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Optimizing 3D printing parameters for PLA and PETG: advancing high-quality skull implant production

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HIGHLIGHTS

- 3D printing parameters for PLA and PETG were optimized using Box-Behnken design and ANOVA.
- Optimal settings were PLA: grit pattern, 80% infill, 0.15 mm layer; PETG: tri-hexagonal, 80% infill, 0.3 mm.
- PLA was highly sensitive to the infill pattern (p = 0.003) regarding ductility.
- A functional skull implant was successfully printed using the optimized PETG parameters.

Keywords:
Skull implant
Mechanical properties
Analysis of variance (ANOVA)
PETG
PLA
Optimization

ABSTRACT

This study investigates the mechanical performance of 3D-printed polylactic acid and polyethylene terephthalate glycol materials by examining the effects of three crucial printing parameters (layer thickness, infill density, and infill pattern). Each material was tested mechanically for impact toughness, flexural strength, ductility, and ultimate tensile strength (UTS) using a Box-Behnken Design (BBD) to create 15 samples. The statistical significance of each parameter's impact was evaluated using ANOVA. The findings showed that, for PLA, layer thickness had no discernible impact on impact toughness ($p = 0.726$), while infill density ($p = 0.031$) and infill pattern ($p = 0.049$) had the most significant effects. In PETG, layer thickness ($p = 0.038$) and infill pattern ($p = 0.021$) significantly impacted impact toughness. None of the parameters had a statistically significant impact on the flexural strength of either material.PETG was highly responsive to the same factor ($p = 0.022$), and PLA was highly sensitive to the infill pattern ($p = 0.003$) regarding ductility. Both materials' UTS were significantly impacted by infill density, and PETG showed a high sensitivity to the infill pattern ($p = 0.004$). The ideal parameters for polyethylene terephthalate glycol (PETG) were a tri-hexagonal pattern, a 0.3 mm layer thickness, and an 80% infill density; for polylactic acid (PLA), they were a 0.15 mm layer thickness, an 80% infill density, and a grid infill pattern. These optimized settings were successfully used to create a PETG-based skull implant and functional test prints, demonstrating the applicability of the optimization strategy in practical situations.

1. Introduction

Printing standards hinder the use of PLA and PETG in medical implants, despite their promising properties, and are not permitted. Furthermore, the effects of overlapping printing standards on bio- and mechanical harvesting have not been studied interactively. Both materials (PLA and PETG) have biomedical potential, despite their varying mechanical properties according to destructive and non-destructive testing. However, the lack of details such as testing conditions and sample size undermines reliability [1]. PLA+ showed a deviation of ±0.18 mm compared to Acrylonitrile Butadiene Styrene (ABS), but the absence of statistical analysis reduces the accuracy of the conclusions [2]. Software such as Cranial Rebuild has been used to develop low-cost cranial implants, but the need for manual processing limits the efficiency of automation [3]. PETG outperforms PLA in appearance, but the lack of print quality details limits the generalizability of the results [4]. The response of these polymers to changing temperatures and strain rates remains unclear, and the effects of print orientation and structural complexity have not been analyzed [5]. The study focused on different print orientations to evaluate mechanical properties, but the small sample size reduces statistical power. Tensile tests revealed differences in tensile strength, Young's modulus, and ultimate stress depending on the material and print orientation, indicating the need to improve printing parameters for biomedical applications [6]. Research aims to enhance implant design by utilizing biocompatible materials, including PETG and TPU. Hybrid implants have shown

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promising stability and cytocompatibility for medical use [7]. A Prusa MK3 printer was used to print PLA and PETG implants with a thickness of 0.15 mm and a density of 100%. CEAST 9050 motion tests showed that PETG outperformed PLA in terms of drift, while PLA exhibited higher strength [8]. 3D printing contributes to the fabrication of customized implants with high accuracy and aesthetic appeal; however, the fact that some studies are limited to polymethyl methacrylate (PMMA) reduces generalizability, in addition to the lack of cost analysis [9,10]. PETG's properties, including printability, mechanical strength, chemical resistance, and cytocompatibility, make it a preferred material for medical implants, such as cranial implants [7,11]. However, some studies have focused solely on improving flexural strength using the Taguchi method, suggesting the need for broader analysis and testing methods [11].

