [19]. Therefore, the goal of this research is to carefully analyse the effects of important process elements, such as the nozzle size, printing pattern, layer thickness, and nozzle temperature, while keeping the other parameters at their typical levels and keeping others constant process parameters.

2.3. Process Parameters of FDM

By aiming at these selected parameters, this investigation aims to achieve a thorough recognition of each one's distinct influence on the mechanical properties of the FDM-based printed specimens. The infill pattern, which influences factors like strength and surface polish, is the exact path the nozzle follows during printing. The layer thickness, which also affects the final object's strength and resolution, establishes the depth of every printed layer. The nozzle size may impact mechanical properties like product density and impact strength. Finally, its impact strength, compressive strength, compressive modulus, water absorption, fluidity, and bonding strength can all be strongly impacted by nozzle temperature. This study emphasizes selecting and analyzing the printing parameters thoroughly.

2.4. Design of Experiments (DOE)

The Taguchi design yields reliable and solid results, reduces the time and cost associated with conducting trials, and provides valuable information about the factors that most strongly influence the response variable. The parameters with their level are shown in Table 2. In this paper, the influence of specific components and levels was examined by statistical analysis.

2.5. Manufacturing and Testing of Specimen

The CAD model was loaded into the G-code creation program Ultimaker Cura. The banana fibers/PLA based biocomposite specimens were produced with a Creality CR 10 Max 3D Printer, an FDM-based 3D printer. Table 3's parameters were set; recommendations were followed to modify the other variables for every experiment run.

Impact testing was conducted in compliance with ASTM D256 requirements using the Izod impact testing machine. For impact testing, strip-shaped specimens measuring 64 mm in length, 3.2 mm in thickness, and 13 mm in width were employed (see Figure 2).

To reduce the width to 10.16 mm and 45° angles, a v notch is produced along its length using a motorized notch cutter. The impact strength of the banana fibers/PLA biocomposite was assessed. Banana Fibers/PLA composite test specimens and impact test are displayed in Figure 5.

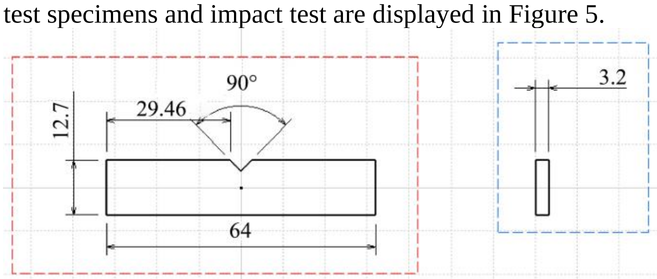

Fig. 2 Impact test specimen dimensions in mm.

The ASTM D695 guidelines were followed for conducting the compression testing. A 10 KN load cell was included with the Universal Testing Machine (UTM), and a 1.3 mm/min rate of loading was used to test specimens measuring a length of 12.7 mm, height of 25.4 mm, and width of 12.7 mm. (see Figure 3).

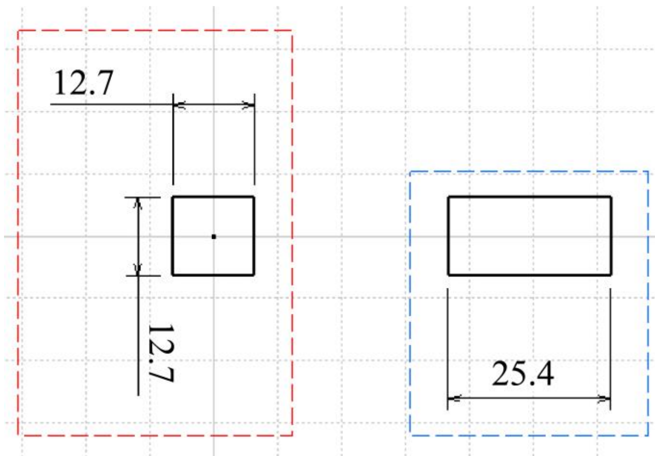

Fig. 3 Compression test specimen dimensions in mm.

