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Modeling and Analysis of Process Parameters Affecting Flexural Behavior of FDM-Printed Wood/PLA Composites

Jahid Hasan Ashik and Mst. Nazma Sultana
Department of Industrial Engineering and Management
Khulna University of Engineering & Technology
Khulna-9203, Bangladesh
jhashik@iem.kuet.ac.bd, n.sultana@iem.kuet.ac.bd

Abstract

Fused deposition modeling (FDM) has gained popularity as one of the polymer additive manufacturing techniques. This is due to the minimization of material waste, cost effectiveness, simplicity, and rapid fabrication of complex objects in diverse fields. In recent years, wood/PLA has been widely used as filament for fabricating FDM 3D printed parts for its certain features, e.g., biodegradability, low density, and improved environmental compatibility. However, the influence of various process parameters on the mechanical properties of the printed polymer composite parts needs to be clearly understood so that the fabricated parts can be reliably used. In this study, the influences of four process parameters, i.e., nozzle temperature (NT), raster angle (RA), infill density (ID), and layer thickness (LT), on flexural properties of the 3D printed parts were evaluated. A response surface methodology (RSM) with central composite design (CCD) was used to conduct experimental analysis. Three-point bending tests were performed to obtain values of flexural strength and flexural modulus. ANOVA was used to determine the statistical significance of process parameters and validate the regression models, which is standard practice in RSM-based experimental studies. Statistical analysis showed that ID was the main factor that affected flexural strength, while LT was the main factor that affected flexural modulus. The obtained models for both responses were statistically significant with R^2 values of 98.68% for flexural strength and 90.64% for flexural modulus. Contour plots also demonstrated that higher flexural properties came from a high infill density, a low layer thickness, and a raster orientation that was near 45°. The study provides a comprehensive multi-parameter analysis, offering practical guidelines for optimizing FDM process settings for biodegradable composites.

Keywords
Additive manufacturing, Fused deposition modeling (FDM), Wood/PLA, Flexural properties.

1. Introduction
In the last few decades, additive manufacturing (AM), which is more often known as 3D printing, has become an inexpensive and flexible means to swiftly manufacture prototypes. AM builds three-dimensional objects by putting down layers of material one at a time. This cuts down on waste and gets the shapes very precise, which is not the case with standard subtractive manufacturing methods (Yang & Yeh, 2020). In the previous twenty years, 3D printing technologies and their uses have gotten a lot better as these technologies have significantly reduced cost by minimizing material waste. Moreover, this expansion has accelerated a lot in the last 10 years since AM systems can manufacture intricate structures directly from digital or virtual models. This makes them valuable in more types of businesses (Ayrilmis et al., 2021).

With FDM both regular and biodegradable thermoplastic polymers, such as polylactic acid (PLA), polypropylene (PP), and acrylonitrile butadiene styrene (ABS) can be used to construct 3D objects. People use polymer-based AM a lot in biomedical engineering, civil engineering, aerospace, and art design, among other fields (Chacón et al., 2017; Kuznetsov et al., 2018; Song et al., 2017). This is because these materials are easy to get and may be used in many different ways. PLA is one of these thermoplastics that people are extremely interested in since it breaks down organically and performs well as a material. It is a better choice for the environment than petroleum-based polymers. However, it is very challenging to utilize it in load-bearing and functional applications because it is naturally weak, brittle, and cannot handle low temperatures. A lot of research has gone into ways to make the polymer matrix stronger, stiffer, and more useful in general, such as by adding fibers to it. In this case, natural fibers have become useful reinforcements for PLA because they can be replaced, broken down by microorganisms, are light and cheap, and have very precise mechanical properties (Mukherjee & Kao, 2011; Oksman et al., 2003). Earlier research has shown that biobased composites, which are natural fiber-reinforced PLA composites, work better, have less of an impact on the environment, and can be thrown away in a more environmentally friendly way when they are no longer needed. So, manufacturing these kinds of composite filaments is becoming more frequent in production that uses FDM.