PLA is a practical alternative due to its low cost and ease of printing; however, it has lower mechanical performance than PETG [4,12]. To improve precision and mechanical performance, the ideal parameters for PETG printing are a temperature of 230–265 °C, a speed of 20–50 mm/s, and a layer height of 0.1–0.4 mm. However, a single-operator setup and limited material range reduce the generalizability of these parameters [13]. PETG is considered a safe option for medical applications because it produces fewer particles during processes such as etching compared to resin-based materials [14]. Engineers require analytical tools like ANSYS to reduce the time and energy required to analyze manufacturing processes [15]. For PLA, the study showed that the best strength was achieved at 80% fill, a mesh pattern, and a thickness of 0.3 mm, with accurate predictions of tensile (44.03 MPa) and compressive (45.23 MPa) strengths, but the small sample size reduces the generalizability of the results [16]. In PETG, aggregate patterns influence bond strength, with quantitative aggregates used to mitigate surface roughness; however, the absence of an analysis of variance (ANOVA) limits the validity of the results [17]. Additive manufacturing using PLA and PETG enables the production of mechanically stable implants; however, the introduction of drug loading significantly reduces flexural and compressive strength, thereby impairing structural performance [18]. The study showed that increasing the filler density enhanced the tensile strength and elastic modulus of PLA samples, with the linear pattern at 75% fill achieving the highest values (42.67, 1222.78 MPa) [19]. High density contributes to improved tensile strength and flexural resistance, but excessive density can make parts brittle, while too low a density reduces strength [20]. The study identified key parameters for enhancing tensile and flexural strength using techniques such as Taguchi, ANOVA, and design of experiments (DOE). Still, its focus on PLA and three parameters reduces the generalizability of the results [21–24]. FDM printing faces problems such as poor layer adhesion and layer separation, which limit its industrial applications [25]. The lack of details on statistical procedures and filament type also reduces reproducibility, while the desirability method lacks sufficient clarity [26]. Some studies rely on simplified models without validation under dynamic or biological conditions, and ignore long-term biocompatibility and in vivo performance [27,28]. Studies have focused on the mechanical improvement of PLA using 3D printing for medical applications, relying on thermal and mechanical testing; however, they have not comprehensively investigated the actual durability and performance, nor have they studied the biocompatibility and environmental impact [29,30]. The study focuses on mechanical testing and finite element analysis (FEA), without assessing biocompatibility or long-term behavior, thereby ignoring PLA degradation issues and biological factors such as fatigue, shock, and corrosion, which limit its clinical validity [31]. The study lacks experimental validation to support the simulation results. Limited material combinations were tested, potentially overlooking better-performing alternatives. The long-term biological response and degradation of the materials were not evaluated [32].

It addresses the gaps in controlled material comparison and statistical optimization for practical medical applications. Earlier research does not provide a detailed comparison of PLA and PETG materials, supported by statistics, that use identical experimental conditions and demonstrate effectiveness in medical implants. By employing Box-Behnken Design and ANOVA, this research aims to optimize the 3D printing parameters (layer thickness, infill density, and infill pattern) for PLA and PETG materials. This study uniquely integrates experimental, statistical, and practical components to offer a validated optimization of FDM parameters for two key biomaterials. This results in a real, high-quality skull implant prototype, something previous studies lack.

2. Experimental work

2.1 Filament used

The superior mechanical qualities of 1.75 mm diameter PLA and PETG filaments are utilized in 3D printing. PLA is ideal for eco-friendly applications and biocompatible medical models due to its high stiffness and biodegradability. PETG offers enhanced durability while maintaining flexibility due to its toughness and chemical resistance. Both materials guarantee high printing accuracy and dependability in working prototypes. Due to their mechanical strength and integrity, they are crucial for various applications, including consumer, medical, and engineering uses.

2.2 Selecting process parameters

The samples were made of PLA and PETG. All the experimental PLA samples were printed using the Creality K1 Max FDM 3D printer. The other modified PET samples were printed using a Sunlu S9 plus printer, which displays three FDM parameters: fill density (20, 50, and 80%), layer thickness (0.15, 0.225, and 0.3 mm), and fill pattern type (Grid, Concentric, and Tri-Hexagon).

2.3 The design of the experiment

Employed the response surface methodology (RSM) technique to create multivariate experiments. By methodically assessing the connections between independent and response variables, this approach is beneficial for process optimization. In this work, we optimize the system for three chosen parameters after performing 15 experiments using the Box-Behnken Design [33]. Minimizing the number of necessary trials while guaranteeing a balanced distribution of experimental conditions through the Box-Behnken Design. The three independent variables were carefully chosen based on their impact on the response variable. Three levels (low, medium, and high) of each parameter were examined, enabling a thorough statistical analysis of interactions and quadratic effects. A regression model was created to determine the relationship between the independent variables and the response following the completion of the experiments and the collection of response data. The desirability function approach was used to optimize the response variable to reach the highest possible goal. The 15 experiments were designed using the Box-Behnken Design, with parameter values in Table 1.

Table 1: The experimental design using the Box-Behnken design

Experiment No.	Layer thickness (mm)	Infill density(%)	Infill pattern
1	0.15	20	Concentric
2	0.3	20	Concentric
3	0.15	80	Concentric
4	0.3	80	Concentric
5	0.15	50	Grid
6	0.3	50	Grid
7	0.15	50	Tri-hexagonal
8	0.3	50	Tri-hexagonal
9	0.225	20	Grid
10	0.225	80	Grid
11	0.255	20	Tri-hexagonal
12	0.225	80	Tri-hexagonal
13	0.225	50	Concentric
14	0.225	50	Concentric
15	0.225	50	Concentric

2.4 3D printer machine and tests

The ISO 179 standard, which specifies procedures for evaluating the impact resistance of plastics, was followed in the design and testing of impact specimens. The ISO 178 standard, which outlines the method for measuring the flexural properties of plastic materials, was also followed in preparing the bending samples. Figure 1(a and b) show the impact and bending samples after testing.