As required by ASTM D570, the specimens were prepared for water absorption test with 50.8 mm diameter and 3.2 mm thick specimen (see Figure 4).

In order to determine the proportion of water absorbed, the specimens were dipped in distilled water, and measurements were made every 24 hours.

Fig. 4 Water absorption test specimen

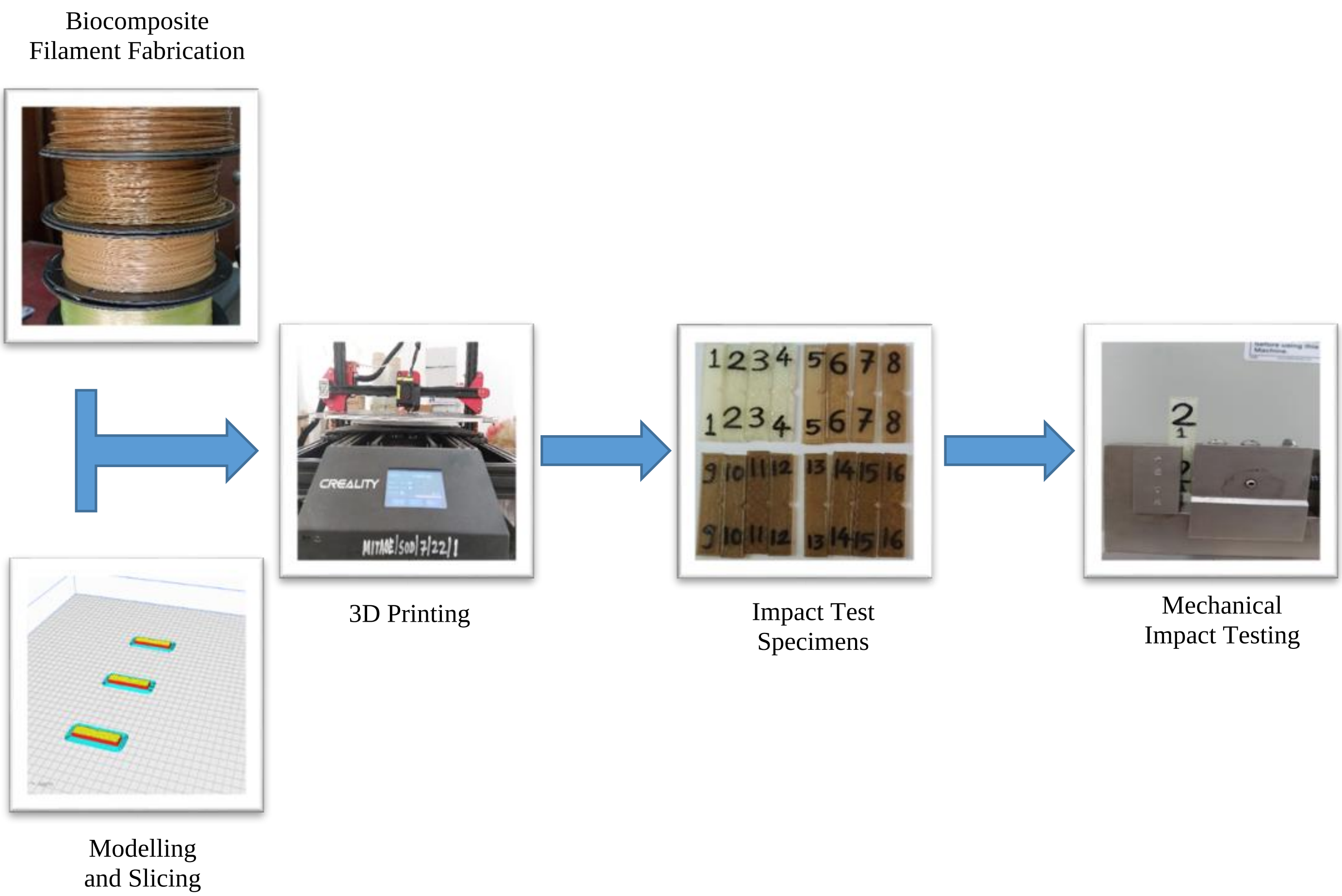

Fig. 5 The process from printing to mechanical impact testing of specimen

Table 3. Design of experiment taguchi L16 orthogonal array with Izod impact and compression test results