Adding wood fibers to PLA matrices has several advantages. This not only makes the composite stronger and less likely to change size, but it also makes the surface feel and look nicer. This makes it a good choice for things that need to look good and be strong at the same time. Wood-filled PLA composites are also good for the environment because they use a lot of lignocellulosic resources and minimize the cost of materials. This is why using PLA filaments with wood fibers in additive printing is now a better way to make products that work well and are good for the environment (Ayrilmis et al., 2019).

Previously, various studies were conducted to understand the influence of building parameters on the mechanical properties of 3D printed wood/PLA parts. Anerao et al. (2025) adopted the Taguchi L27 design to evaluate the influence of raster orientation, layer thickness, and infill density on tensile and flexural strength. Their study revealed that an infill density of 100% resulted in the highest tensile and flexural strength with values 42.46 MPa, and 83.43 MPa respectively. Additionally, Faidallah et al. (2024) evaluated the comprehensive and bending properties of wood/PLA parts varying several process parameters, such as layer thickness and core topologies. The results indicated that increased layer thickness resulted in enhanced bending properties. On the other hand, in the flatwise compression test, the specimen without a face layer demonstrated the highest compressive strength. Moreover, the effects of core configuration and infill speed on tensile strength were investigated by Ayrilmis et al. (2021). Among various infill patterns, the hexagonal pattern indicated the highest tensile strength. In addition to that, tensile strength sharply increased when the infill rate increased from 50% to 80%. However, there are few studies that include process parameters- raster angle (RA), infill density (ID), nozzle temperature (NT), and layer thickness (LT) altogether to evaluate their influence on the flexural properties of wood/PLA parts. The objectives of this research are as follows:

i. To evaluate the influence of key process parameters- RA, ID, NT, and LT on the flexural properties of the 3D printed wood/PLA parts
ii. To predict the flexural properties of 3D printed wood/PLA parts

This study offers a thorough comprehension of the impact of FDM process parameters on composite performance, facilitating the development of more efficient and sustainable manufacturing procedures.

2. Material and Method

2.1 Production of 3d printed wood/PLA specimen

Bambu Lab P1S Desktop printer with 0.4 mm nozzle diameter was used to fabricate the flexural test specimen. This printer also provides 256 × 256 × 256 mm^3 build space for your large projects. Commercial SUNLU Wood PLA (15% wood powder, 85% PLA) was sourced with a diameter of 1.75 ± 0.02 mm, a density of 1.10 g/cm^3, and a melting point of 164°C. The filament provides an authentic wood-like texture with a subtle woody scent during printing. To evaluate the flexural properties, the specimens were fabricated according to ASTM D790 standard (127 mm×12.7 mm×3.2 mm) having a support span of 51.2 mm (Dong et al., 2018). Initially, the part was fabricated using SolidWorks 25. Later, the STL (.stl) file was imported to Bambu Studio for slicing. After that, the G codes for the given part was generated and exported to Bambu Lab P1s desktop printer for fabrication.

2.2 Experimental Design

In this work four process parameters varying at three levels were included. Response Surface Methodology (RSM) was adopted in this study. This method is used for finding the best response by changing the input factors. The chosen methodology for this study was the Central Composite Design (CCD) method, first introduced by Box & Wilson (1951). This design was able to find the quadratic effect for the response. Also, CCD can run the design in blocks. If there are two blocks in the design, they could be called a factorial block and a center point block, or an axial point block. The use of CCD also allows for the ability to check for lack of fit. Finally, the analysis leads to the conclusion that the regression equation can be used to predict the response variable. In this study, four process parameters, along with three levels, resulted in 30 experimental runs. The process parameters along with the corresponding levels are shown in Table 1.

Table 1. Flexural test specimen fabrication parameters and coded levels

Factor	Coded Level		
	-1	0	+1
Nozzle temperature (ºC)	205	215	225
Infill density (%)	50	70	90
Raster angle (°)	0	45	90
Layer thickness (mm)	0.1	0.2	0.3

2.3 Determination of flexural properties

The flexural strength and flexural modulus were determined using a three-point bending test. Autograph AGX-V2 universal testing machine (Shimadzu, Kyoto, Japan) was used to conduct the test. The machine has a maximum load capacity of 300 kN. The crosshead speed was set to 1.4 mm/min. A preload of 1.5 N was applied so that the flexural specimen was kept in contact with the loading nose. A support span-to-depth ratio of 16:1 was maintained during testing (Zandi et al., 2020). Also, the loading nose and supports had cylindrical surfaces. For precise control, real-time data acquisition, and data export TrapeziumX software was used.

