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Optimization of FDM 3D Printing Parameters for Tensile Strength of PLA-CF using Taguchi Method

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Abstract: This study presents the experimental investigation and optimization of tensile strength of carbon fiber reinforced polylactic acid (CF-PLA) composites fabricated using fused deposition modeling (FDM). The influence of key process parameters, namely layer height, infill density, nozzle temperature, and print speed, was analyzed using the Taguchi L9 orthogonal array. Tensile testing was performed according to ASTM D638 standards. The experimental results showed that tensile strength varied from 23.44 MPa to 31.00 MPa. Signal-to-noise (S/N) ratio analysis indicated that infill density is the most influential parameter, followed by layer height and print speed, while nozzle temperature showed minimal effect. Analysis of variance (ANOVA) revealed that infill density contributes approximately 83.75% to tensile strength variation. The optimal parameter combination was identified as 0.1 mm layer height, 80% infill density, 220°C nozzle temperature, and 40 mm/s print speed. A regression model developed for prediction showed high accuracy with R^2 = 99.82%. The findings demonstrate the importance of parameter optimization in enhancing the mechanical performance of FDM-printed composite components.
Keywords: FDM, CF-PLA, Taguchi Method, ANOVA, Tensile Strength, Additive Manufacturing.

I. INTRODUCTION

Additive manufacturing (AM), commonly known as 3D printing, has revolutionized modern manufacturing by enabling the fabrication of complex geometries with reduced material waste and shorter production cycles. Among various AM techniques, fused deposition modeling (FDM) is widely used due to its simplicity, cost-effectiveness, and compatibility with thermoplastic materials.

Polylactic acid (PLA) is one of the most commonly used materials in FDM due to its biodegradability and ease of processing. However, pure PLA exhibits limitations such as brittleness and moderate mechanical strength. To overcome these limitations, reinforcement materials such as carbon fibers are incorporated into the PLA matrix, resulting in carbon fiber reinforced PLA (CF-PLA) composites with improved mechanical properties.

The mechanical performance of FDM-printed components is highly dependent on process parameters such as layer height, infill density, nozzle temperature, and print speed. Improper parameter selection can lead to weak interlayer bonding and reduced strength. Therefore, optimization of process parameters is essential to achieve improved mechanical performance.

This study aims to optimize the tensile strength of CF-PLA composites using the Taguchi method and ANOVA analysis to identify the most influential parameters and determine the optimal printing conditions.

II. LITERATURE REVIEW

Several researchers have investigated the effect of Fused Deposition Modeling (FDM) process parameters on the mechanical properties of PLA-based materials. It has been widely reported that parameters such as infill density, layer height, printing speed, and nozzle temperature significantly influence the strength and structural integrity of printed components. Among these, infill density and layer height are consistently identified as the most dominant factors affecting tensile strength.

To systematically analyze and optimize these parameters, statistical techniques such as the Taguchi method and Analysis of Variance (ANOVA) have been extensively employed. These methods enable efficient experimental design with a reduced number of trials while providing insights into the contribution and significance of each parameter.

In recent years, carbon fiber-reinforced PLA (CF-PLA) composites have gained attention due to their enhanced mechanical properties. Studies have shown that the addition of carbon fibers improves stiffness, tensile strength, and dimensional stability, making CF-PLA suitable for load-bearing and engineering applications. However, the presence of fibers also introduces challenges such as anisotropy and interlayer bonding variations. Despite the growing interest in CF-PLA, limited research has focused on the comprehensive optimization of multiple FDM parameters using structured experimental approaches. Most existing studies consider individual parameters or a limited combination, leaving a gap in understanding the combined effects of key process variables.

Therefore, the present study aims to address this gap by evaluating the influence of multiple FDM process parameters using a Taguchi L9 experimental design. The results are further analyzed using ANOVA to determine the significance and contribution of each parameter toward tensile strength.

III. MATERIALS AND METHODOLOGY

A. Material Selection

Carbon fiber reinforced PLA (CF-PLA) filament with 1.75 mm diameter was used. The material consists of approximately 85% PLA and 15% carbon fiber. The material was selected due to its enhanced stiffness and strength compared to conventional PLA, making it suitable for structural applications.

Table 1. Material composition of CF-PLA filament

Component	Percentage
Polylactic Acid (PLA)	85 %
Carbon Fiber	15 %

B. 3D Printer and Software

The specimens were fabricated using an FDM 3D printer (Anycubic Kobra 2 Neo) equipped with a 0.4 mm nozzle. The STL model of the tensile specimen was processed using Orca Slicer software to generate G-code for printing.