Experiment Number	% weight of Banana fibers	Nozzle size in mm	Infill pattern	Layer thickness in mm	Nozzle temperature in °C	Impact Strength in J/m	Compressive Strength In Mpa	Compressive Modulus In Mpa
1	0	0.4	Grid	0.1	190	24+-11	32+-9	1195+-349
2	0	0.6	Gyroid	0.2	195	35+-11	29+-4	1092+-147
3	0	0.8	Cubic	0.3	200	24+-8	26+-5	964+-183
4	0	1.0	Zig-zag	0.4	205	24+-11	33+-7	1225+-250
5	1	0.4	Gyroid	0.3	205	38+-12	35+-8	1290+-281
6	1	0.6	Grid	0.4	200	33+-10	25+-9	928+-355
7	1	0.8	Zig-zag	0.1	195	31+-7	38+-10	1409+-381
8	1	1.0	Cubic	0.2	190	35+-13	22+-10	804+-363
9	3	0.4	Cubic	0.4	195	29+-12	44+-9	1653+-334
10	3	0.6	Zig-zag	0.3	190	41+-14	26+-7	981+-255
11	3	0.8	Grid	0.2	205	25+-11	41+-11	1528+-421
12	3	1.0	Gyroid	0.1	200	31+-14	25+-11	923+-398
13	5	0.4	Zig-zag	0.2	200	28+-14	17+-11	648+-411
14	5	0.6	Cubic	0.1	205	35+-12	27+-7	1010+-257
15	5	0.8	Gyroid	0.4	190	36+-16	26+-19	963+-720
16	5	1.0	Grid	0.3	195	28+-20	37+-26	1373+-983

3. Result and Discussion

3.1. Effect on Impact Properties

Three specimens were manufactured by an FDM-based 3D printer, and each experiment was mechanically tested. The mean readings for each specimen across all tests run are displayed in Table 3. The maximum impact strength was found to be 41 J/m with 3 % banana fibers loading in biocomposite,0.6 mm nozzle size, zig-zag infill pattern, 0.3 mm layer thickness, and 190°C nozzle temperature (see Figure 6).

The dispersion of the nanoparticles, the aspect ratio of the particles, and the bond among the reinforcement and matrix may all have a significant impact on the impact behavior. Additionally, the spreading and interaction of the banana fibers with the PLA may have improved the biocomposite's impact capabilities. It is evident from the impact data that the addition of banana fibers significantly improves the impact qualities. Table 3 shows that there is an improvement in the impact strength of 3D-printed banana fibers/PLA Biocomposite compared to neat PLA. The composite absorbs more energy during fracture as a result of the reinforcement's addition, which also strengthens the contact between the reinforcement and matrix.

The second highest values are found for experiment number 5, where impact strength is 38 J/m with 1 % banana fibers loading in biocomposite,0.4 mm nozzle size, Gyroid infill pattern, layer thickness 0.3 mm, and 205°C nozzle temperature. To gain an exceptional understanding of the impact of process factors upon impact strength, main effect plots were developed (see Figure 7). Experiment number 1 and 3 showed least values of impact strength (24 J/m). All listed printing process factors were discovered to have a significant effect on the impact strength of the printed specimens by looking at the analysis of variance (ANOVA) (refer to Table 4); however, the composition of banana fiber was found to be second dominant with a 27.31 % contribution, first being nozzle size with a 30.44 % contribution. The optimized parameters displaced by the main effect plot include a 0.6 mm nozzle size, a Gyroid infill pattern, 0.3 mm layer thickness, and 190°C for 1 % Banana Fibers. Density and tensile strength are improved with larger nozzle sizes. The printed object's overall strength is increased as a result. Interlayer adhesion is provided by thicker layers, which enhances the printed object's strength and integrity [18]. Accordingly, the biocomposite material showed an increment in impact strength. An increase in impact strength is correlated with an increase in banana fibers, according to numerous studies [20-22].