2.4 Statistical Analysis

The response surface design was analyzed using the statistical tool Minitab 22.2.0. Initially, the tool was used to obtain the design of experiment framework. Four process parameters were used as input factors, and the responses of ultimate flexural strength and flexural modulus were obtained for analysis. Analysis of variance (ANOVA) was performed to validate the model. A P-value of less than 0.05 was considered to evaluate the statistical significance of factors. A quadratic regression equation was also obtained to predict the mechanical properties of the 3D printed specimens.

3. Results and Discussion

The results in Table 2 show that the process parameters play significant roles in the printed samples' flexural properties. The flexural strength was between 26.2965 and 42.483 MPa, and the flexural modulus was between 1309.47 and 1985.24 MPa. This kind of change clearly shows that the chosen parameters have a significant effect on how well the material bends. Run 9, with NT = 205, ID = 90, RA = 0, and LT = 0.1, had the maximum flexural strength and flexural modulus with values 42.483 MPa and 1985.24 MPa, respectively. This combination yielded the highest observed values within the experimental range, indicating a strong interaction between high infill density and low layer thickness in enhancing structural integrity. In average, tests with higher ID values showed stronger and stiffer results. This trend is in line with what Karad et al. (2023) found, which was that higher infill density greatly improves both tensile and flexural properties by reducing internal voids and making load transfer better. On the other hand, increasing LT from 0.1 to 0.3 tended to lower both responses. Hu et al. (2023) also observed this behavior, where thinner layers made interlayer bonding better and made the material stiffer. Runs 7 and 6 had the lowest flexural strength and modulus, respectively, which means that bending performance was not good with those combinations of process parameters.

Table 2. Flexural properties of printed specimens with various process parameters

Run	NT	ID	RA	LT	Flexural Strength (MPa)	Flexural Modulus (MPa)
1	205	50	90	0.3	26.4538	1312.67
2	215	70	45	0.1	38.1411	1754.71
3	205	50	0	0.1	30.7926	1705.6

4	215	70	45	0.2	35.1438	1502.58
5	215	70	45	0.2	36.4728	1484.77
6	225	50	90	0.3	26.9796	1309.47
7	205	50	90	0.1	26.2965	1639.98
8	215	70	45	0.2	35.8715	1576.05
9	205	90	0	0.1	42.483	1985.24
10	215	70	45	0.2	35.8237	1495
11	215	70	0	0.2	31.3646	1491.92
12	215	70	45	0.2	35.6109	1484.97
13	205	70	45	0.2	35.5955	1517.72
14	205	90	90	0.1	40.3645	1943.3
15	225	70	45	0.2	35.85	1438.5
16	225	90	0	0.1	41.1277	1932.96
17	215	70	90	0.2	30.2745	1594.93
18	215	70	45	0.3	34.3559	1426.6
19	225	90	90	0.1	40.7315	1718.76
20	225	90	0	0.3	34.5424	1674.18
21	215	70	45	0.2	35.6387	1426.88
22	215	50	45	0.2	30.3933	1441.7
23	205	90	0	0.3	34.9371	1541.51
24	225	50	90	0.1	30.1404	1678.34
25	225	90	90	0.3	34.2649	1500.72
26	225	50	0	0.1	30.3547	1582.8
27	225	50	0	0.3	27.38	1471.92
28	205	50	0	0.3	27.6518	1346.96
29	215	90	45	0.2	41.2835	1655.54
30	205	90	90	0.3	35.1376	1542.21

The ANOVA results for flexural strength shown in Table 3 indicate that the proposed model is very significant, with an F-value of 122.08 and a p-value of 0.000. The model accounts for 98.68% of the overall variability in the response. The adjusted R^2 (97.87%) and anticipated R^2 (95.02%) show that the experimental and predicted values are in good agreement. Infill density is the most important linear term, accounting for 69.08% of the total and having a very significant influence ($p = 0.000$). Layer thickness (13.25%) and raster orientation (0.88%) come next. But the temperature of the nozzle is not statistically significant ($p = 0.572$). The quadratic terms, notably raster orientation^2, also have a big effect, which shows that the behavior is not linear. The interaction between infill density and layer thickness is the most important of the interaction terms. Also, the small lack-of-fit ($p = 0.115$) shows that the model is well enough to show the response in the chosen experimental domain. The quadratic model for flexural strength is displayed in Equation 1.