SolidWorks software was used to design these specimens, allowing for accurate preparation of test models and modeling. Furthermore, the ASTM D638 standard, which specifies the tensile testing procedure for plastic materials, served as the basis for designing the tensile specimens shown in Figure 1c. Using a 3D printer, these samples were specifically manufactured for PLA and PETG materials. The measurement control program of the Times Group Inc.-made WDW-200E tensile testing machine conducted the tensile and flexural tests. The Chinese-made XJU-22 impact tester was used to conduct an impact test to compare the mechanical qualities of the two. Guaranteeing precise measurements and constant quality for mechanical testing. Using the Box-Behnken design, 15 experiments were conducted to examine the mechanical properties systematically. A thorough assessment of the mechanical characteristics unique to each experimental condition was made possible by testing the samples according to the criteria outlined in Table 1.

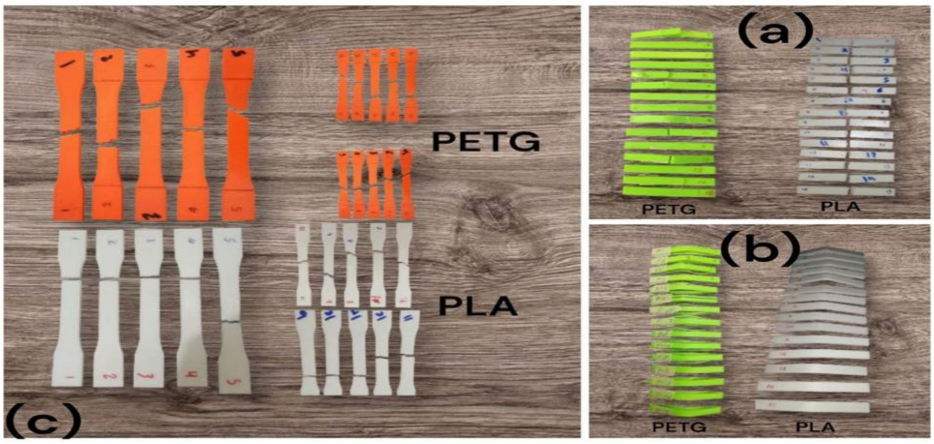


Figure 1: a) Impact test run samples, b) Bending test run samples, and c) Tension test run samples

3. Results and discussion

Table 2 shows the experimental results for 15 3D-printed PLA and PETG samples. Four mechanical properties—impact toughness, flexural strength (MPa), ductility, and ultimate tensile strength (UTS) are measured for each material in the table. The table displays the measured values for PLA and PETG under identical test conditions, with each row corresponding to a specific sample number. According to established procedures, the mechanical performance of the printed specimens is assessed through impact, bending, and tensile testing.

Table 2: Test results for 15 samples created using the Box-Behnken design

No.	PLA				PETG			
	Impact toughness	Flexural strength (MPa)	Ductility	UTS	Impact toughness	Flexural strength	Ductility	UTS
1	0.00625	50	0.3	28.07	0.01500	93	1.8	28.26
2	0.00875	54	0.3	32.69	0.02250	72	0.7	30.38
3	0.01000	72	0.6	45.57	0.01750	63	1.2	46.34
4	0.01000	59	0.7	39.61	0.02800	64	1.8	39.80
5	0.01000	48	4.0	29.03	0.01625	45	3.0	27.69
6	0.00875	45	3.0	32.11	0.03750	47	2.4	29.23
7	0.00750	54	1.2	32.12	0.03500	73	1.2	33.65
8	0.00750	63	3.0	32.11	0.03250	54	1.0	32.30
9	0.00750	59	2.4	25.76	0.02000	36	2.0	25.76
10	0.01125	54	1.8	33.26	0.01500	55	1.5	34.03
11	0.00625	53	0.6	28.65	0.03000	50	1.3	27.88
12	0.00750	50	1.2	37.11	0.03500	70	1.2	41.34
13	0.00750	55	0.3	34.61	0.02375	48	1.0	35.00
14	0.00700	59	0.3	34.42	0.01250	65	1.3	36.53
15	0.01000	53	0.4	35.00	0.02050	68	0.6	36.15

3.1 The effect of printing factors on the impact toughness for both PLA and PETG

Important printing parameters, such as layer thickness, infill type, and infill density, significantly impact the mechanical performance of 3D-printed parts. These factors impact the printed parts' overall impact resistance, energy absorption, and structural integrity. An analysis of variance (ANOVA) is performed on impact test results to determine the statistical significance of each factor and any possible interactions, thereby quantifying their effects. Interpretation of ANOVA tables: the significance of each factor is highlighted by the ANOVA table, which displays the p-values and F-statistics for each: Impact resistance is significantly impacted by the factor if $p < 0.05$, the effect of the factor is statistically insignificant if $p > 0.05$.