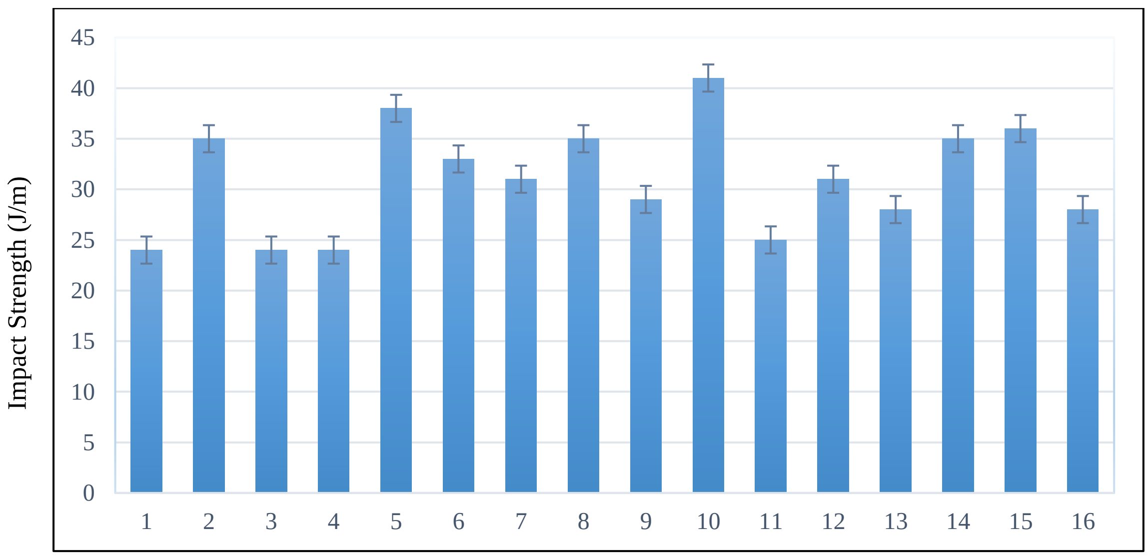

Fig. 6 Plot of experimental impact strength values of 16 experiments.

Table 4. ANOVA for impact strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	117.688	117.688	39.2292	*	*	27.31%
Nozzle Size	3	131.187	131.187	43.7292	*	*	30.44%
Infill Pattern	3	113.188	113.188	37.7292	*	*	26.27%
Layer Thickness	3	15.687	15.687	5.2292	*	*	3.64%
Nozzle Temperature	3	53.188	53.188	17.7292	*	*	12.34%
Residual Error	0	*	*	*			
Total	15	430.938					100.00%