C. Experimental Design

The Taguchi L9 orthogonal array was used to design experiments with four parameters at three levels:

- Layer height (0.1, 0.2, 0.3 mm)
- Infill density (40%, 60%, 80%)
- Nozzle temperature (220°C, 230°C, 240°C)
- Print speed (40, 50, 60 mm/s)

The L9 orthogonal array reduces the number of experiments from 81 to 9 while maintaining accuracy.

Table 2: Taguchi L9 orthogonal array table

Experiment No.	Layer Height (mm)	Infill Density (%)	Nozzle Temperature (°C)	Print Speed (mm/s)
1	0.1	40	220	40
2	0.1	60	230	50
3	0.1	80	240	60
4	0.2	40	230	60
5	0.2	60	240	40
6	0.2	80	220	50
7	0.3	40	240	50
8	0.3	60	220	60
9	0.3	80	230	40

D. Specimen Preparation

All specimens were printed using a standard FDM 3D printer with a gyroid infill pattern and horizontal build orientation.

Figure 1: printed specimen according to ASTM D638 standard

E. Tensile Testing

Tensile tests were conducted using a Universal Testing Machine (UTM). The maximum stress before failure was recorded as tensile strength.

F. S/N Ratio

The larger-is-better criterion was used for S/N ratio calculation.

$$S/N = -10\log\left(\frac{1}{n}\sum\frac{1}{y^2}\right)$$

G. ANOVA

ANOVA was used to identify the percentage contribution and statistical significance of each process parameter.

IV. RESULTS AND DISCUSSION

The experimental results demonstrate a significant variation in tensile strength as a function of FDM process parameters, with measured values ranging from 23.44 MPa to 31.00 MPa. This variation highlights the sensitivity of CF-PLA mechanical performance to parameter selection. The maximum tensile strength of 31.00 MPa was obtained in Experiment 9, corresponding to a layer height of 0.3 mm, infill density of 80%, nozzle temperature of 230°C, and print speed of 40 mm/s. The enhanced strength can be primarily attributed to the higher infill density, which reduces internal voids and improves load transfer efficiency within the printed structure. Conversely, the minimum tensile strength of 23.44 MPa was observed in Experiment 4, associated with a low infill density (40%) and higher print speed (60 mm/s). These conditions likely resulted in insufficient material deposition and weaker interlayer bonding, leading to increased porosity and reduced mechanical integrity. Overall, the results confirm that infill density plays a dominant role in determining tensile strength, while layer height and print speed exhibit secondary influences.

Table 3: Experimental Results (Tensile Strength).

Experiment	Layer Height (mm)	Infill Density (%)	Nozzle Temp (°C)	Print Speed (mm/s)	Tensile Strength (MPa)
1	0.1	40	220	40	26.58
2	0.1	60	230	50	27.71
3	0.1	80	240	60	30.57
4	0.2	40	230	60	23.44

5	0.2	60	240	40	25.95
6	0.2	80	220	50	29.31
7	0.3	40	240	50	24.88
8	0.3	60	220	60	25.78
9	0.3	80	230	40	31

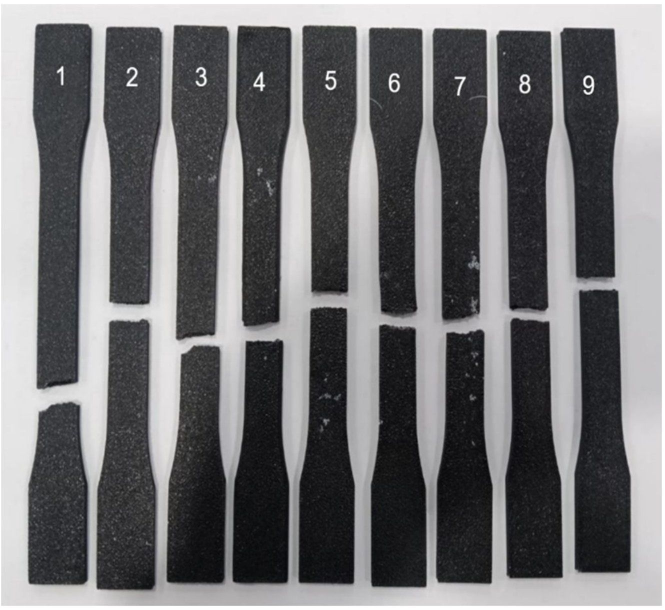

Figure 2: tensile strength tested specimen


Figure 3: UTM setup used for tensile testing

A. S/N ratio

The Taguchi method uses the signal-to-noise (S/N) ratio to determine the optimal parameter levels that maximize the response while minimizing variability. Since the objective of this study was to maximize tensile strength, the larger-is-better criterion was selected. (Larger is better)