The analysis of variance (ANOVA) for impact toughness, listed in Table 3, shows that the layer thickness's effect P-value is 0.726, which is greater than 0.05. A high P-value indicates that layer thickness has no discernible impact on impact resistance. This suggests that varying layer thicknesses have a minimal impact on the ability of PLA prints to absorb shock. However, the filler density significantly affects the impact resistance, as indicated by the P value of 0.031 (significant because it is less than 0.05). While lower fill densities may have an impact on mechanical strength, higher infill densities are likely to produce more substantial, more impact-resistant parts. The P value in the infill pattern, which is slightly less than 0.05 and marginally significant, is 0.049. This suggests that the type of filler pattern influences the impact resistance. Improved shock absorption is probably the result of specific padding patterns that more evenly distribute impact forces. Figure 2 a shows the percentage of printing parameters on impact toughness.

Table 3: Analysis of variance for impact toughness of PLA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.042782	0.004754	2.09	0.216
Linear	3	0.035625	0.011875	5.21	0.054
layer thickness	1	0.000312	0.000312	0.14	0.726
infill density	1	0.020000	0.020000	8.78	0.031
infill pattern	1	0.015312	0.015312	6.72	0.049
Error	5	0.011392	0.002278		
Total	14	0.054173			

Table 4 presents the ANOVA analysis of the printing factors' effect on PETG material, with a P-value of 0.036; the linear terms (layer thickness, infill density, and infill pattern) are statistically significant ($p < 0.05$). This suggests that these linear parameters have a significant overall impact on PETG print performance.

The P-value for Layer Thickness is 0.038, indicating a significant impact. This indicates a significant impact with an F-value of 7.81. implies that changing the thickness of a layer can have a noticeable impact on the properties or quality of the print. The P-value for Infill Density = 0.570. It's not important. Has minimal impact on the response variable of this particular experiment. It may suggest that PETG is less sensitive to infill density alone or that returns are declining. 0.021 is the infill pattern value, which indicates high significance. Out of all the parameters, the F-value a linear regression model was created to examine the connection between PLA, PETG's impact toughness, and processing parameters. The model assumes that certain variables (layer thickness, infill density, and infill pattern) have a linear relationship with impact toughness. The following are the regression equations (1and 2) for PLA and PETG, respectively.

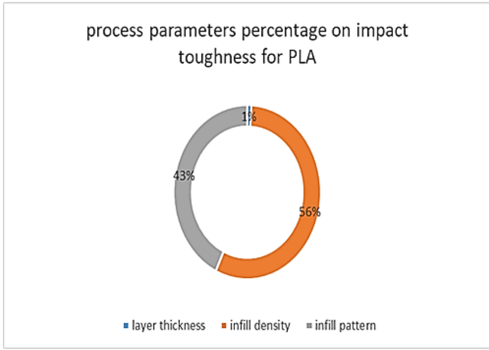
Table 4: Analysis of variance for impact toughness of PETG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.000867	0.000096	4.46	0.057
Linear	3	0.000416	0.000139	6.41	0.036
layer thickness	1	0.000169	0.000169	7.81	0.038
infill density	1	0.000008	0.000008	0.37	0.570
infill pattern	1	0.000239	0.000239	11.06	0.021
Error	5	0.000108	0.000022		
Total	14	0.000976			

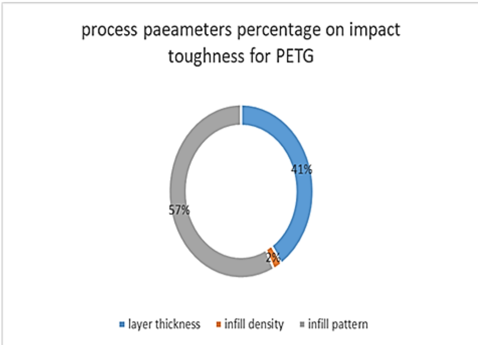
$$\text{Impact toughness (PLA)} = 0.2333 + 0.083 \text{ layer thickness} + 0.001667 \text{ infill density} - 0.0437 \text{ infill pattern} \quad (1)$$

$$\text{Impact toughness} = 0.00862 + 0.0613 \text{ layer thickness} + 0.000033 \text{ infill density} + 0.00547 \text{ infill pattern} \quad (2)$$

This model helps optimize 3D printing conditions for improved material performance by predicting toughness values based on specific processing settings.



(a)



(b)

Figure 2: Percentage printing parameters on impact toughness for a) PLA, and b) PETG

3.2 The effect of printing factors on the flexural properties of both PLA and PETG

Experimental values for flexural properties are presented in Table 2 for PLA and PETG, providing a comprehensive summary of the flexural performance of the tested samples. Additionally, ANOVA analyses are presented in Tables 5 and 6 for the PLA and PETG samples, respectively, to illustrate the factors that have the most significant effects on the flexural performance of the tested samples.

