Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(4), 50–64
https://doi.org/10.12913/22998624/200088
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.12.27
Accepted: 2025.01.14
Published: 2025.02.19

Optimization of fused deposition modeling parameters for polyethylene terephthalate glycol flexural strength and dimensional accuracy

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ABSTRACT

Fused deposition modeling (FDM) is a type of additive manufacturing (AM) that has received significant interest from researchers and industries due to its flexibility in design, efficient use of materials, and affordable costs. In this paper, the main objective is to investigate the influences of FDM process parameters on the flexural properties as well as the accuracy of the final part made from polyethylene terephthalate glycol (PETG) material, which is widely used for 3D printing due to its strength and ease of use. A response surface methodology (RSM) approach based on a Box–Behnken design was employed, with three key process parameters: infill line distance, wall line count, and build plate temperature. The analysis of the data indicated that all three parameters affected the inherent characteristics of the printed parts, including mechanical and dimensional characteristics of the printed parts. The build plate temperature was identified as the most significant parameter, contributing 53% of the variability in the flexural strength of the printed specimens and 39.7% to deviation in the dimensional accuracy of the specimens, as indicated by the analysis of variance (ANOVA). A comparison between the predicted values of the model and the corresponding experimental results showed the suitability of the developed model with high accuracy. The maximum percentage errors observed in this study were 3.4% for the flexural strength and 7.5% for the dimension accuracy, establishing the efficacy of the optimization technique. These outcomes are meaningful to understand the influences of the process parameters on material response and offer a systematic approach to develop structurally enhanced PETG parts with improved mechanical characteristics and geometric dimensions.

Keywords: PETG, FDM, process parameters, flexural strength, dimensional accuracy.

INTRODUCTION

FDM is one of the most common forms of AM technology that builds an object layer by layer by extruding thermoplastic material through a heated nozzle. Some of the familiar thermoplastics used in FDM are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate glycol (PETG) that are successively deposited on a construct platform to cool and solidify before layer formation. Compared to others, FDM offers some advantages, such as low cost, versatility in application, and the capability of forming intricate structures; therefore, FDM can be applied at various stages, ranging from design to the operation part [1]. Among all these materials, PETG is most popular for its high tensile strength, dimensional stability, and compatibility with FDM printers. One of the most important mechanical properties of the material is the flexural strength, which characterizes the ability of the material to withstand the loads acting in the cross-section of the member in bending and makes this material suitable for application in structures. Furthermore, PETG has very low shrinkage and excellent layer adhesion, which have a further improving influence on the FDM process and help to make components that are of high mechanical durability and stability if the PETG is processed under the best conditions [2, 3].

Several studies exist that define how mechanical properties and part dimensions of FDM-printed parts are highly dependent on process parameters. Another crucial aspect of part quality is dimensional accuracy, which guarantees that the printed components align with the design and fit appropriately within assemblies. It was therefore important to establish that flow rate, the distance between the nozzle and the platform or the previous layer, and other parameters such as nozzle temperature, nozzle movement velocity, and infill patterns were vital in achieving high levels of dimensional accuracy.

Reducing the layer thickness will reduce the errors in the vertical direction, and imposing a large layer thickness will increase the buildup rate, though the possible accuracy may be low. Likewise, the temperature of the nozzle affects the dimensional accuracy because correct temperature enables a steady flow of the filament, and there is less opportunity to get distorted by high temperature [4, 5]. It has been established that the increase of infill line distance is helpful in enhancing particular mechanical properties, including the flexural strength, as well as enhancing the dimensions' reliability due to the improved material distribution in the structure. Likewise in the wall line count, the structures that contain higher wall line counts are also stronger and possess better dimensional stability and accuracy [6]. Another parameter is the build plate temperature, which aids in improving layer bonding and warping, which remains the primary cause of dimension inaccuracies. For PETG, having the wrong build plate temperature results in distortions due to varying contraction and expansion, so that the printed part has to be in the right dimensions on the build plate [7].

The fine-tuning of these parameters and the development of other build plate adhesives lead to improvement in interlayer adhesion and dimensional stability of PETG in FDM technology to produce functional, high-performance parts in aerospace, automotive, and health care industries. Experimental techniques such as RSM, Taguchi Design of Experiments, and machine learning have also been employed to obtain optimal parameters of PETG. Investigations indicate enhanced flexural strength and dimensional accuracy, which can be 20% better than the base value when optimal settings are used [8]. Furthermore, all of these improvements mitigate issues that are basically associated with FDM technology, which lays down layers on top of each other. This makes the material property adjustments to provide stable and reliable outcomes in PETG-printed parts regarding anisotropy, defects, and dimensional variations. However, it is noted that future studies have to be conducted to establish new material types and find new ways of altering processes to overcome current challenges [1].

Numerous studies have conducted analyses focused on the relationship of process parameters on the mechanical properties of the printed FDM parts, particularly the flexural strength and dimensional stability. These parameters must be controlled for better mechanical performance and conform to the design specifications concerning structural integrity and use. In their study, Hsueh et al. [9] examined the properties of polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) materials of FDM under four loading conditions: Direct forces on structures include tensile force, compression force, bending force, and thermal force. For the PLA and PETG, the tensile and compression asymmetry were also observed, and all of the tested mechanical properties were improved with increased printing temperatures. Furthermore, it is clearly seen that speed influences these properties in a different manner as well. Mechanically, PLA will be better profiled than PETG, but things such as thermal warping will act otherwise. Such findings may similarly be useful for other researchers in achieving the sustainability of polymers and FDM technology. In a study by Agarwal et al. [10], the impact of six print parameters was examined on the specimens printed with ABS material. The experiments were performed with a three-factor small resolution central composite design (CCD). Research also revealed that layer thickness and print speed are the most influential features for dimensional accuracy, where layer thickness that is smaller than the optimal value coupled with higher print speed gives higher accuracy.

In another work, Chicos et al. [11] focused on the investigation of infill density (ID) effects on the characteristics of carbon fiber-reinforced composites through the Fused Filament Fabrication (FFF) process. The tensile and flexural strengths of the specimens were evaluated by differential scanning calorimeter (DSC) and thermal gravimetric analysis (TGA). It was also observed from the results that specimens with 100% ID exhibited the highest tensile and flexural strengths, and specimens with 25% had the lowest. The study also noted with the increase of the ID, the glass transition temperature was influenced, where specimens with 100 percent of ID had lower temperatures of onset degradation. Alexopoulou et al. [12] assessed the dimensional precision of resolution holes in the PETG material produced by FDM together with reference to the ISO ASTM 52902-2021 standards. Specimens of 0.5, 1, 2, 3, and 4 mm nominal diameter were fabricated at either slow speed (20 mm/s), medium speed (50 mm/s) or fast speed (80 mm/s) or at different layer heights of 0.1 mm, 0.2 mm and 0.3 mm. Quantitative analysis by microscopy and computer vision showed that there were marked differences between the measured and nominal diameters, although differences within each set of comparisons were small, signifying a high degree of consistency. The study pointed out that for a printer to have high accuracy for hole making, the nominal diameter was found to be above 2 mm, not influenced by speed or layer height but completely unsuitable for 0.5 mm and 1 mm diameters due to large errors. It is noted that higher printer sophistication is preferable for improved tolerances in smaller nominal diameters.