Table 4: S/N Ratio Values

Exp. No.	Tensile Strength (MPa)	S/N Ratio (dB)
1	26.58	28.49
2	27.71	28.85
3	30.57	29.7
4	23.44	27.4
5	25.95	28.28
6	29.31	29.34
7	24.88	27.92
8	25.78	28.22
9	31	29.82

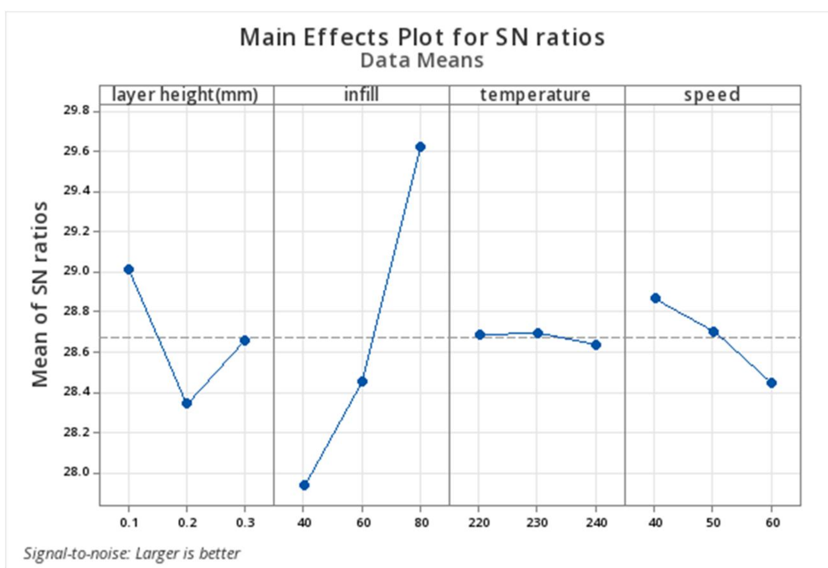

Figure 4: main effects plot for SN ratios

"The response table indicates that infill density has the highest delta value (1.69), confirming that it is the most influential factor affecting tensile strength. Layer height ranks second, followed by printing speed, while nozzle temperature has minimal influence on the response**"**

Table 5: Response Table (S/N Ratio)

Parameter	Level 1	Level 2	Level 3	Delta
Layer Height	29.02	28.34	28.66	0.68
Infill Density	27.93	28.45	29.62	1.69
Nozzle Temp	28.68	28.69	28.63	0.06
Print Speed	28.86	28.7	28.44	0.42

- Infill density is the most significant parameter
- Layer height is the second most influential
- Print speed has moderate influence
- Nozzle temperature has minimal effect

B. *Mean Response Analysis*

The mean response analysis was conducted to determine the average influence of each process parameter on the tensile strength of the printed CF-PLA specimens. The response table for means obtained from Minitab is presented in Table 6**.**

Table 6 Response Table for Means

Level	Layer Height (mm)	Infill Density (%)	Nozzle Temp (°C)	Print Speed (mm/s)
1	28.29	24.97	27.22	27.84
2	26.23	26.48	27.38	27.30
3	27.22	30.29	27.13	26.60
Delta	2.05	5.33	0.25	1.25
Rank	2	1	4	3