Table 5 evaluates the impact of various printing parameters on the flexural strength of the PLA material. The findings show the following: F-value = 0.43, P-value = 0.872, overall model. Given that the model is not statistically significant, it can be concluded that the variation in flexural strength is not primarily explained by the selected parameters (layer thickness, infill density, and infill pattern). Figure 3a shows the percentage of influence of each factor, as indicated in Table 5, where the P-value for Layer Thickness is 0.903. There is no discernible impact on flexural strength when the P-value is exceptionally high—P-value for Infill Density: 0.455. Although not statistically significant, it was lower than the others. Although it's weak in this data, there may be a minor influence—P-value for the infill pattern: 0.577. This is not important either. Different patterns do not significantly impact flexural strength. The infill pattern, however, suggests a possible influence, as shown in Figure 3b. Based on the regression analysis of the flexural strength of PLA, Equation 3 was derived:

$$\text{Flexural strength (MPa)} = 52.37 - 5.0 \text{ layer thickness} + 0.0792 \text{ infill density} + 1.75 \text{ infill pattern} \quad (3)$$

This equation suggests that layer thickness has a significant negative impact on flexural strength, while filler pattern has a relatively positive effect, and filler density has a minor effect.

In the case of PETG, as shown in Table 6, flexural strength was not significantly affected by any of the tested parameters (layer thickness, filler density, and filler pattern). However, the regression Equation 4 showed the following:

$$\text{Flexural strength} = 73.9 - 61.7 \text{ layer thickness} + 0.004 \text{ infill density} + 8.00 \text{ infill pattern} \quad (4)$$

Here, too, we note that layer thickness has a negative effect, albeit less pronounced than in the case of PLA, while the effects of the filling pattern and density are slight.

Table 5: Analysis of variance for flexural strength of PLA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	265.983	29.554	0.43	0.872
Linear	3	70.750	23.583	0.34	0.797
layer thickness	1	1.125	1.125	0.02	0.903
infill density	1	45.125	45.125	0.66	0.455
infill pattern	1	24.500	24.500	0.36	0.577
Error	5	344.417	68.883		
Total	14	610.400			

Table 6: Analysis of variance for flexural strength of PETG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	1910.98	212.331	1.08	0.491
Linear	3	683.25	227.750	1.16	0.411
layer thickness	1	171.13	171.125	0.87	0.393
infill density	1	0.13	0.125	0.00	0.981
infill pattern	1	512.00	512.000	2.61	0.167
Error	5	979.42	195.883		
Total	14	2890.40			

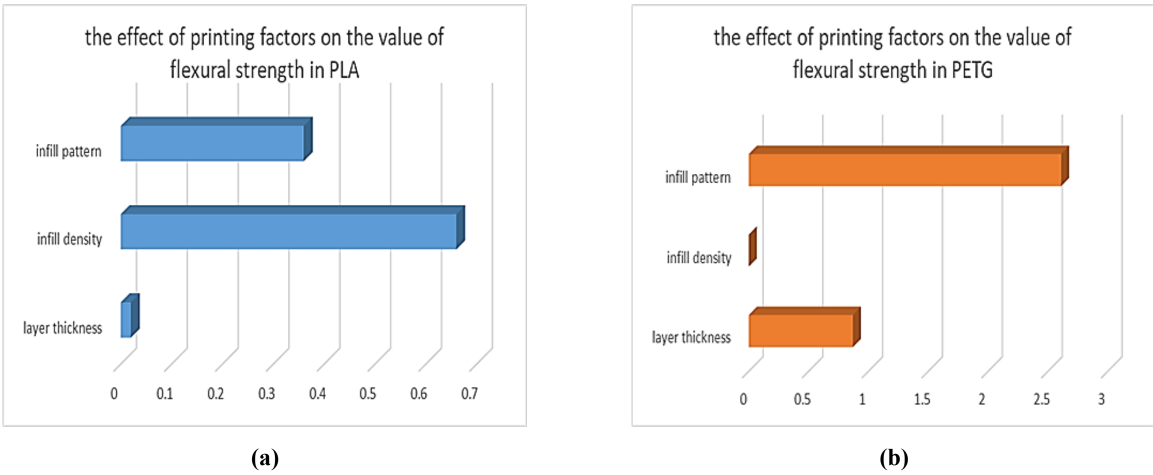


Figure 3: Effect of the printing factors on flexural strength a) PLA, b) PETG

3.3 The effect of printing factors on the ductility of both PLA and PETG

In Table 7, the main printing parameters have a significant influence on ductility, as evidenced by a linear effect (P = 0.014). The infill pattern is the most influential parameter, with a high F-value (27.16) and a substantial, statistically significant effect on ductility (P=0.003). There are no significant effects of infill density and layer thickness (P values 0.158 and 0.289, respectively), as shown in Figure 4a. To understand the quantitative relationship between these parameters and ductility, linear regression analysis was employed, yielding the Equation 5.

$$\text{Ductility} = 0.86 + 1.50 \times \text{layer thickness} + 0.0029 \times \text{infill density} - 0.650 \times \text{infill pattern} \quad (5)$$

This equation suggests that layer thickness has a positive effect on ductility, as does infill density, albeit with a slight impact. Infill pattern, however, exhibits an apparent negative effect, which explains the high statistical significance of this factor in influencing ductility.