Darsin et al. [13] aimed at establishing the most favorable parameters for achieving a high degree of dimensional stability and the highest bending strength while using Cu-PLA filament in FDM 3D printing. The analysis of results indicates that in order to achieve the highest degree of dimensional accuracy, the recommended parameters should be set as follows: the nozzle temperature of 220 °C, the layer height of 0.3 mm, and the line infill pattern The highest degree of bending strength is reached at the nozzle temperature of 240 °C. Obaeed and Hamdan [14] evaluate and optimize the medical-grade polymethylmethacrylate PMMA by examining the effect of three printing parameters: layer height, infill density, and skewing angle on flexural strength. The flexural strength rises significantly with decreased layer height, and the skewing angle is in the zero direction. Genetic algorithms have been utilized to optimize the FDM process parameters. Gohar et al. [15] focused on flexural, edgewise compression, and interfacial bond strength of high-cost composite sheets (HCSS) produced through FDM and their mechanical behavior. Four types of specimens were prepared, and changes were made to the raster lay-up direction at 0/90 and 45/−45 degrees. When investigating the results, the best material was identified as ABS core with composite face sheets in a raster layup of 0°/90°. It is found that FDM can construct the HCSS with sophisticated lamination profiles and acceptable mechanical characteristics, implying an augmentation of application fields of FDM.

Frunzaverde et al. [16] focused on the effects of dyeing agents concerned with filament colors on the dimensional accuracy and mechanical performance of FDM-printed PLA parts. Specifically, the researchers prepared various tensile specimens with different layer heights and filament colors. The analysis of the results revealed that the variation in the dyeing agents and the related color affects both the dimensional stability and tensile properties. Layer height and PLA color (and its dyeing agent), and their interaction, contributed to have a strong effect on tensile strength. In terms of dimensional accuracy, black PLA had the highest values, while in terms of ultimate tensile strength, Grey PLA was observed to have the highest values. Mushtaq et al. [17] invented the laser polishing technique to optimize the mechanical characteristics of nylon-6 polymers printed by means of 3D techniques, decreasing the surface roughness coefficient and increasing the flexural and tensile strengths. Response surface methodology was applied to evaluate the effectiveness of the method to pre-polish workpieces. It was found that the set of laser scanning parameters provided a decrease of the surface roughness of specimens by 20.2%, an increase of the flexural strength by 8.27%, and the tensile strength by 1.45%. Therefore, the time optimal for laser scanning was 0.23 min, and the energy consumption was 1.58 mWh. Indeed, this new post-processing laser polishing process is very useful for the 3D printing industry.

Sukindar et al. [18] examined the surface roughness of the material through FDM based on the modification of print parameters including, layer height, print speed, and raster angle. It employs Taguchi's method, and a specimen model was used using PLA-Al filament. Analysis of variance for layer thickness and raster angle revealed that these two factors have a strong influence on surface roughness, particularly the most suitable printing conditions. The dimensional accuracy of the fabricated part was also assessed, and from the result obtained, it was evident that the FDM had a high accuracy for most shapes with a deviation below 5%. The finding of the study is useful in determining the best printing parameters for specific surface roughness. Raj et al. [19] analyzed various machine learning models on the flexural characteristics of graphene-poly-lactic acid composites fabricated through fused-filament fabrication.

The parameters were raster orientation, thickness of layers, and feed rate. The specimens were subjected to flexural tests and fractography tests. The flexural strength variations were analyzed by employing linear regression, random forest regression, gradient boosting regression, extreme gradient boosting regression, the voting regression algorithm, and artificial neural networks. According to the results, the linear regression provided a higher value with a 98.9% coefficient of determination, more than any other options. This work enriches the state of the art in multi-scale modeling and simulation in material science and additive manufacturing by showing that even with a moderate number of parameters, machine learning combined with metaheuristic algorithms can yield accurate predictions.

This current study used FDM technology to create a number of PETG test specimens with varying process variables like infill line distance, wall line count, and build plate temperature. These printed specimens were then used for flexural strength and dimensional accuracy tests to evaluate the effect of these parameters. To do this, a desirability analysis approach was conducted to allow systematic studies of the trade-offs for mechanical performance and geometrical accuracy. The study offers extensive information on how to optimize FDM process parameters, or adjust them, to achieve ideal mechanical and dimensional characteristics of PETG, a highly relevant thermoplastic material for structural parts.

METHODOLOGY

Material and method

As described in Figure 1, a Creality Ender-3 Pro 3D printer was used to print all of the specimens. The work material chosen for the current study was a 1.75mm diameter green polyethylene terephthalate glycol (PETG) filament because of its high mechanical strength, good thermal stability, and easy printability. Suitable for functional prototypes and final application parts in automotive, aviation, medical, and other industries, possessing high tensile strength, flexural strength, low shrinkage rate, and good interlayer adhesion. This material is also biocompatible, which means that it can be used in more applications, including medical and food-related industries [20]. Despite challenges like surface roughness being some of the problems that can be met during the use of PETG, it is still considered to be one of the most efficient types of filaments suitable for high-performance 3D printing.

A standard triangle language (STL) file comprising a set of linked triangles was utilized to generate the geometry of the 3D model. Through the slicing process, this 3D design was transformed into G-Code, the language of machines, and prepared for printing. Ultimaker Cura 4.13.1 was employed to prepare the STL file and create the appropriate G-codes. The part's sliced model and solid work model (ASTM D790 v1) are presented in Figure 2a, b, respectively. The three input parameters and