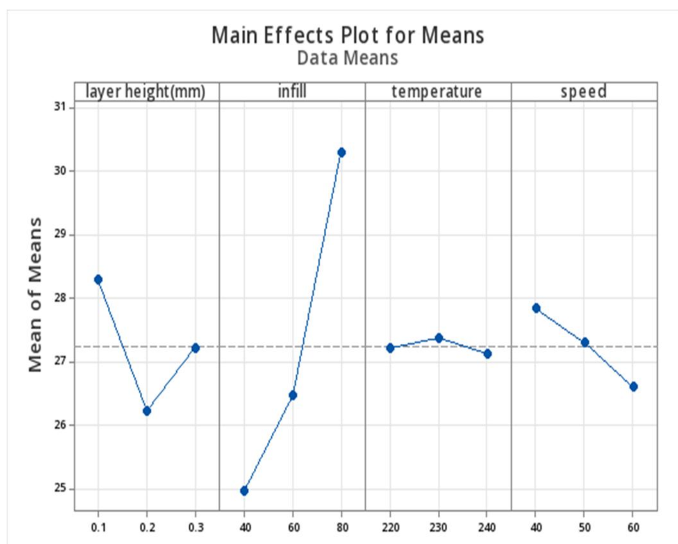

Figure 5 Main effects plot for Means Data Means

From the response table, the delta value represents the difference between the maximum and minimum mean response values for each parameter. A larger delta indicates a stronger influence on the response variable.

The results indicate that infill density has the highest delta value (5.33), suggesting that it has the most significant influence on tensile strength. Layer height shows the second highest influence, followed by print speed. Nozzle temperature shows the least effect within the selected parameter range**.**

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C. ANOVA

ANOVA was performed to determine the statistical significance of each process parameter. The results reveal that infill density is the most statistically significant factor, with the highest F-value (469.91) and the lowest P-value (0.002). Layer height and print speed are also statistically significant since their P-values are less than 0.05.

Table 7: ANOVA result

Parameter	DF	SS	MS	F-Value	P-Value
layer	2	6.3275	3.1637	65.77	0.015
infill	2	45.2051	22.6025	469.91	0.002
speed	2	2.3441	1.1720	24.37	0.039
Error	2	0.0962	0.0481		
Total	8	53.9728			

The ANOVA results indicate that infill density is the most statistically significant parameter influencing tensile strength, with a contribution of 83.75% and a high F-value of 469.91. This dominance can be attributed to the increased material continuity and reduced void content at higher infill levels, which enhance stress distribution and load-bearing capacity. Layer height contributes 11.72% to the variation, suggesting its influence on interlayer bonding and structural uniformity. Print speed, with a contribution of 4.34%, affects the deposition rate and bonding time between layers, while nozzle temperature exhibits a negligible effect within the selected parameter range. The low error percentage (0.18%) confirms the reliability and adequacy of the experimental design.

Table 8: process parameter contribution percentage

Parameter	Sum of Squares	Contribution (%)
Infill Density	45.2051	83.75%
Layer Height	6.3275	11.72%
Print Speed	2.3441	4.34%
Error	0.0962	0.18%
Total	53.9728	100%

The percentage contribution analysis shows that:

- Infill Density: 83.75%
- Layer Height: 11.72%
- Print Speed: 4.34%
- Error: 0.18%

The very low error percentage confirms the reliability and accuracy of the experimental design.

D. Regression Analysis

Regression analysis was performed to develop a mathematical model for predicting tensile strength based on the selected process parameters.

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Table 9: Model Summary

Statistic	Value
R^2	99.82 %
Adjusted R^2	99.29 %
Predicted R^2	96.39 %

A linear regression model was developed to predict tensile strength based on the selected process parameters using coded variables. The model demonstrates excellent predictive capability, as evidenced by a high coefficient of determination (R^2 = 99.82%), indicating a strong correlation between experimental and predicted values. The regression coefficients reveal that infill density has the most significant positive influence on tensile strength, while variations in layer height and print speed also contribute to the response. The model can be effectively utilized for predicting tensile strength within the specified parameter range and for guiding process optimization in FDM applications.

E. Regression Coefficients

The statistical significance of each parameter was evaluated using P-values. Parameters with P-values less than 0.05 are considered statistically significant. Infill density (P = 0.002) is highly significant, while layer height and print speed ($P < 0.05$) also significantly influence tensile strength.

Table 10: regression co-efficients

Parameter	Coefficient	P-Value
Layer Height	Significant	<0.05
Infill Density	Highly Significant	<0.01
Print Speed	Significant	<0.05

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	27.2467	0.0731	372.70	0.000	
layer					
0.1	1.040	0.103	10.06	0.010	1.33
0.2	-1.013	0.103	-9.80	0.010	1.33
infill					
40	-2.280	0.103	-22.05	0.002	1.33
60	-0.767	0.103	-7.42	0.018	1.33
speed					
40	0.597	0.103	5.77	0.029	1.33
50	0.053	0.103	0.52	0.657	1.33

F. Regression Equation

The regression equation is expressed using coded (dummy) variables, where each parameter level is represented as a binary variable. This approach allows the effect of individual parameter levels to be quantified relative to a reference level.

