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Optimizing the Hardness of 3D Printed Novel PETg-PLA Based Polymer Blend using RSM

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Abstract: 3D printing is the prevalent technique applicable for prototyping and end-use products. In this study, a filament of polymer blend of glycol-modified polyethylene terephthalate (PETg) and polylactic acid (PLA) is manufactured with the injection moulding process, and printed using the Fused Deposition Modelling (FDM) technique. To enhance wear resistance and structural integrity and to provide durability, hardness is essential. The hardness of the polymer blend was assessed by designing the trials based on Response Surface Methodology (RSM). Thickness of the layer, infill density, and type of patterns were selected as the machine variables. The hardness for the present trial range lied between 73 and 91 HRR. All the selected variables were crucial for hardness as suggested by variance analysis (probability value < 0.0001). The investigation found that the layer thickness must be kept minimum so as to achieve better bonding between the layers, leading to better hardness. Moreover, higher infill density provides a greater solid fraction and leads to printing a stronger part. Similarly, Cubic pattern provides a more rigid structure and thus was found to be the hardest among the selected patterns. The forecasted R^2 of 0.9065 complies with the adjusted R^2 of 0.9737. Furthermore, the model validation performed depicted a residual error of 1.11% that illustrates that the model is significant.

Keywords: Polymer Blend, Hardness, RSM, 3D Printing

1. Introduction

3D Printing is a modern technique of manufacturing the contour by adding material layer over the other. The prepared 3D model is divided into n layers according to the specified dimensions, and the selected material is deposited layer by layer to achieve the anticipated dimensions. In polymer printing, technology is advancing day by day. Among the numerous 3D printing methods, Fused Deposition Modelling (FDM) is widely used as it is simple, cheap, and quick customization through the computer designed model. However, the hardness and strength of 3D-printed product rely upon the material composition and machine variables such as layer thickness, infill density, orientation, and pattern type. Many materials like PETg (Polyethylene Terephthalate Glycol), PLA (Polylactic Acid), ABS, and ASA are used alone or in combination to explore the applicability to various fields. PETg and PLA are the two most commonly utilized thermoplastic polymers in FDM printing. PLA is stiff, biodegradable, and offers dimensional accuracy, whereas PETg enhances ductility, impact strength, and thermal stability. Blending these two materials may yield a material with balanced mechanical properties for functional applications, leading to both rigidity and durability.

In a study, equal parts of PLA and PETg, i.e., 50% PLA and 50% PETg, were selected to prepare the composite [1]. They selected speed of print, nozzle, and bed temperature as machine variables. It was suggested that the composite possesses better mechanical and thermal properties. Another study selected 20% Ramie Fibre and 80% PLA as the composite composition [2]. They found that the composite, when printed at elevated nozzle temperature, low thickness of deposition, and speed, exhibits better mechanical performance. Moreover, an investigation has used a commercially fabricated wood (30%) and PLA (70%) composite [3]. They suggested decreasing the thickness of deposition to improve the mechanical performance. An increase in deposition thickness increases the porosity, which reduces part strength. In another study, a composite of Bamboo (20%) and PLA (80%) was investigated [4]. Furthermore, investigations have also used a composite of wood (30%) along with PLA (70%) for assessing the mechanical characteristics of the composite [5]. A composite of PETg and PLA was developed, and it was revealed that PLA exhibits higher tensile strength and modulus in some orientations, while PETg shows greater toughness [6]. Mechanical response is highly orientation/process dependent. Another research used PLA/PETg (80:20) blend and found that compatibilization (PLA-g-MA) reduces dispersed phase size and improves the mechanical properties [7].

An investigation on a tri-layered composite of PLA, PETG, and ABS in equal parts was carried out using the Taguchi technique and ANOVA [8]. They found that mechanical properties depend strongly on stacking order and process parameters; equal-layer composites show trade-offs between stiffness and toughness. Another study was conducted on PLA/PETG blends with a compatibilizer, and the common test blends include 80/20 and 70/30 (PLA: PETG) [9]. They used the compatibilization as 3 wt% PLA-g-MA and found that it significantly reduced the dispersed phase size, improved storage modulus, and mechanical properties vs non-compatibilized blends. An experimental investigation carried out on pure PLA, CF-reinforced PLA, and PLA/PETg polymer revealed that PLA exhibits ultimate strength in disparity to other polymers [10]. Among the reinforced polymers, carbon fibre with PLA had better tensile properties. Moreover, the polymer of PETg-PLA was found to be the hardest with a Rockwell hardness of 93 on the R-scale. An assessment conducted for evaluating the influence of print speed, thickness of deposit, and density of infill for mechanical performance using the BPNN analysis and ANOVA found that the print speed is a significant variable for the mechanical performance, especially hardness. The optimum value of performance measure was achieved by setting the speed at 40 mm/s [11]. Infill density was the only significant variable, and the best hardness is achieved at 100% density.