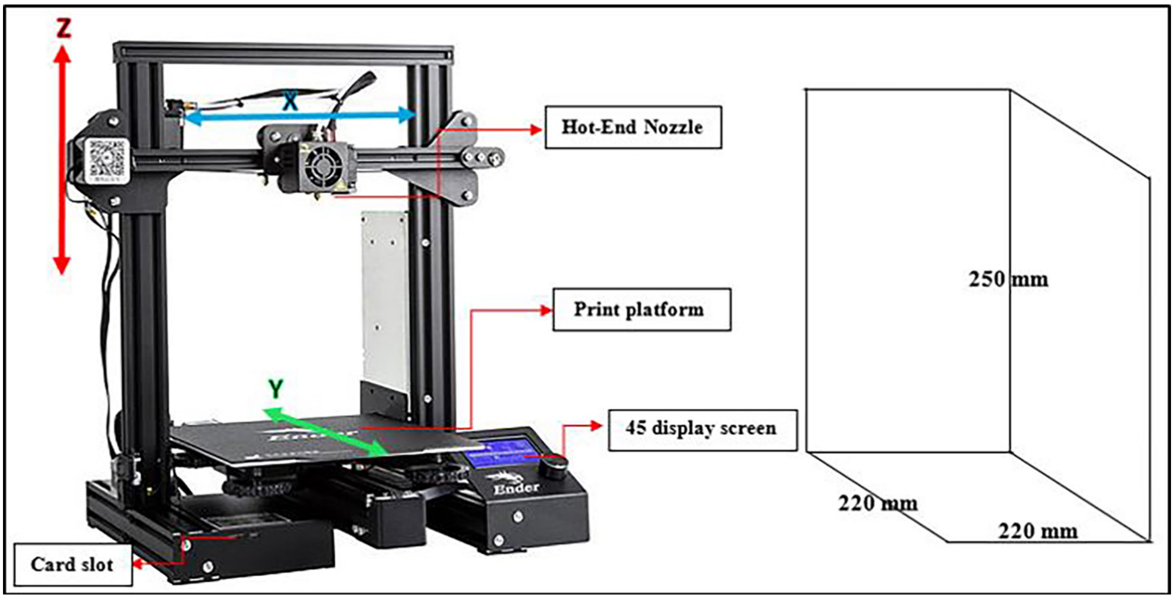

Figure 1. Creality Ender-3 pro 3D printer

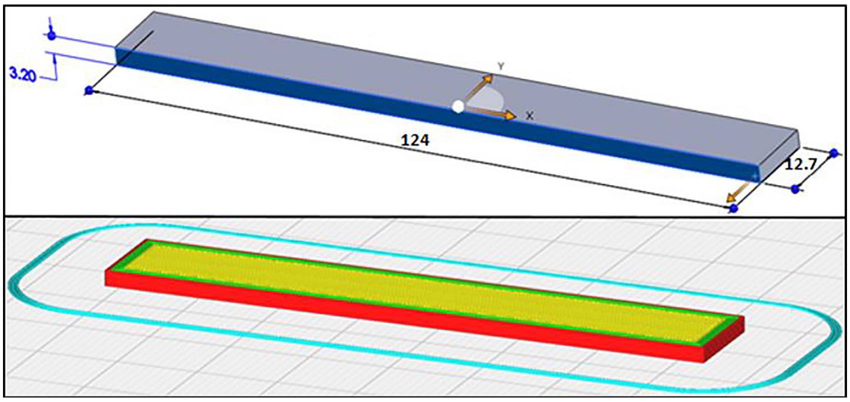

Figure 2. CAD and sliced models for flexural specimens

their varying levels utilized to produce the PETG filaments are listed in Table 1, while Table 2 demonstrates that the remaining FDM parameters are preserved at their set levels. The workflow for this work, which begins with selecting the FDM parameters and continues until the optimization approach, is depicted in Figure 3.

Response surface methodology (RSM) is a potent statistical technique for modeling and optimizing systems where multiple parameters affect a response of interest. With the fitting of polynomial equations, commonly of the second order, it is particularly useful for examining the relationships between input parameters and a response as

Table 1. The selected FDM settings and their levels

FDM parameters	Units	Levels		
		1	2	3
Infill line distance	mm	1	1.5	2
Wall line count	–	3	4	5
Build plate temperature	°C	70	75	80

Table 2. The remaining FDM settings' fixed level

Parameters	Values	Units
Layer height	0.1	mm
Wall thickness	1.2	mm
Infill density	75	%
Infill pattern	Cubic	–
Printing temperature	240	°C

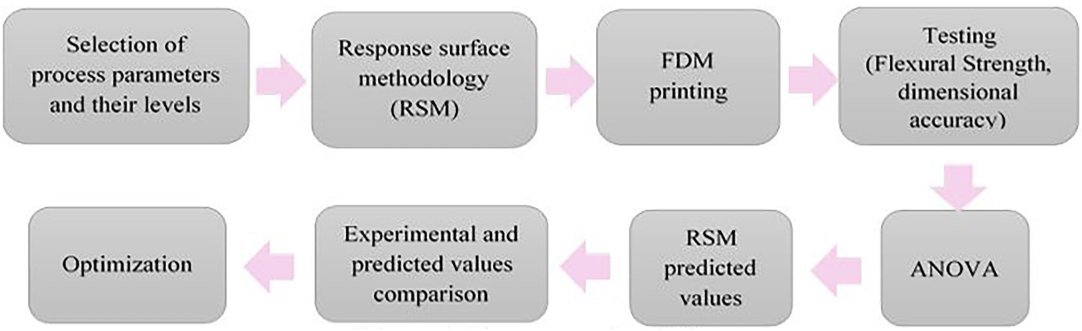

Figure 3. The proposed work flow

well as for identifying the optimal conditions for operation. RSM utilizes experimental designs like Box-Behnken Design (BBD) and central composite design (CCD) to efficiently evaluate the influence of components and their interactions. The visualization of these relationships is further made easier by graphical techniques such as contour plots and response surface plots. In manufacturing, engineering, and process optimization, RSM is frequently utilized and provides insights for enhancing quality and performance [21, 22].

In accordance with Box Behnken Design's response surface methodology, which calls for 15 runs, the experiments' specimens are manufactured using a 3D printer. Depending on the Box-Behnken design for RSM, Table 3 illustrates combinations of coded and actual parameter levels. The statistical tool Minitab 17 is employed for DOE. The infill line distance, wall line count, and build plate temperature are coded parameters with the names A, B, and C, respectively.

A three-point bending test in accordance with standards (ASTM D790) was performed on a WDW-200E computer-controlled electronic universal testing machine, as shown in Figure 4. The testing was carried out in the Strength of Materials Laboratory at the University of Technology's Production Engineering and Metallurgy Department, Baghdad, Iraq. The PETG specimens used for the three-point bending test are shown in Figure 5. The crosshead speed of loading is 2 mm/min for assessing the mechanical characteristics of the fabricated specimens [23, 24].

Table 3. Coded and actual printer parameters combination according to Box Behnken Design

Exp. No.	Coded parameters			Actual parameters		
	A	B	C	Infill line distance (mm)	Wall line count	Build plate temperature
1	-1	-1	0	1.0	3	75
2	1	-1	0	2.0	3	75
3	-1	1	0	1.0	5	75
4	1	1	0	2.0	5	75
5	-1	0	-1	1.0	4	70
6	1	0	-1	2.0	4	70
7	-1	0	1	1.0	4	80
8	1	0	1	2.0	4	80
9	0	-1	-1	1.5	3	70
10	0	1	-1	1.5	5	70
11	0	-1	1	1.5	3	80
12	0	1	1	1.5	5	80
13	0	0	0	1.5	4	75
14	0	0	0	1.5	4	75
15	0	0	0	1.5	4	75

Figure 4. The three-point bending test configuration utilized in this study

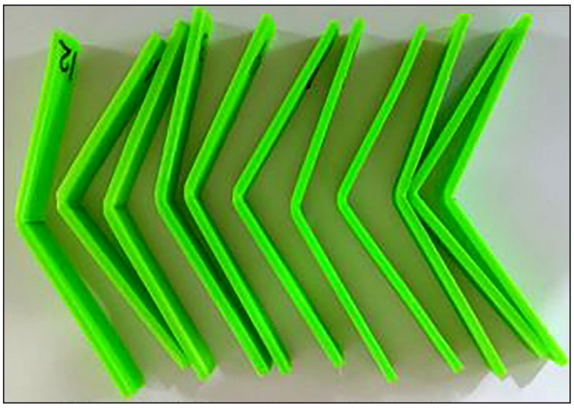

Figure 5. PETG specimens after bending tests

The influence of the FDM parameters on the deviation in dimensional accuracy was evaluated through the comparison of all of the manufactured specimens to the CAD model. Each specimen's dimensions were measured utilizing digital vernier calipers, and each piece of geometry was measured three times for every run. Eqs. (1–3) [25] were subsequently employed to determine the deviation in dimensional accuracy.

$$D_i = |Specified\ dimension - Observed\ value| \quad (1)$$

$$D_{pi} = \frac{D_i}{Specified\ dimension} \times 100 \quad (2)$$

$$Deviation\ in\ dimensional\ accuracy\ \% = \frac{D_{p1}+D_{p2}+D_{p3}}{3} \quad (3)$$

where: D_i – represents the deviation, and D_{pi} – represents the percentage deviation.