Table 3. ANOVA Table for flexural strength

Source	DF	Contribution	Adj SS	Adj MS	F-Value	P- Value
Model	11	98.68%	620.562	56.415	122.08	0.000
Linear	4	83.24%	523.459	130.865	283.20	0.000
Nozzle Temperature	1	0.02%	0.153	0.153	0.33	0.572
Infill Density	1	69.08%	434.432	434.432	940.13	0.000
Raster Orientation	1	0.88%	5.545	5.545	12.00	0.003
Layer Thickness	1	13.25%	83.329	83.329	180.33	0.000
Square	3	11.62%	73.049	24.350	52.69	0.000
Infill Density*Infill Density	1	2.95%	1.410	1.410	3.05	0.098
Raster Orientation*Raster Orientation	1	8.10%	52.830	52.830	114.33	0.000
Layer Thickness*Layer Thickness	1	0.56%	3.529	3.529	7.64	0.013
2-Way Interaction	4	3.82%	24.054	6.014	13.01	0.000
Nozzle Temperature*Infill Density	1	0.35%	2.187	2.187	4.73	0.043
Nozzle Temperature*Raster Orientation	1	0.40%	2.499	2.499	5.41	0.032
Infill Density*Layer Thickness	1	2.77%	17.443	17.443	37.75	0.000
Raster Orientation*Layer Thickness	1	0.31%	1.925	1.925	4.17	0.056
Error	18	1.32%	8.318	0.462		
Lack-of-Fit	13	1.17%	7.377	0.567	3.01	0.115
Pure Error	5	0.15%	0.941	0.188		
Total	29	100.00%				
R^2= 98.68% R^2 (Adjusted)= 97.87% R^2 (Predicted)= 95.02%						

$$\begin{aligned}\text{Flexural strength} = {} & 4.1 + 0.0991\ \text{Nozzle Temperature} + 0.501\ \text{Infill Density} \\ & - 0.0249\ \text{Raster Orientation} - 33.0\ \text{Layer Thickness} \\ & + 0.00176\ \text{Infill Density*Infill Density} \\ & - 0.002130\ \text{Raster Orientation*Raster Orientation} \\ & + 111.5\ \text{Layer Thickness*Layer Thickness} \\ & - 0.001849\ \text{Nozzle Temperature*Infill Density} \\ & + 0.000878\ \text{Nozzle Temperature*Raster Orientation} \\ & - 0.5221\ \text{Infill Density*Layer Thickness} \\ & + 0.0771\ \text{Raster Orientation*Layer Thickness}\end{aligned} \quad (1)$$

The ANOVA findings show that the regression model for flexural modulus is statistically significant, with an F-value of 37.13 and a p-value of 0.000. The model explains 90.64% of the total variability in the response, and the adjusted R^2 (88.20%) and anticipated R^2 (82.63%) show that it is useful at making predictions. Layer thickness is the most important linear factor, accounting for 51.10% of the total, and infill density is the second most important, accounting for 25.92%. Both parameters have very strong effects on flexural modulus ($p = 0.000$). On the other hand, the nozzle temperature and raster orientation are not statistically significant, with p-values of 0.374 and 0.062, respectively. The quadratic term of layer thickness is particularly important because it shows that it has a nonlinear effect on the response. The relationship between nozzle temperature and layer thickness also has a big impact on the flexural modulus. The insignificant lack-of-fit (p = 0.297) further suggests that the model we built is good enough. The quadratic model for flexural modulus is displayed in Equation 2.