Regression Equation

uts	=	27.2467 + 1.040 layer_0.1 - 1.013 layer_0.2 - 0.027 layer_0.3 - 2.280 infill_40 - 0.767 infill_60 + 3.047 infill_80 + 0.597 speed_40 + 0.053 speed_50 - 0.650 speed_60

The regression model is expressed using coded (dummy) variables, where each term represents a specific level of the corresponding process parameter. A value of 1 indicates the presence of that level, while 0 indicates its absence. The coefficients represent the contribution of each parameter level to tensile strength.

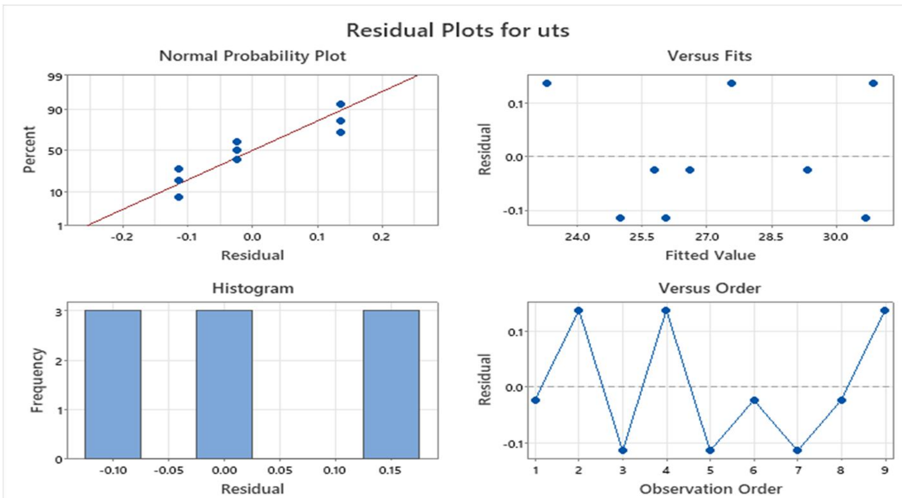

Figure 5: residual plots

G. Young's Modulus Analysis

Young's modulus, representing the stiffness of the material, was determined from the slope of the linear elastic region of the stress–strain curves. The measured values ranged from 1959 MPa to 3128 MPa, indicating a strong dependence on process parameters. The highest modulus was observed at 80% infill density, which can be attributed to improved internal material continuity and enhanced stress transfer mechanisms. In contrast, lower infill densities resulted in increased internal voids and reduced stiffness. These findings further reinforce the critical role of infill density in governing both strength and stiffness characteristics of CF-PLA composites.