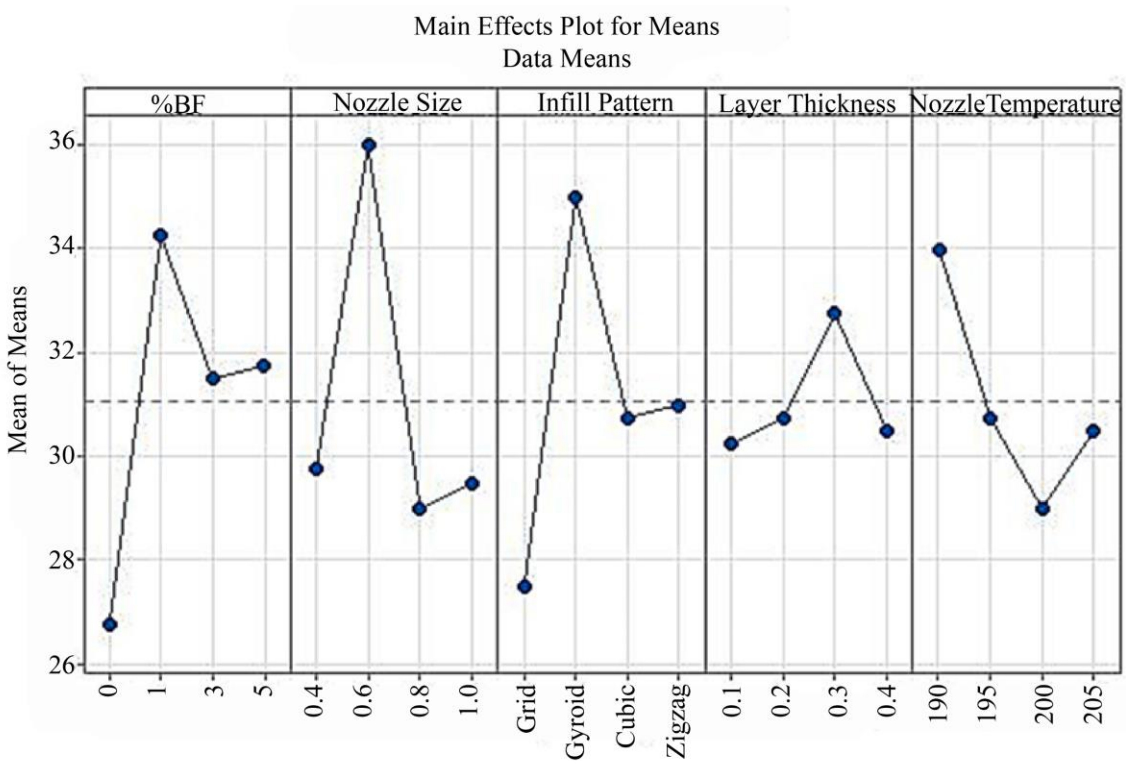

Fig. 7 Main effects plot for impact strength

Fig. 8 3D printed specimen and compression test

3.2. Effect on Compression Properties

Table 3 summarizes the experimental findings for the PLA specimens that were 3D-printed using the Taguchi experimental design. Table 3 shows that the printed specimens had compressive strengths between 17 MPa and 44 MPa and a compressive modulus between 648 MPa and 1653 MPa. Maximum values of Compressive Strength (44 MPa) and Compressive Modulus (1653 MPa) are found with 0.4 mm nozzle size, a cubic pattern, 0.4 mm layer thickness, and nozzle temperature of 195°C with 3 % Banana fibers.

The superior interfacial connection between the fibers and matrix and the evenly distributed fibers could be the cause of this. Experiment number 13 (see Table 3) showed the least Compressive strength (17 MPa) value and Compressive Modulus (648 MPa) value with 0.4 mm nozzle size, zig-zag infill pattern, 0.2 mm layer thickness, and 200°C nozzle temperature with 5 % banana fibers.

Figures 9 and 10 revealed that the Compressive strength and Compressive Modulus of the BF/PLA composites increase with the increase of fibers content by 3%. Then, it decreases for 5% fibers content composites. The experimental investigation proved that the filaments manufactured from Banana Fibers and Polylactic Acid Biocomposites can be used for fused deposition modeling applications.