Table 4. ANOVA Table for flexural modulus

Source	DF	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	6	90.64%	781074	130179	37.13	0.000
Linear	4	78.92%	680069	170017	48.49	0.000
Nozzle Temperature	1	0.33%	2876	2876	0.82	0.374
Infill Density	1	25.92%	223330	223330	63.70	0.000
Raster Orientation	1	1.57%	13487	13487	3.85	0.062
Layer Thickness	1	51.10%	440375	440375	125.61	0.000
Square	1	9.33%	80399	80399	22.93	0.000
Layer Thickness*Layer Thickness	1	9.33%	80399	80399	22.93	0.000
2-Way Interaction	1	2.39%	20607	20607	5.88	0.024
Nozzle Temperature*Layer Thickness	1	2.39%	20607	20607	5.88	0.024
Error	23	9.36%	80639	3506		
Lack-of-Fit	18	8.03%	69166	3843	1.67	0.297
Pure Error	5	1.33%	11472	2294		
Total	29	100.00%				
R^2= 90.64% R^2 (Adjusted)= 88.20% R^2 (Predicted)= 82.63%						

$$\text{Flexural modulus} = 3697 - 8.44\ \text{Nozzle Temperature} + 5.569\ \text{Infill Density} - 0.608\ \text{Raster Orientation} - 13507\ \text{Layer Thickness} + 10567\ \text{Layer Thickness*Layer Thickness} + 35.9\ \text{Nozzle Temperature*Layer Thickness} \quad (2)$$

Table 5 shows the measured and predicted values of flexural strength and flexural modulus, as well as the differences between the two sets of data. For most of the runs, the projected values are quite similar to experimental data. This indicates that the regression models that were created are good enough. The narrow, random distribution of the residuals around 0 for flexural strength shows that the model is quite good at making predictions. On the other hand, the residuals for flexural modulus are higher for some experimental runs, but the projected values are still capable of showing the overall trend of the observed data. This indicates that the model for flexural modulus has satisfactory predictive power.

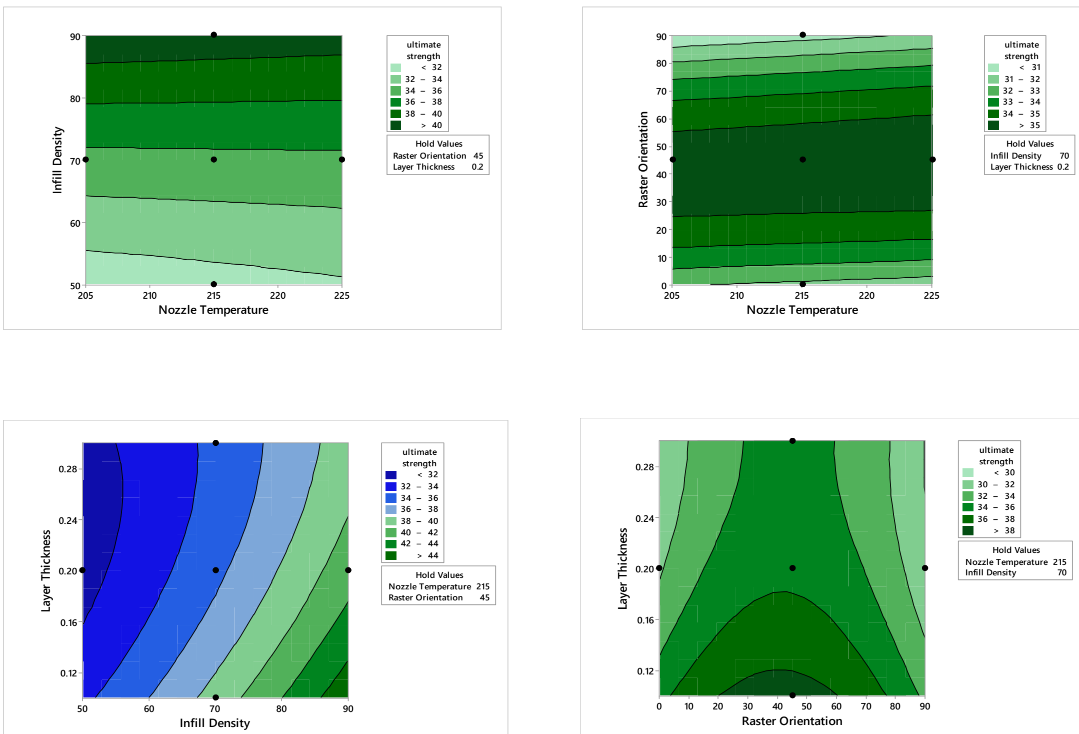
Table 5. Experimental, predicted, and residual values of flexural strength, and flexural modulus