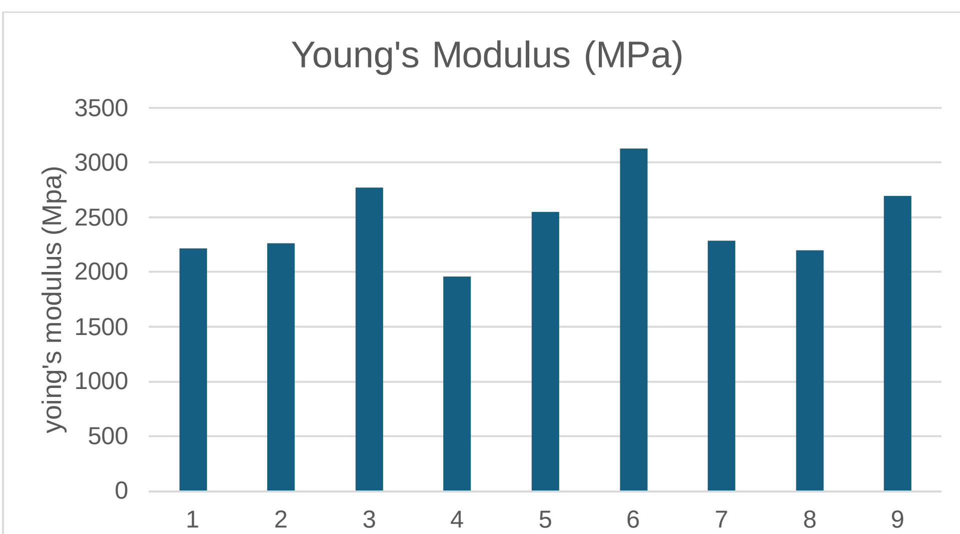

Figure 6: Variation of Young's modulus for different experimental runs

H. Stress–Strain Behaviour

The stress–strain response of CF-PLA specimens exhibited typical polymer composite behavior, characterized by an initial linear elastic region followed by nonlinear deformation and eventual fracture. The slope of the elastic region corresponds to Young's modulus, while the peak stress represents the ultimate tensile strength. Specimens fabricated with higher infill density demonstrated steeper slopes and higher peak stresses, indicating improved stiffness and strength, whereas lower infill densities resulted in reduced strength but relatively higher strain at break, suggesting enhanced ductility. Variations in the stress–strain curves are attributed to differences in interlayer bonding, internal porosity, and material distribution governed by FDM parameters. These results highlight the inherent trade-off between strength and ductility and emphasize the importance of optimizing process parameters, particularly infill density and layer height, to achieve desired mechanical performance.

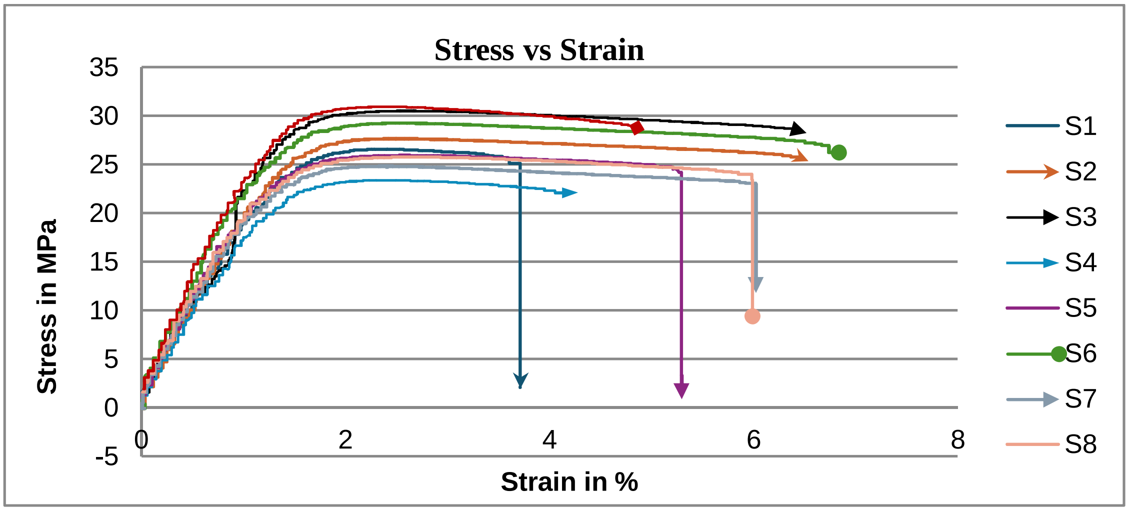

Figure 7: Stress–strain curve obtained from tensile testing of CF-PLA Specimen

V. CONCLUSION

This study presented a systematic investigation into the effects of key fused deposition modeling (FDM) process parameters—layer height, infill density, nozzle temperature, and print speed—on the tensile performance of carbon fiber reinforced polylactic acid (CF-PLA) composites. A Taguchi L9 orthogonal array was employed to design the experiments, and statistical tools including signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) were used to quantify the influence of each parameter.

The experimental results demonstrated that tensile strength varied significantly with process parameters, ranging from 23.44 MPa to 31.00 MPa. Among the factors considered, infill density was identified as the dominant parameter, contributing approximately 83.75% to the overall variation in tensile strength. Layer height and print speed exhibited moderate influence, whereas nozzle temperature showed comparatively limited impact within the selected parameter range. The optimal parameter combination for maximizing tensile strength was determined to be 0.1 mm layer height, 80% infill density, 220°C nozzle temperature, and 40 mm/s print speed.

Furthermore, the developed regression model exhibited strong predictive capability, with a coefficient of determination (R^2) of 99.82%, indicating excellent agreement between experimental and predicted values. The analysis also revealed that higher infill densities enhance stiffness and tensile strength, while lower infill densities improve ductility, highlighting an inherent trade-off between strength and elongation characteristics. In conclusion, the findings confirm that precise optimization of FDM process parameters plays a critical role in enhancing the mechanical performance of CF-PLA components. This study provides a reliable framework for parameter selection and process optimization, contributing to the development of high-performance, lightweight additively manufactured parts for engineering applications such as automotive and aerospace sectors.

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