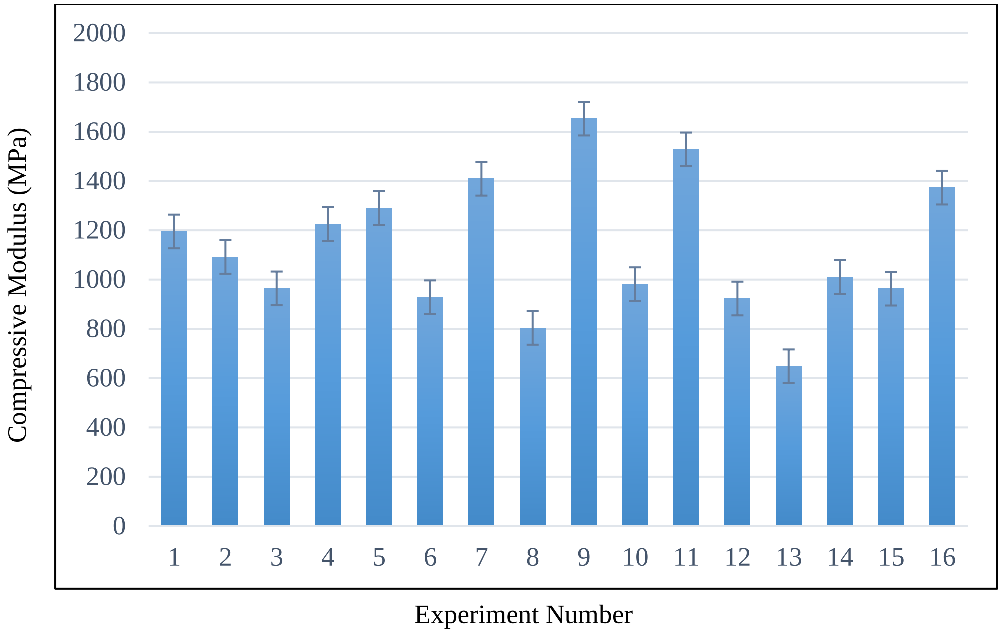

Fig. 9 Plot of experimental compressive strength values of 16 experiments.

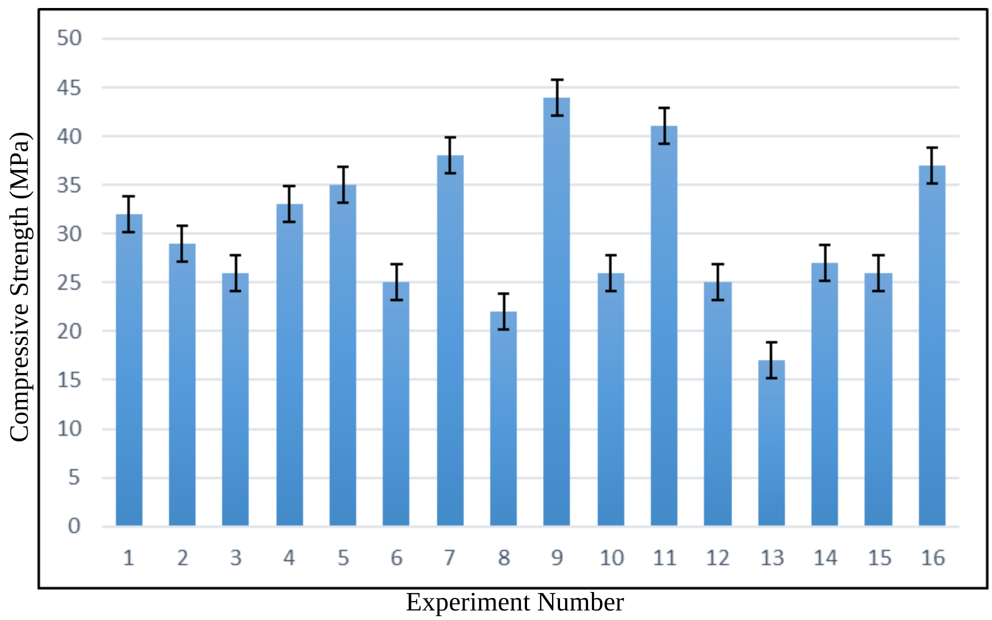

Fig. 10 Plot of experimental compressive strength values of 16 experiments.