Table 7: Analysis of variance for ductility of PLA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	31.3135	3.4793	17.35	0.003
Linear	3	6.2775	2.0925	10.44	0.014
layer thickness	1	0.5512	0.5512	2.75	0.158
infill density	1	0.2813	0.2813	1.40	0.289
infill pattern	1	5.4450	5.4450	27.16	0.003
Error	5	1.0025	0.2005		
Total	14	32.3160			

Table 8 for PETG shows that the linear effects (P = 0.086) indicate some influence but are not decisive. The filler pattern significantly affects ductility (P = 0.022), while the layer thickness and filler density do not significantly affect ductility (P =

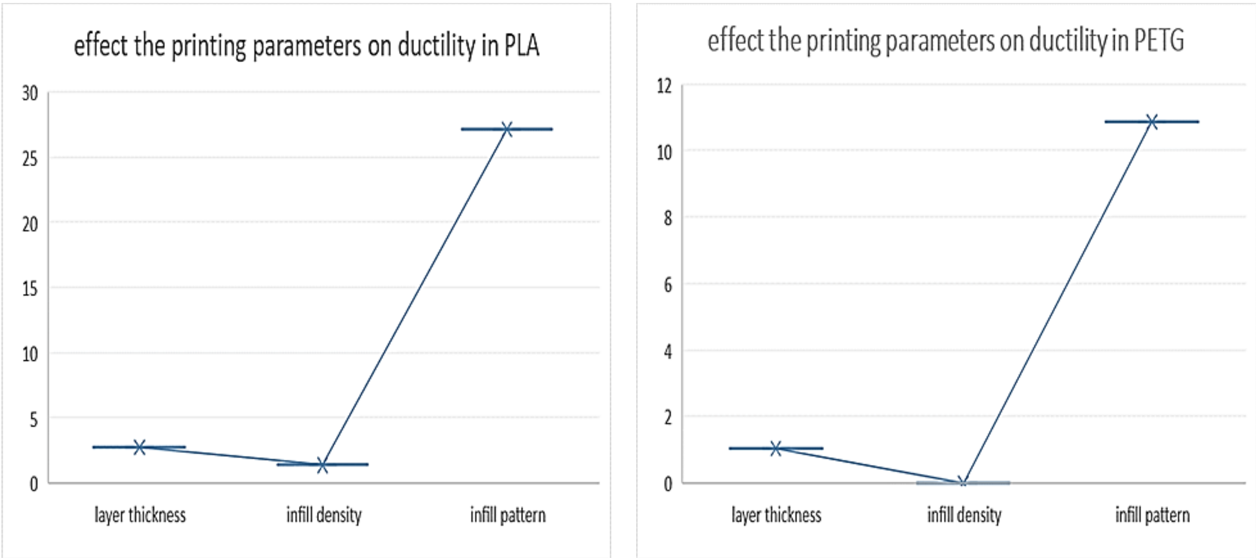
0.354 and 0.940, respectively), as shown in Figure 4b. Through linear regression analysis, Equation 6 was derived, describing the relationship between printing parameters and the plasticity of PETG:

$$\text{Ductility} = 1.975 - 2.17 \times \text{layer thickness} - 0.00042 \times \text{infill density} - 0.525 \times \text{infill pattern} \tag{6}$$

This equation indicates that all three parameters negatively affect plasticity, with the infill pattern and layer thickness having a relatively more significant effect than the infill density, which is consistent with the statistical analysis results.

Table 8: Analysis of variance for ductility of PETG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	4.75917	0.52880	2.61	0.152
Linear	3	2.41750	0.80583	3.97	0.086
layer thickness	1	0.21125	0.21125	1.04	0.354
infill density	1	0.00125	0.00125	0.01	0.940
infill pattern	1	2.20500	2.20500	10.87	0.022
Error	5	1.01417	0.20283		
Total	14	5.77333			



(a) (b)

Figure 4: Effect of the printing factors on ductility, a) PLA, b) PETG

3.4 The effect of printing factors on ultimate tensile strength for both PLA and PETG

In the ANOVA analysis and P values shown in Tables 9 and 10 for PLA and PETG, respectively, filler density is crucial for increasing UTS. Generally, increasing density results in a higher amount of material per volume, which enhances strength. The relationship between the three printing parameters (layer thickness, infill density, and infill pattern) and the ultimate tensile strength of PLA can be represented by the regression Equation 7:

$$\text{UTS (PLA)} = 24.28 + 2.9 \times \text{layer thickness} + 0.1683 \times \text{infill density} + 1.23 \times \text{infill pattern} \tag{7}$$

This equation indicates that all parameters have a positive influence on the ultimate tensile strength, with the precise contribution of infill density being the most significant, followed by infill pattern and layer thickness.