Runs	Flexural Strength (MPa)			Flexural Modulus (MPa)		
	Observed	Predicted	Residual	Observed	Predicted	Residual
1	26.4538	25.96539	0.488407	1312.67	1296.464	16.20583
2	38.1411	38.81166	-0.67056	1754.71	1771.299	-16.5889
3	30.7926	30.08092	0.71168	1705.6	1735.813	-30.2125
4	35.1438	35.54509	-0.40129	1502.58	1509.213	-6.63333
5	36.4728	35.54509	0.927714	1484.77	1509.213	-24.4433
6	26.9796	27.67963	-0.70003	1309.47	1342.957	-33.4869
7	26.2965	27.48668	-1.19018	1639.98	1681.067	-41.0869
8	35.8715	35.54509	0.326414	1576.05	1509.213	66.83667
9	42.483	42.7341	-0.2511	1985.24	1958.588	26.65194
10	35.8237	35.54509	0.278614	1495	1509.213	-14.2133
11	31.3646	31.78614	-0.42154	1491.92	1536.586	-44.6661
12	35.6109	35.54509	0.065814	1484.97	1509.213	-24.2433
13	35.5955	35.45293	0.14257	1517.72	1521.854	-4.13444
14	40.3645	40.13985	0.224646	1943.3	1903.843	39.4575
15	35.85	35.63724	0.212758	1438.5	1496.572	-58.0722
16	41.1277	41.38848	-0.26078	1932.96	1861.531	71.42917
17	30.2745	30.67607	-0.40157	1594.93	1481.841	113.0894
18	34.3559	34.50845	-0.15255	1426.6	1458.471	-31.8711
19	40.7315	40.37516	0.356335	1718.76	1806.785	-88.0253
20	34.5424	34.30335	0.239055	1674.18	1620.478	53.70194
21	35.6387	35.54509	0.093614	1426.88	1509.213	-82.3333
22	30.3933	31.3372	-0.9439	1441.7	1397.826	43.87444
23	34.9371	35.64896	-0.71186	1541.51	1573.985	-32.4753
24	30.1404	29.20091	0.939485	1678.34	1584.01	94.33028
25	34.2649	34.67745	-0.41255	1500.72	1565.733	-65.0125
26	30.3547	30.21423	0.140468	1582.8	1638.755	-55.9553
27	27.38	27.30552	0.07448	1471.92	1397.703	74.2175
28	27.6518	27.17221	0.479591	1346.96	1351.21	-4.24972
29	41.2835	41.1627	0.120797	1655.54	1620.601	34.93889
30	35.1376	34.44214	0.695457	1542.21	1519.24	22.97028

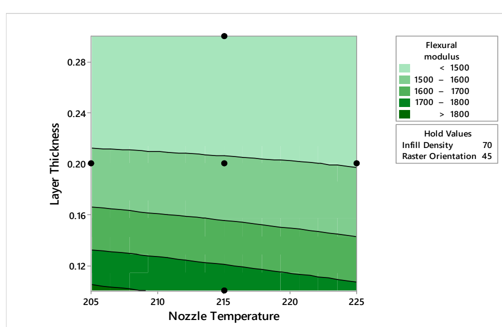
The contour plots shown in Figure 1 visualize the individual and combined effects of process parameters on the flexural properties of the 3D printed specimens. Figure 1(a) shows how the key process parameters influence the flexural strength of the parts. The plots show that infill density and layer thickness are the most important factors for flexural strength. The temperature of the nozzle only has a small effect in the range. The contour bands in the plot of nozzle temperature versus infill density are almost horizontal. This means that flexural strength changes mostly with infill density, not with nozzle temperature. The dominance of infill density can be attributed to the reduction of internal porosity, which improves stress distribution and increases resistance to bending loads.