In another study carried out to assess the hardness of ABS evaluated the influence of orientation, thickness of deposit, temperature of nozzle, and the density of infill. Hardness was found to follow an increasing trend initially, but tends to decrease with further increase in orientation, infill density, and thickening of layer. The temperature of the nozzle directly governs the hardness [12]. Moreover, researchers investigated the influence of deposition thickness and the density of infill on hardness of PLA using the Taguchi technique [13]. They kept the range of layer thickness between 0.15 and 0.35 mm while density was kept between 55 and 65%. They concluded that hardness initially increases with layer thickness and then it is reduced with thicker layers. Hardness was found to follow an increasing trend with the infill density. Furthermore, another study assessed the influence of layer thickness on the hardness of PLA. They found that the hardness reduces with thicker layers [14].

A study evaluated the influence of the infill pattern on the mechanical characteristics of PLA using the Taguchi technique. It was found that the stiffness is enhanced by using a triangular pattern, while better dimensional accuracy is achieved by using hexagonal patterns [15]. In another investigation, carried out to assess the infleunce of pattern type on the strength of ABS, PLA, and PETg, it was found that better results are attained with cubic patterns. The maximum strength is recorded for PETg [16]. The mechanical characteristics of 3D-Printed PLA, PETg and ABS were found to exhibit better results with hexagonal patterns [17]. A PLA-PHA blend was analyzed using TOPSIS and GA-ANN optimization [18]. Layer height significantly governs the mechanical performance of the polymer blend. TOPSIS suggested a medium level of machine variables for optimizing the performance.

Another researcher studied the mechanical performance of recycled PETg using RSM technique [19]. The data was analyzed, and the report suggested that infill density enhances the strength of the printed parts. The type of pattern also influences the mechanical performance. PLA and wood composites have also been studied for their performance and analyzed using RSM and ANN [20]. ANN exhibits enhanced performance and its combination with RSM provides a comprehensive framework to derive the relation between machine variables and composite performance. RSM with GRA and Grey Wolf Optimization was used to analyze the strength of PA 12-CF [21]. The fill angle, layer thickness, and speed of print were the variables chosen for assessment. GWO showcased better performance in enhancing the mechanical performance by optimizing machine variables. The tensile performance of PLA was assessed in research using Taguchi-based ANFIS analysis [22]. The research reported an improvement in the performance of printed material.

From the previous literature, it is found that random trials were conducted on various polymers and composites to assess the performance of the materials and the influence of machine variables. Earlier studies mainly focused on a single polymer. The researchers have only interpreted the outcome, and no physical explanation of the results was provided. The prime aim of this research is to prepare a PETg-PLA polymer blend filament and optimize its hardness. Based on the literature review, machine variables such as the thickness of layer, density of infill, and the pattern type will be analyzed to determine their individual and combined influence on the hardness of the polymer blend. The optimized variable combination is expected to improve the hardness and surface integrity of the PETg-PLA polymer blend part, contributing to the development of a high-performance, sustainable material for additive manufacturing applications.

2. Materials and Methodology

The composition ratio of the composite was selected based on literature reviews [1, 3, 6-9, 18]. A PLA-rich polymer blend composition was selected for the present study with 30 wt% PETg and 70 wt% PLA. It was chosen to preserve the stiffness, hardness, and dimensional stability of PLA and the ductility of PETg. Prior PLA/PETg blends have been shown to rely strongly on composition and have been adopted to balance rigidity and toughness [7, 9]. Moreover, PLA and PETg display noticeably different mechanical responses in 3D Printing [6]. PETg is tougher and more ductile compared to PLA. Increasing PETg reduces brittleness but generally lowers the overall hardness since PETg is softer and more impact-resistant. Balanced PETg can enhance ductility while retaining moderate hardness. On the other hand, PLA is stiffer and more brittle with a higher inherent hardness compared to PETg. With an increase in PLA composition, it will raise the hardness but reduce toughness and impact resistance. Figure 1 depicts the flowchart for the present trial's workflow.