Table 5. ANOVA for compressive strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	105.687	105.687	35.229	*	*	13.07%
Nozzle Size	3	90.188	90.188	30.063	*	*	11.16%
Infill Pattern	3	71.187	71.187	23.729	*	*	8.81%
Layer Thickness	3	50.687	50.688	16.896	*	*	6.27%
Nozzle Temperature	3	490.687	490.687	163.562	*	*	60.70%
Residual Error	0	*	*	*			
Total	15	808.437					100.00%

Table 6. ANOVA for compressive modulus

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
%BF	3	9.1288	9.1288	3.0429	*	*	12.98%
Nozzle Size	3	5.4599	5.4599	1.82	*	*	7.76%
Infill Pattern	3	6.5765	6.5765	2.1922	*	*	9.35%
Layer Thickness	3	6.7432	6.7432	2.2477	*	*	9.59%
Nozzle Temperature	3	42.4201	42.4201	14.14	*	*	60.32%
Residual Error	0	*	*	*			
Total	15	70.3286					100.00%

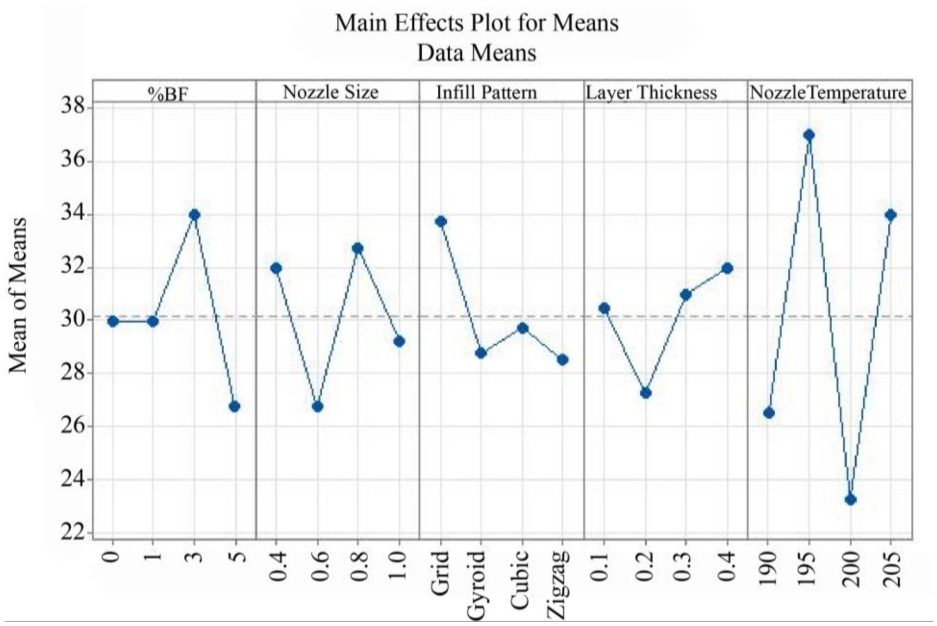

Fig. 11 Main effects plot for compressive strength

To find the ideal configuration of process variables, Taguchi optimization with the analysis of variance method is employed. The compressive strength and modulus ANOVA results are shown in Tables 5 & 6. According to this analysis, the nozzle temperature had the biggest effect on compressive strength, explaining 60.70% of the variance. Conversely, features such as nozzle size, infill pattern, and layer thickness had the least impact on compressive strength. The study recommends that the FDM process settings be set at a layer height of 0.4 mm, nozzle size of 0.8 mm, grid infill pattern, and nozzle temperature of 195°C so that it optimizes the mechanical qualities of three-dimensional printed items. The main effects plot for compressive strength is shown in Figure 11.

3.3. Effect on Water Absorption Properties

The percentage of water absorption in PLA and banana fiber biocomposites is displayed in Figure 12. In composites, water can mostly be found in three places: the lumen, the cell wall, and, in the event of weak interface adhesion, the space between the fibers and resin. The proportion of water absorption is greater in composites containing more bananas. Whilst the addition of banana fibers leads to enhancement in the biodegradability of the BF/PLA composites when exposed to water.