RESULTS AND DISCUSSION

In a three-point bending test, in which a beam is supported at two of the points and loaded at the third, the outer surface of the test specimen experiences the highest level of stress. The flexural stress and strain equations, denoted by Eqs. (4 and 5), have been utilized in order to transform the load-deflection curves acquired from the test into stress-strain curves.

$$\sigma_f = \frac{3FL}{2bd^2} \quad (4)$$

$$\varepsilon_f = \frac{6Dd}{L^2} \quad (5)$$

where: σ_f and ε_f - represent stress and strain at the midpoint in the outermost fibers, respectively, F – represents the applied force, L - represents the support span, b - represents the specimen width, and d - represents the thickness of the beam.

The flexural strength and dimensional accuracy deviations of the tested PETG-manufactured specimens are presented in Table 4, and for better visualization, the responses are displayed as bar charts in Figures 6 and 7. The flexural strength of the specimen fabricated with an infill line distance of 1 mm (level 1), a wall line count of 5 (level 3), and a build plate temperature of 75 °C (level 2) increased experimentally from 60.1 MPa to 71 MPa, based on the results in Table 4. This is noteworthy as it surpasses the 44.2 MPa maximum expected

Table 4. Experimental results for flexural strength and deviation in dimensional accuracy

Exp. No.	Infill line distance (mm)	Wall line count	Build plate temperature	Flexural strength (MPa)	Deviation in dimensional accuracy %
1	1.0	3	75	65.4	2.5
2	2.0	3	75	63.7	2.8
3	1.0	5	75	71.0	2.1
4	2.0	5	75	67.4	2.1
5	1.0	4	70	60.3	1.0
6	2.0	4	70	61.4	2.2
7	1.0	4	80	66.1	2.5
8	2.0	4	80	70.7	2.3
9	1.5	3	70	61.7	1.9
10	1.5	5	70	60.1	2.4
11	1.5	3	80	65.4	3.5
12	1.5	5	80	69.8	2.7
13	1.5	4	75	68.2	2.2
14	1.5	4	75	66.4	2.1
15	1.5	4	75	69.4	2.4

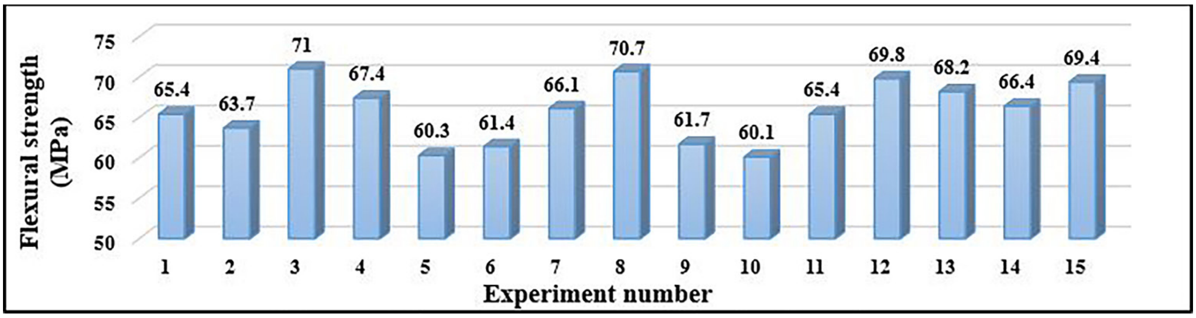

Figure 6. Flexural strength of PETG printed specimens

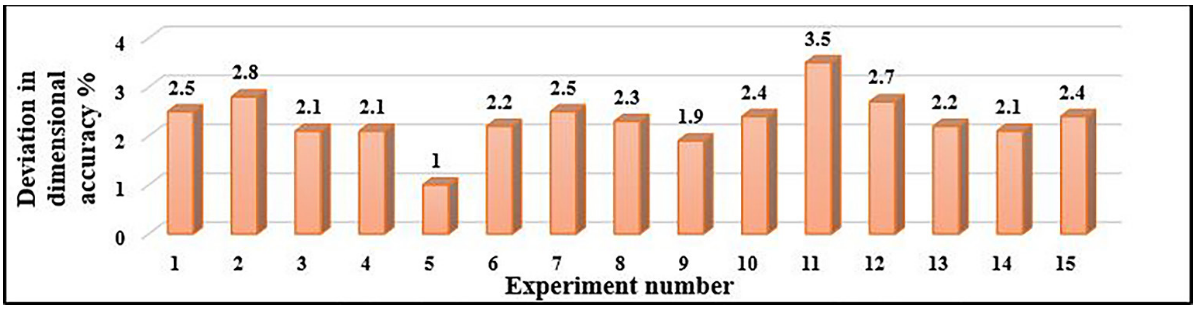

Figure 7. Deviation in dimensional accuracy of PETG printed specimens

flexural strength reported in reference [26]. On the other hand, with a specimen manufactured with an infill line distance of 1 mm (level 1), a wall line count of 4 (level 2), and a build plate temperature of 75 °C (level 2), the dimensional accuracy deviation experimentally reduced from 3.5% to 1%.

Analysis of Variance (ANOVA) utilizing the RSM approach in MINITAB 17 software was employed to evaluate the influence of the input parameters on flexural strength and dimensional accuracy deviation based on the experimental results summarized in Table 5. In order to determine the model's statistical significance, an ANOVA was performed with a significance threshold set at a P-value of less than 0.05, or a 95% confidence interval. A model term is considered to have a statistically significant influence on the response if its P-value is less than this threshold.

Based on Table 5, the build plate temperature significantly influences both flexural strength and dimensional accuracy, with p-values of 0.006 and 0.001, respectively, at a 95% confidence level. Strong layer adhesion and reduced internal stresses are ensured through preserving a proper build plate temperature, which enhances flexural strength. Additionally, by preserving stable thermal conditions during printing, it minimizes warping and shrinking, enhancing dimensional accuracy. These low p-values illustrate how important build plate temperature is to manufacture 3D-printed parts with high mechanical performance and accuracy.

The effects of build plate temperature, wall line count, and infill line distance on flexural strength and dimensional accuracy are presented in Figures 8 and 9. Figure 8 further shows that the temperature of the build plate has a notable effect on the flexural strength, which plays an influential role in the flexural strength when the temperature of the build plate rises drastically from 70 °C to 80 °C. Moreover, flexural strength enhances with the rise of wall line count from 3 to 5, making its significance moderate. On the other hand, the distance of the infill line has no significant effect, and it reveals low variability in the flexural strength. The Pareto chart also supports these findings and shows that infill line distance has the least impact, while wall line count and build plate temperature have the most impact.

Similarly, Figure 9 depicts that dimensional accuracy is mostly affected by the build plate temperature in which the accuracy increases rapidly by increasing the temperature of the build plate from 70 °C to 80 °C. This underlines the importance of the temperature for reducing the warping risk and ensuring stable interaction of the layers. However, wall line count has a moderately negative effect, where dimensional accuracy reduces as wall line count goes up from 3 to 5, possibly due to thermal non-uniformities or variations in extrusion.