The filler pattern becomes more important for PETG, which is softer and more flexible than PLA and interacts better with structural supports. The relationship for PETG is expressed using the regression Equation 8:

$$\text{UTS (PETG)} = 24.95 - 7.1 \times \text{layer thickness} + 0.2051 \times \text{infill density} + 2.31 \times \text{infill pattern} \tag{8}$$

From this equation, we observe that layer thickness negatively affects the ultimate tensile strength of PETG, while filler density and filler pattern increase it, highlighting the importance of the internal structure in supporting the material's mechanical properties. In both tested materials, layer thickness had no statistically significant effect on the modulus of elasticity (UTS), supporting the results of the ANOVA. This can be summarized in Figures 5 (a and b).

Table 9: Analysis of variance for ultimate tensile strength of PLA

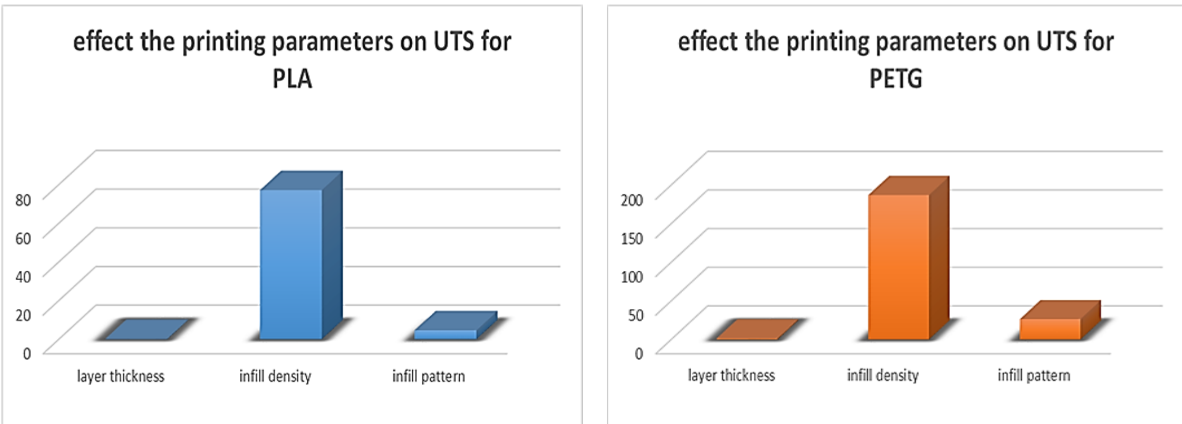
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	326.161	36.240	13.71	0.005
Linear	3	216.271	72.090	27.27	0.002
layer thickness	1	0.374	0.374	0.14	0.722
infill density	1	203.818	203.818	77.10	0.000
infill pattern	1	12.079	12.079	4.57	0.086
Error	5	13.218	2.644		
Total	14	339.378			

Table 10: Analysis of variance for ultimate tensile strength of PETG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	458.558	50.951	31.42	0.001
Linear	3	347.782	115.927	71.49	0.000
layer thickness	1	2.237	2.237	1.38	0.293
infill density	1	302.949	302.949	186.84	0.000
infill pattern	1	42.596	42.596	26.27	0.004
Error	5	8.107	1.621		
Total	14	466.665			