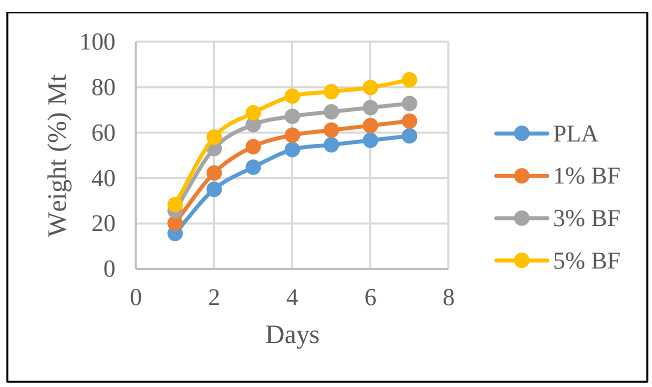

Fig. 12 Water absorption curves of PLA and BF/PLA biocomposite

4. Conclusion

With successful extrusion, a banana fibers/PLA Biocomposite 3D printing filament can now be utilized for Fused Deposition Modeling (FDM). When banana fibers were added, the impact strength increased. This suggests that using the 3D-printed banana fibers/PLA Biocomposite can be very advantageous for various applications needing a larger impact. The mechanical properties of Biocomposite are greatly influenced by parameters such as nozzle temperature, infill pattern, nozzle size, and layer thickness. Impact strength with a composition of 3% banana fibers had the greatest rating. The items with the highest impact strength ratings were those printed with 0.3 mm layer thickness, nozzle size 0.6 mm, 190°C, zig-zag infill pattern, and 3% banana fibers composition. The lowest value for impact strength is achieved with pure PLA, 0.4 mm nozzle size, grid infill pattern, 0.1 mm layer thickness, and 190°C nozzle temperature.

The development of banana fibers-reinforced FDM printed goods could lead to new opportunities for high-performing, environmentally responsible engineering applications. According to the experimental study's findings, 3% banana fibers composition can be added to PLA Biocomposite material to create a composite material that can withstand higher impact loads than conventional fibers reinforced polymer composites.

The experimental work sought to identify the optimal input factor combination to enhance the mechanical qualities of FDM-printed Banana Fibers/PLA Biocomposite specimens by examining their compressive properties. Printed Biocomposite specimens were inspected using the ASTM compressive test protocol. The Taguchi methodology was employed for optimization, and tests were planned to test the Taguchi method of the L16 orthogonal array for five parameters, each with four levels.

ANOVA analysis revealed that various process factors, including the nozzle size, infill pattern, layer thickness, and nozzle temperature, were taken into account throughout the investigation. Biocomposite with 3 % Banana Fibers exhibits the highest compressive strength and modulus. Experimental analysis showed that as weight % increases from 3 to 5%, corresponding compressive strength and modulus decreases. Excellent availability, reduced cost, and superior mechanical qualities of banana fibers-reinforced banana fibers composites allow for the production of lightweight materials with domestic and automotive applications.

The current study examined the effects of banana fiber hybridization on the characteristics of water absorption. The water absorption test, which lasted seven days, indicates that 5% of the banana fiber/PLA composite could absorb the most water.

The study recommends that the FDM process settings be set at 0.4 mm layer thickness, nozzle size of 0.8 mm, grid infill pattern, and nozzle temperature of 195°C so that it optimizes the mechanical qualities of three-dimensional printed items. The experimental investigation proved that the filaments manufactured from Banana Fibers and Polylactic Acid Biocomposite can be used for Fused Deposition Modeling applications. Finally, using banana fibers significantly increases the mechanical performance and sustainability of FDM manufactured items. Additional investigation is necessary to maximize the printing circumstances and amount of banana fibers in order to acquire the desired attributes.

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