The contour plot of nozzle temperature against raster orientation exhibits a similar tendency, with the contour lines nearly horizontal once more. This suggests that the direction of the raster angle has a bigger effect than the temperature of the nozzle. The flexural strength is highest in the middle of the raster orientation region, notably around 45°. But the strength is reduced close to 0° and 90°. The better performance near 45° raster orientation can be explained by the fact that stress is spread out more evenly in all directions, which lowers stress concentration compared to 0° or 90° orientations. This means that a balanced raster orientation can better handle bending loads**.** Strength increases significantly with higher infill density and lower layer thickness. This behavior highlights the synergistic effect of dense internal structure and improved interlayer bonding, which together enhance resistance to bending deformation. The highest values are found in areas with high infill density and low layer thickness. The lowest values are found in areas with low infill density and high layer thickness. This suggests that a denser internal structure with thinner deposited layers improves interlayer bonding and bending resistance. The raster orientation–layer thickness plot also shows that the maximum flexural strength is reached near the intermediate raster orientation of about 45° at a lower layer thickness. The curved contour pattern confirms the nonlinear effect of raster orientation, which is in line with the significant quadratic term found in the ANOVA analysis (Figure 1).

The contour plot of nozzle temperature against layer thickness for flexural modulus shows that layer thickness is the most critical parameter.The temperature of the nozzle doesn't change much. The contour lines are almost flat and quite close together in the direction of the layers' thickness. This indicates that the layer gets a lot less stiff as it gets thicker. There is only a small change along the nozzle temperature axis, which shows that temperature has a small effect on flexural modulus.



(a)



(b)

Figure 1. Contour plots for (a) Flexural strength, and (b) Flexural modulus

4. Conclusion

This study investigated the influence of crucial FDM process parameters, i.e., nozzle temperature, infill density, raster angle, and layer thickness, on the flexural properties of 3D-printed wood/PLA composites The study utilized response surface methodology with central composite design. The results confirmed that process parameters significantly affect mechanical performance, with well-fitted quadratic models demonstrating high prediction accuracy for both flexural strength and modulus.

The most important parameter that affected flexural strength was infill density, while the most important parameter that affected flexural modulus was layer thickness. A higher infill density and a lower layer thickness always led to superior flexural performance, which suggests greater internal bonding and structural integrity. The raster angle had a nonlinear influence, with the best results happening at about 45°. Nozzle temperature, on the other hand, didn't have as big of an influence in the range that was chosen. The models that were built demonstrate a great match between the experimental and projected findings. The R^2 values are high, and the lack of fit is not noteworthy. This means they are useful for making processes better. In general, the results demonstrate that using a high infill density, a low layer thickness, and a middle raster orientation can make items made of wood and PLA bend much better.

This study improves the mechanical dependability of biodegradable composite materials in additive manufacturing and provides a useful foundation for optimizing FDM process parameters in engineering settings. Future study may explore other performance indicators and multi-objective optimization to improve the applicability of wood/PLA composites.

Conflict of Interest

The authors declare no financial or personal interests that may have influenced the work presented in this study.

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Data availability statement

No data associated with the study has been deposited into a publicly available repository. The authors confirm that the data supporting the findings of this study are available within the article.

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Biographies

Jahid Hasan Ashik received BSc Engineering degree in Industrial and Production Engineering from Khulna University of Engineering & Technology. His research interests include Operations Research, System Dynamics, Human Factors, Supply Chain Management, and Operations Management. He is currently pursuing his MSc Engineering in the Department of Industrial Engineering and Management at Khulna University of Engineering & Technology, Khulna, Bangladesh. Email: jhashik@iem.kuet.ac.bd

Dr. Mst. Nazma Sultana serves as an Associate Professor in the Department of Industrial Engineering and Management at Khulna University of Engineering and Technology (KUET), Bangladesh. Her research is dedicated to advancing sustainable and high-performance manufacturing, with a particular focus on enhancing the machinability of superalloys under high-pressure cooling conditions. She actively explores the innovative use of nanofluids to improve machining efficiency and sustainability. Dr. Sultana has authored numerous publications on additive manufacturing, nanofluid-assisted machining, and eco-efficient cooling strategies in metal cutting. Her current research integrates artificial intelligence for modeling and optimization to drive the next generation of sustainable manufacturing solutions. Email: n.sultana@iem.kuet.ac.bd