Table 5. ANOVA results for flexural strength and dimensional accuracy deviation %

ANOVA for flexural strength						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage contribution
Model	9	167.7	18.6	3.7	0.1	86.9
Linear	3	120.1	40.0	8.0	0.02	62.3
A	1	0.0	0.0	0.0	0.96	0.01
B	1	17.9	17.9	3.6	0.1	9.3
C	1	102.2	102.2	20.3	0.006	53.0
Square	3	34.6	11.5	2.3	0.2	17.9
A*A	1	0.6	0.6	0.1	0.7	0.3
B*B	1	2.1	2.1	0.4	0.5	1.1
C*C	1	33.5	33.5	6.7	0.1	17.4
2-Way Interaction	3	13.0	4.3	0.9	0.5	6.7
A*B	1	0.8	0.8	0.2	0.7	0.4
A*C	1	3.0	3.0	0.6	0.5	1.5
B*C	1	9.2	9.2	1.8	0.2	4.8
Error	5	25.2	5.0			13.1
Lack-of-Fit	3	20.7	6.9	3.1	0.3	10.7
Pure Error	2	4.5	2.2			2.3
Total	14	192.8				100.0
ANOVA for deviation in dimensional accuracy						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage contribution
Model	9	3.7	0.4	13.6	0.01	96.1
Linear	3	2.0	0.7	22.1	0.003	52.2
A	1	0.2	0.2	6.9	0.05	5.4
B	1	0.3	0.3	9.0	0.03	7.1
C	1	1.5	1.5	50.6	0.001	39.7
Square	3	0.8	0.3	8.8	0.02	20.7
A*A	1	0.2	0.2	7.6	0.04	6.0
B*B	1	0.5	0.5	16.9	0.01	13.3
C*C	1	0.0	0.0	0.0	0.95	0.003
2-Way Interaction	3	0.9	0.3	9.8	0.01	23.1
A*B	1	0.0	0.0	0.3	0.6	0.2
A*C	1	0.5	0.5	16.5	0.01	12.9
B*C	1	0.4	0.4	12.7	0.02	10.0
Error	5	0.2	0.0			3.9
Lack-of-fit	3	0.1	0.0	2.7	0.3	3.2
Pure error	2	0.0	0.0			0.8
Total	14	3.9				100.0

Note: The degree of freedom is represented by DF, the adjusted summation of squares by Adj SS, the adjusted mean squares by Adj MS, infill line distance by A, wall line count by B, and build plate temperature by C.

Furthermore, the influence of infill line distance is minimal and inconsistent, showing only slight variations. These trends are supported by the Pareto chart, showing that build plate temperature is the most important parameter, followed by wall line count, while infill line distance has the least influence. The percentage contributions of the investigated parameters to the overall variation can be utilized to quantify their influence on the experimental results. At a 95% confidence level, this study shows that build plate temperature has the most influence on flexural strength and dimensional accuracy, contributing 53% and 39.7%, respectively. Table 6 illustrates the relative importance

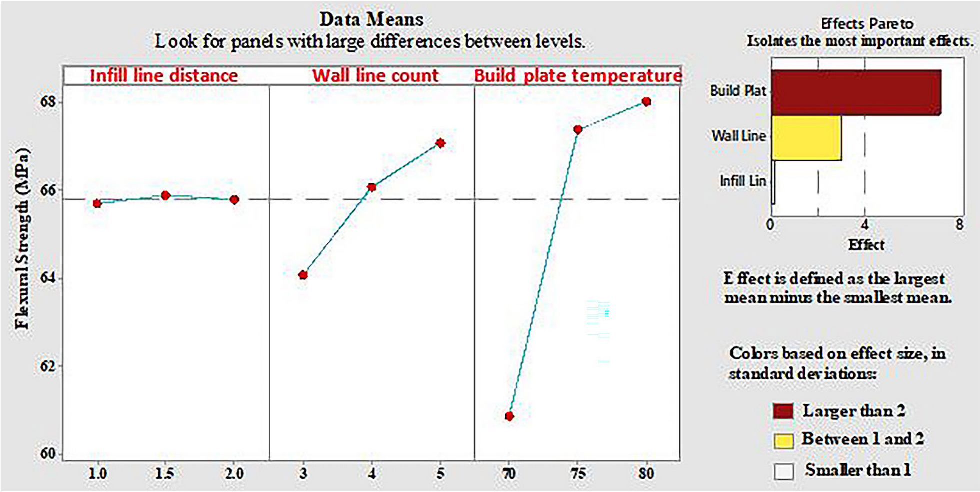

Figure 8. The main effects plot for flexural strength (MPa)

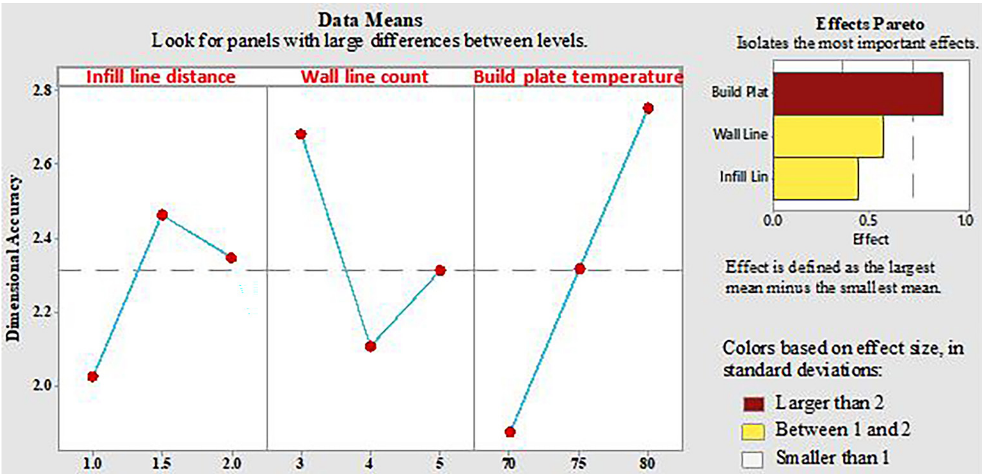

Figure 9. The main effect plot for deviation in dimensional accuracy

of each parameter in the process by providing its optimal values and significance levels.

Interaction graphs that demonstrate how process parameter interactions influence flexural strength and dimensional accuracy are displayed in Figures 10 and 11. These graphs indicate how the relationship between a first category parameter and the continuous response is influenced by the value of a second categorical parameter. Separate lines represent the levels of one parameter, whereas the x-axis shows the mean values for the levels of another. Significant interaction influences between the FDM process parameters are revealed by the non-parallel pattern of the lines displayed in these graphs, indicating how these parameters all work together to influence the test specimens' characteristics.

As shown in Figure 10, with a build plate temperature of 80 °C, a wall line count of 5, and an infill line distance of 1 mm, the maximum flexural strength can be achieved. On the other hand, Figure 11 indicates that the minimum

Table 6. The optimum levels and significance for each parameter

Parameters	Infill line distance	Wall line count	Build plate temperature (°C)	Significant
Optimized flexural strength	1.5 mm	5	80	Build plate temperature
Optimized dimensional accuracy	1.5 mm	3	80	Build plate temperature