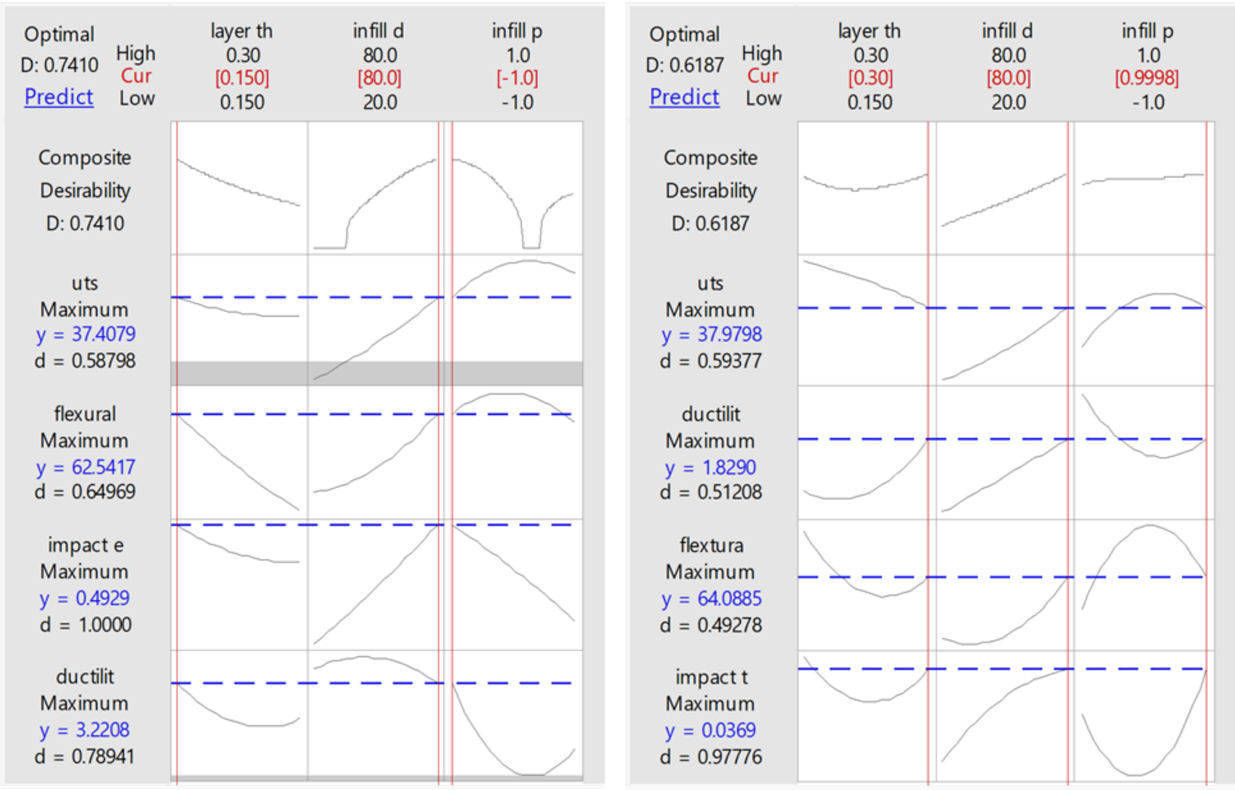
Effectively optimizing polylactic acid (PLA) printing agents was achieved using the Box-Benken design, shown in Figure 6 a. The optimal parameters, which produce the best print quality and performance, are as follows: layer thickness, 0.15 mm; infill density, 80%; and Infill pattern, -1 (grit). These values were obtained through a systematic experimental approach to guarantee reliable and superior PLA prints. The 80% ink density ensures good adhesion and a smooth surface finish, while the selected thickness allows for accurate layer deposition. The Grit Level 1 pattern's balanced texture enhances the material's mechanical properties and visual appeal. For PLA-based 3D printing applications, this optimization promotes increased print reliability and material efficiency. The use of BBD for PETG optimization, as shown in Figure 6 b, indicates that infill density is the primary factor influencing all important mechanical properties. Although layer thickness has little effect on most responses (UTS excluded), the infill pattern has a non-linear impact on results and should be adjusted to mid or high levels based on the desired performance. As determined by BBD, the ideal parameter combination for PETG is as follows: Thickness of Layer, 0.3 mm; Infill Density, 80%; and Coded Infill Pattern, 1 (tri-hexagonal). This combination is ideal for functional PETG components, as it ensures a balanced improvement across all key properties.

The samples were printed using these ideal PLA and PETG material parameters to investigate the aforementioned mechanical characteristics. After determining the best factors for each material, the final skull implant, depicted in Figure 7 (a and b), was printed using the PETG material that performed best in the lab.



(a) **(b)**

Figure 5: Effect of the printing factors on ultimate tensile strength, a) PLA, and b) PETG



(a (b)

Figure 6: The optimal printing parameters for a) PLA and b) PETG

(a) (b)

Figure 7: (a, and b) PETG-optimized skull implant

4. Conclusion

This study carefully looked at how three key 3D printing factors—layer thickness, infill density, and infill pattern—affected the mechanical properties of PLA and PETG materials using a Box-Behnken Design (BBD) approach. Impact toughness, flexural strength, ductility, and ultimate tensile strength (UTS) were the assessed mechanical attributes. In PLA, impact toughness and UTS were greatly influenced by infill density and pattern, whereas layer thickness had little effect on mechanical properties. The most significant influence on ductility came from the infill pattern. Flexural properties are less sensitive to the tested parameters, as evidenced by the fact that none of the parameters significantly impacted flexural strength.

The most crucial factor affecting impact toughness, ductility, and UTS for PETG was found to be the infill pattern. While layer thickness only significantly impacted impact toughness, infill density had a strong positive impact on UTS. Similar to PLA, none of the parameters significantly impacted the flexural strength of PETG. Each material's ideal parameters, as established by BBD, were: PLA: grit infill pattern, 80% infill density, 0.15 mm layer thickness. PETG: tri-hexagonal pattern, 80% infill density, 0.3 mm layer thickness. High-performance samples were printed and tested successfully with these optimized settings. The study's practical application was demonstrated by fabricating a functional skull implant using the best-performing PETG parameters.

Author contributions

Conceptualization, **R. Khzzal, M. Nafaa,** and **W. Hamdan**; data curation, **R. Khzzal**; formal analysis, **M. Nafaa**; investigation, **W. Hamdan**; methodology, **R. Khzzal**; project administration, **R. Khzzal**, and **M. Nafaa**; resources, **M. Nafaa**; software, **M. Nafaa**; supervision, **M. Nafaa**, and **W. Hamdan**; validation, **R. Khzzal, M. Nafaa**, and **W. Hamdan**; visualization, **W. Hamdan**; writing—original draft preparation, **M. Nafaa**; writing—review and editing, **M. Nafaa**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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