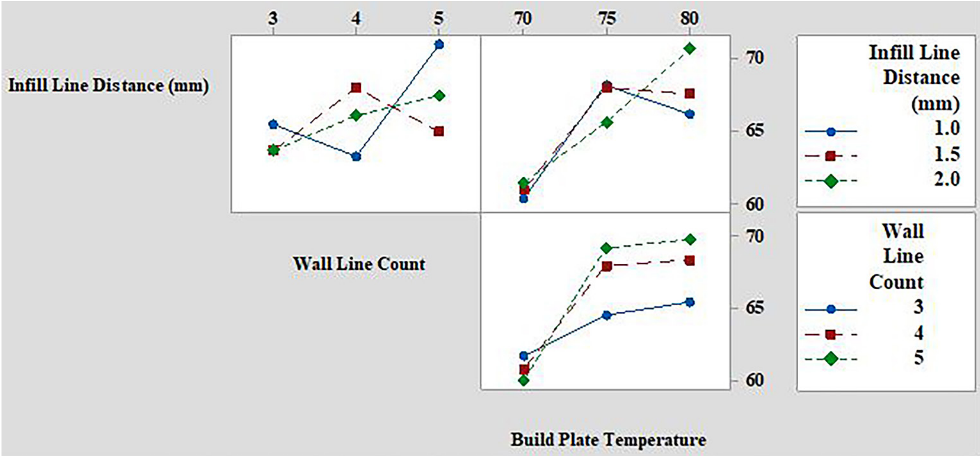

Figure 10. Flexural strength's interaction plot

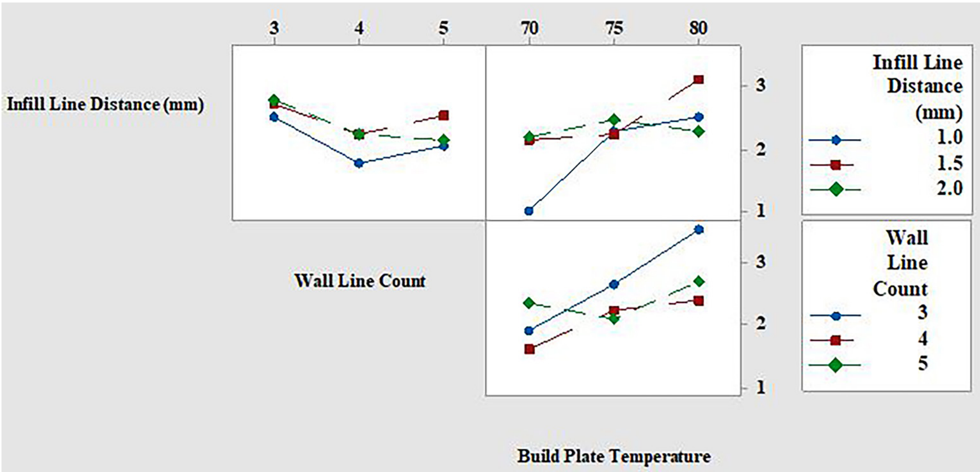

Figure 11. Deviation in dimensional accuracy's interaction plot

deviation on the dimensional accuracy of the parts manufactured is obtained by using an infill line distance of 1 mm, a wall line count of 4, and printing the parts at a build plate temperature of 70 °C. Based on these results, it can be seen how important it is to incorporate the interaction effects of parameters to achieve the optimal mechanical performance and accuracy of the 3D-printed components.

The interaction between the input parameters and the responses is qualitatively captured by the quadratic mathematical model in Eqs. (6 and 7) for the dependent variables of flexural strength and variation in dimensional accuracy. These equations are as follows: the linear terms, quadratic terms, and interaction terms, such that these terms can capture the total effects of the input parameters on the responses. Within the parameters of this study, these equations will possess an influential tool for prediction as well as optimization by offering a wide range of insight on any parameter and its interactions within the system and how it affects the results.

$$\sigma_f\ (MPa) = -560 - 17.5 \times A - 14.0 \times B + 17.06 \times C - 1.60 \times A^2 - 0.75 \times B^2 - 0.1205 \times C^2 - 0.88 \times A \times B + 0.345 \times A \times C + 0.304 \times B \times C \quad (6)$$

$$Dimensional\ accuray\ deviation\ \% = -34.2 + 14.34 \times A + 1.63 \times B + 0.515 \times C - 1.001 \times A^2 + 0.3734 \times B^2 + 0.00023 \times C^2 - 0.096 \times A \times B - 0.1417 \times A \times C - 0.0622 \times B \times C \quad (7)$$

where: A – represents infill line distance, B – represents wall line count, and C – represents build plate temperature by C.

Table 7 shows the comparison between the experimental finding of (flexural strength and dimensional accuracy deviation) of PETG parts

Table 7. RSM vs. experimental values for flexural strength and deviation in dimensional accuracy %

No.	Flexural strength (MPa)	RSM predicted flexural strength (MPa)	% Error	Deviation in dimensional accuracy %	RSM Predicted deviation in dimensional accuracy %	% Error
1	65.4	64.9	0.8	2.5	2.3	6.4
2	63.7	65.9	3.4	2.8	2.8	0.6
3	71.0	68.8	3.1	2.1	2.1	0.8
4	67.4	68.0	0.8	2.1	2.3	7.5
5	60.3	61.9	2.6	1.0	1.0	2.3
6	61.4	60.2	1.9	2.2	2.1	5.5
7	66.1	67.3	1.7	2.5	2.6	4.8
8	70.7	69.1	2.2	2.3	2.2	1.1
9	61.7	60.7	1.7	1.9	2.1	7.1
10	60.1	60.7	1.0	2.4	2.3	1.7
11	65.4	64.8	0.9	3.5	3.6	1.1
12	69.8	70.9	1.5	2.7	2.6	5.0
13	68.2	68.0	0.3	2.2	2.2	0.0
14	66.4	68.0	2.4	2.1	2.2	5.7
15	69.4	68.0	2.0	2.4	2.2	5.2

with that of the RSM values estimated by the Eq. (8) [27]. From Table 7 and Figures (12 and 13), the percentage error between the experimental and predicted values is as follows: 3.4% for flexural strength and 7.5% for dimension accuracy deviation. These low percentages of error indicate the validity and reliability of the RSM model in forecasting the mechanical characteristics and the accuracy of the produced PETG specimens.

$$Error\ \% = \left|\left(\frac{Measured\ value - Predicted\ value}{Measured\ value}\right)\right| \times 100 \quad (8)$$

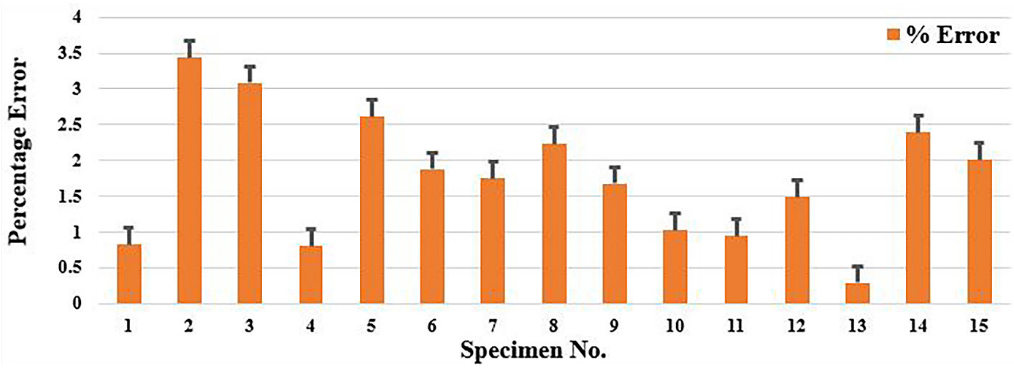

Figure 12. The percentage error between the experimental and predicted strength

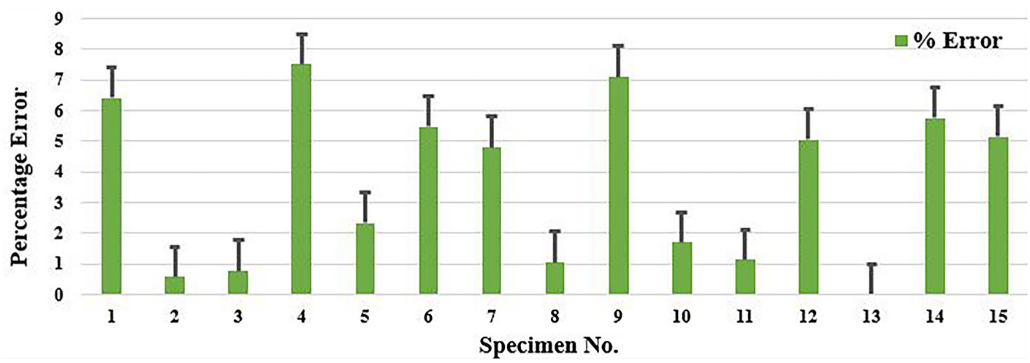

Figure 13. The percentage error between the experimental and predicted dimensional accuracy

Optimized results

In order to maximize strength and minimize dimensional accuracy deviations, the responses were optimized using the response optimizer (desirability analysis) as part of the RSM analyses. Based on the optimization results presented in Figure 14, the response optimization findings yielded a composite desirability value of 0.7589, indicating an acceptable trade-off between the objectives. Using input parameters of 2 mm infill line distance, 4.9394 wall line count, and a build plate temperature of 80 °C, the optimized flexural strength is 70.8502 MPa, with a high desirability value of 0.98952, showing near-perfect optimization for this parameter. In contrast, the optimized dimensional accuracy deviation is 2.0675%, with a desirability value of 0.58204, indicating a slightly lower optimization level. The results indicate that dimensional accuracy improves with decreasing infill line spacing and wall line counts, whereas strength rises with higher wall line counts and build plate temperatures. By balancing these conflicting objectives, the selected parameters promote strength optimization while preserving an acceptable degree of dimensional accuracy.

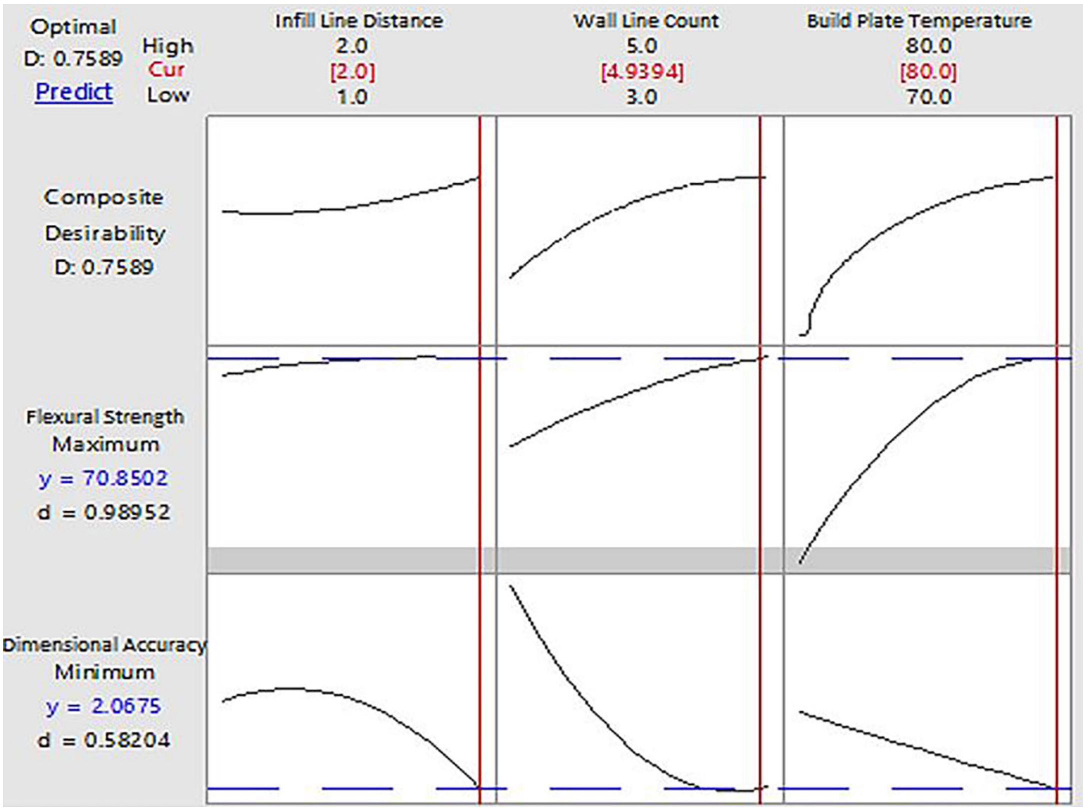

Figure 14. Optimization of flexural strength and dimensional accuracy through desirability analysis

CONCLUSIONS

This study offered a comprehensive investigation of the FDM process parameters for PETG material, focusing on the reduction of dimensional accuracy deviations and improvement of mechanical properties, notably the flexural strength. To achieve this, the response surface methodology (RSM) with a Box–Behnken design was applied to establish the relationship between selected significant parameters, namely infill line distance, wall line count, and build plate temperature, and observed response. The findings offer several key contributions to the field of additive manufacturing:

- The results showed that flexural strength improves as the build plate temperature increases. Conversely, the deviation in dimensional accuracy decreases with a reduction in the build plate temperature.
- The temperature of the build plate is crucial to optimizing both the bending strength and accuracy of dimension in FDM printing. Higher temperatures improve interlayer adhesion, which increases the flexural strength of the

material, whereas lower temperatures give less thermal expansion and reduce the warping for better dimensional control.

- The experimental findings revealed that flexural strength enhanced with increasing build plate temperature and attained the highest flexural strength of 71 MPa at a 1mm infill line distance, 5wall line count, and at 75 °C build plate temperature. To achieve better mechanical properties like flexural strength, a higher build plate temperature reaching 80 °C is recommended to obtain better interlayer adhesion.
- The dimensional accuracy deviation was reduced to 1% with an infill line distance of 1 mm, a wall line count of 4, and a build plate temperature of 75 °C. However, for applications that required high dimensional accuracy, a little reduction in build plate temperature will further reduce the thermal expansion and warping.
- The build plate temperature was identified as the most significant parameter, accounting for 53% of variations in flexural strength and 39.7% of dimensional accuracy deviations, indicating its performance in both mechanical and geometrical optimizations.
- Infill line distance and wall line count were identified as the most important parameters affecting the internal density and the capability to withstand the bending stress, making these attributes crucial to the evaluation of the mechanical strength in relation to preferable dimensional stability.
- A desirability analysis demonstrated that the parameters of 2mm infill line distance, 4.9394 wall lines, and the build plate temperature of 80°C provided the best compromise between flexural strength and dimensional accuracy. This resulted in a flexural strength of 70.85 MPa with a deviation of 2.07% to give an optimal combination of strength for structural as well as precision applications.

This research shows that RSM can be applied to determine the best combination of FDM processing parameters for PETG when it comes to producing components with enhanced mechanical and dimensional properties. Further studies could follow the present work by introducing other factors into the investigation, like the print speed and nozzle temperature, besides the geometry of the parts and the types of the composite materials used. These efforts could also enhance the flexibility and robustness of the FDM process, expanding the scope of its usage across various fields such as aerospace, automobiles, and bioengineering.

REFERENCES

1. Mueller B. Additive manufacturing technologies–Rapid prototyping to direct digital manufacturing. Assembly Automation 2012; 6; 32(2).
2. Mansor KK, Shabeeb AH, Hussein EA, Abbas TF, Bedan AS. a statistical investigation and prediction of the effect of FDM variables on flexural stress of PLA prints. Tikrit Journal of Engineering Sciences 2024; 31(3): 10–17. https://doi.org/10.25130/tjes.31.3.2.
3. García E, Núñez PJ, Caminero MA, Chacón JM, Kamarthi S. Effects of carbon fibre reinforcement on the geometric properties of PETG-based filament using FFF additive manufacturing. Composites Part B: Engineering 2022; 15(235): 109766. https://doi.org/10.1016/j.compositesb.2022.109766
4. Shiaa WQ, Abdulghafour AB, Hassoon OH. 3D reconstruction from CT images utilizing the open-source tool. AIP Conference Proceedings. 2024; 3079(1). AIP Publishing. https://doi.org/10.1063/5.0202322
5. Obaeed NH, Hamdan WK. Reconstruction and evaluation of 3D printing PMMA cranioplasty implants. International Journal on Interactive Design and Manufacturing (IJIDeM) 2024; 18(6): 4233—45. https://doi.org/10.1007/s12008-024-01979-9
6. Hamzah AH, Paijan LH, Bakar MH, Mamat MF, Maidin NA, Musa SI. effect of wall line count on the mechanical properties of FDM 3D-printed PLA parts. Malaysian Journal of Microscopy. 2024; 20(2): 34–44.
7. Mishra P, Sood S, Bharadwaj V, Aggarwal A, Khanna P. Parametric modeling and optimization of dimensional error and surface roughness of fused deposition modeling printed polyethylene terephthalate glycol parts. Polymers 2023; 15(3): 546. https://doi.org/10.3390/polym15030546
8. Maurya NK, Maurya M, Dwivedi SP, Srivastava AK, Saxena A, Chahuan S, Tiwari A, Mishra A. Investigation of effect of process variable on dimensional accuracy of FDM component using response surface methodology. World Journal of Engineering 2021; 18(5): 710–9. https://doi.org/10.1108/WJE-08-2020-0347.
9. Hsueh MH, Lai CJ, Wang SH, Zeng YS, Hsieh CH, Pan CY, Huang WC. Effect of printing parameters on the thermal and mechanical properties of 3d-printed pla and petg, using fused deposition modeling. Polymers 27; 13(11): 1758. https://doi.org/10.3390/polym13111758

10. Agarwal KM, Shubham P, Bhatia D, Sharma P, Vaid H, Vajpeyi R. Analyzing the impact of print parameters on dimensional variation of ABS specimens printed using fused deposition modelling (FDM). Sensors International 2022; 3: 100149. https://doi.org/10.1016/j.sintl.2021.100149
11. Chicos LA, Pop MA, Zaharia SM, Lancea C, Buican GR, Pascariu IS, Stamate VM. Infill density influence on mechanical and thermal properties of short carbon fiber-reinforced polyamide composites manufactured by FFF process. Materials; 22; 15(10): 3706. https://doi.org/10.3390/ma15103706
12. Alexopoulou VE, Christodoulou IT, Markopoulos AP. Effect of printing speed and layer height on geometrical accuracy of FDM-printed resolution holes of PETG artifacts. Engineering Proceedings. 2022; 24(1): 11. https://doi.org/10.3390/IECMA2022-12887
13. Darsin M, Amir RL, Sutjahjono H, Ramadhan M, Hermawan Y, Choiron M. The Effect of nozzle temperature, layer height, and infill pattern on dimensional accuracy and flexural strength of 3D printed Cu-PLA filaments. Advanced Engineering Science 2022; 54(03).
14. Obaeed NH, and Hamdan WH. Optimizing fused deposition modelling process parameters for medical grade polymethylmethacrylate flexural strength. Advances in Science and Technology 2024; 18(1). https://doi.org/10.12913/22998624/182876
15. Sukindar NA, Yasir AS, Azhar MD, Azhar MA, Abd Halim NF, Sulaiman MH, Sabli AS, Ariffin MK. Evaluation of the surface roughness and dimensional accuracy of low-cost 3D-printed parts made of PLA–aluminum. Heliyon 2024; 29; 10(4). https://doi.org/10.1016/j.heliyon.2024.e25508
16. Gohar S, Hussain G, Ali A, Ahmad H. Mechanical performance of honeycomb sandwich structures built by FDM printing technique. Journal of Thermoplastic Composite Materials. 2023; 36(1): 182–200. https://doi.org/10.1177/0892705721997892
17. Frunzaverde D, Cojocaru V, Bacescu N, Ciubotariu CR, Miclosina CO, Turiac RR, Marginean G. The influence of the layer height and the filament color on the dimensional accuracy and the tensile strength of FDM-printed PLA specimens. Polymers 2023; 15(10): 2377. https://doi.org/10.3390/polym15102377
18. Mushtaq RT, Wang Y, Khan AM, Rehman M, Li X, Sharma S. A post-processing laser polishing method to improve process performance of 3D printed new Industrial Nylon-6 polymer. Journal of Manufacturing Processes 2023; 101: 546–560. https://doi.org/10.1016/j.jmapro.2023.06.019
19. Raj T, Tiwary A, Jain A, Sharma GS, Vuppuluri PP, Sahai A, Sharma RS. Machine learning-assisted prediction modeling for anisotropic flexural strength variations in fused filament fabrication of graphene reinforced poly-lactic acid composites. Progress in Additive Manufacturing 2024, 26:1–5 https://doi.org/10.1007/s40964-024-00768-w
20. Algarni M, Ghazali S. Comparative study of the sensitivity of PLA, ABS, PEEK, and PETG's mechanical properties to FDM printing process parameters. Crystals 2021; 11(8): 995.
21. Montgomery DC. Design and analysis of experiments. 9th ed. Hoboken, NJ: Wiley; 2017.
22. Myers RH, Montgomery DC, Anderson-Cook CM. Response surface methodology: Process and product optimization using designed experiments. 4th ed. Hoboken, NJ: Wiley; 2016.
23. Vălean C, Marșavina L, Mihai M, et al. Effect of manufacturing parameters on tensile properties of FDM printed specimens. Procedia Struct Integr. 2020; 313–320. https://doi.org/10.1016/j.prostr.2020.06.040
24. Abeykoon C, Sri-Amphorn P, Fernando A. Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures. Int J Light Mater Manuf. 2020; 3: 284–97. https://doi.org/10.1016/j.ijlmm.2020.03.003
25. Abdulridha HH, Abbas TF. Analysis and investigation of the effect of the printing parameters on the mechanical and physical properties of PLA parts fabricated via FDM printing. Adv Sci Technol Res J. 2023; 17(6): 49–62. https://doi.org/10.12913/22998624/173562
26. Beharry N, Chowdary B. Investigating the effects of process parameters on the flexural strength of 3D printed plastics. J Manuf Process. 2020; 58: 564–572. https://doi.org/10.47412/FBTO9600
27. Abdulridha HH, Abbas TF, Bedan AS. Predicting mechanical strength and optimized parameters in FDM-printed polylactic acid parts via artificial neural networks and desirability analysis. Manag Syst Prod Eng. 2024; 32(3): 428–437. https://doi.org/10.2478/mspe-2024-0040