Figure 2 illustrates the moulded 1.75 mm diameter polymer blend of PETg- and PLA prepared using injection moulding. At a time, two lengths of polymer blend filament of 6-inch length are moulded. The injection moulding technique was used in order to ensure even mixing, melting, and maintaining homogeneity of the polymers. This will reduce the variability in composition and ensure steady properties. Melt compounding was used to prepare the polymer blend.

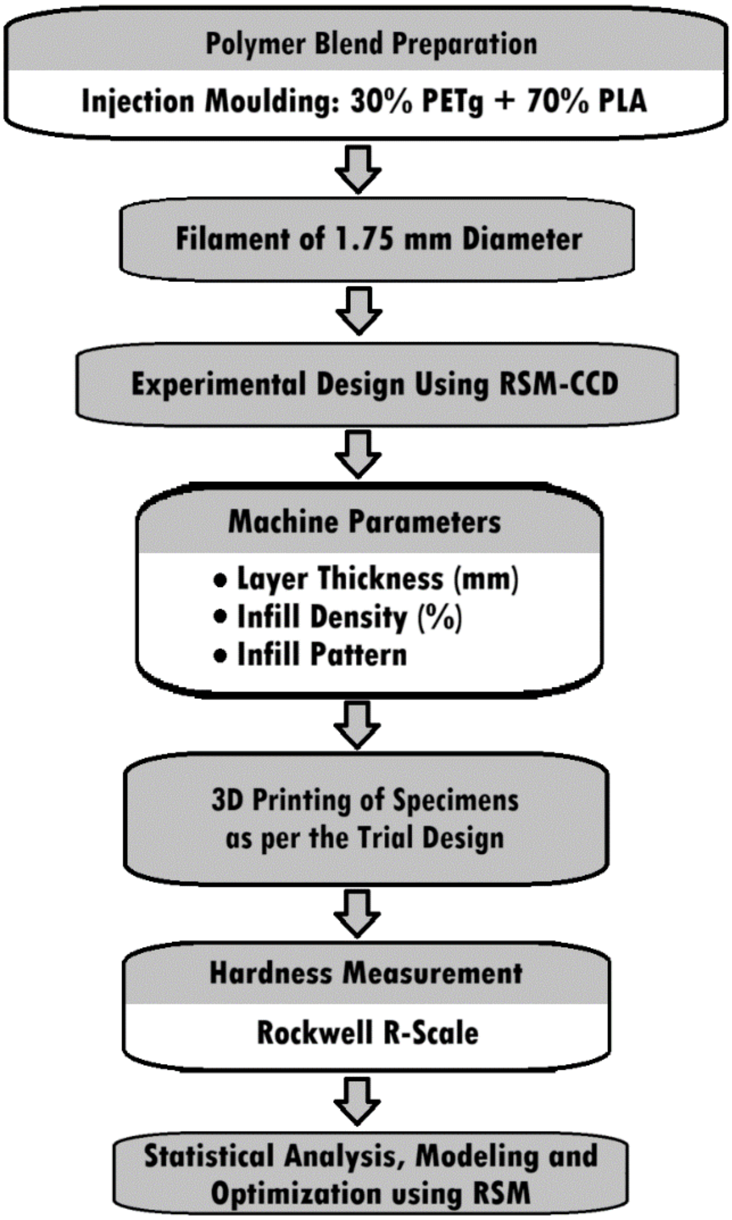

Figure 1. Flowchart for the workflow of the present trials

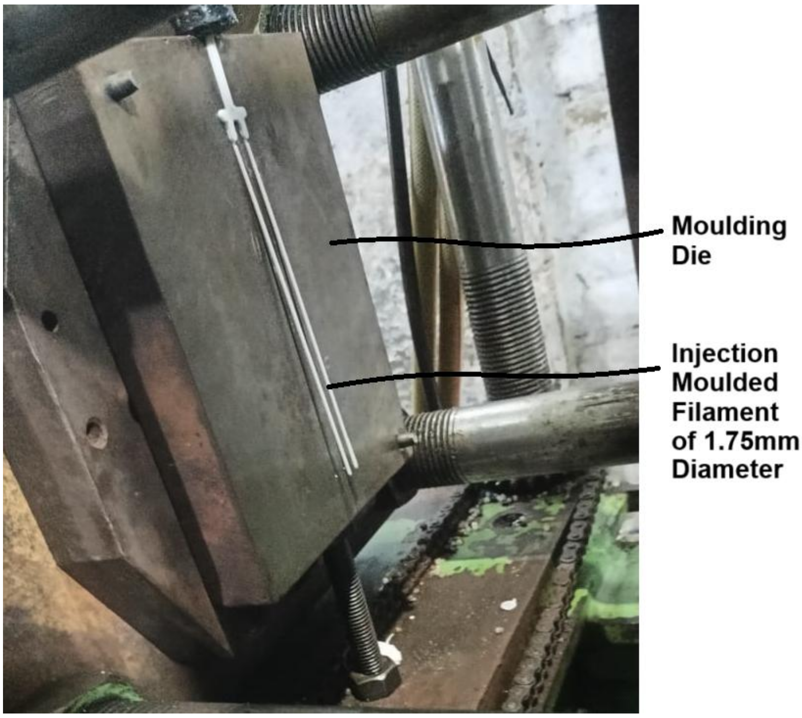

Figure 2. Moulded 1.75 mm diameter and 6-inches long polymer blend filament

Table 1. Range of 3D Printing Variables

Variable	Unit	Extent 1	Extent 2	Extent 3
Density of Infill	%	40	60	80
Thickness of Layer	mm	0.12	0.2	0.28
Pattern Type	type	Grid	Triangle	Cubic

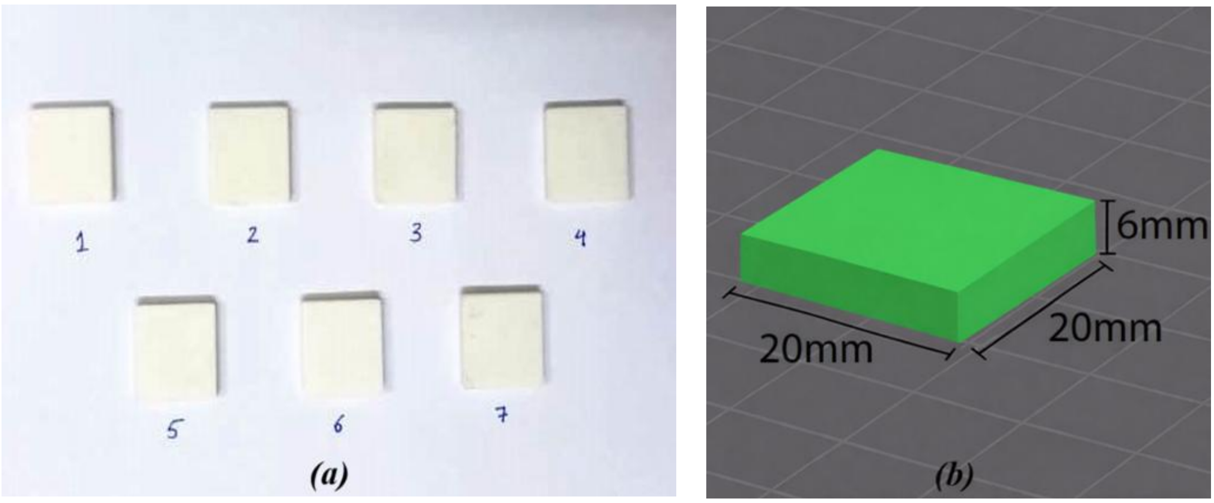

Figure 3 (a). 3D printed samples of Polymer Blend, **(b)** Hardness Sample Design as per ASTM D 785

The experimental trials were prepared as per the Response Surface Methodology. Twenty sets of experiments were designed, depending on which specimens would be printed. The RSM is an efficient statistical tool that enables modelling and optimizing multiple variables with minimum trial effort. RSM facilitates understanding the interaction between the machine variables and helps to develop a predictive mathematical model. CCD was chosen because it is suitable for developing second-order models with estimation for both linear and quadratic effects, including axial points, which permits effective curvature detection. The statistical technique and model progress were conducted on Design Expert software. The adequacy and significance of the model are evaluated using variance analysis. To validate the model, statistical indicators were adapted. The range of the variables was chosen on the basis of past literature and initial trials. The thickness of layer, density of infill, and type of pattern were the chosen machine variables for the study while the nozzle temperature was constant (235˚C) for all the specimens. Table 1 shows the range of 3D Printing parameters selected for our study.

The 3D printed samples of the polymer blend are illustrated in Figure 3 (a). The samples for hardness testing were designed based on ASTM D 785 as represented in Figure 3 (b). All the specimens were tested for hardness on the Rockwell Hardness tester on the R-scale. A 12.7 mm diameter hardened ball indenter was employed with a minor load of 10-kgf and a major load of 60-kgf. The dwell time of the major load was 15 sec before assessing the indentation depth.

3. Results and Discussion

A set of twenty trials were performed based on RSM, and the hardness of all the samples on the R-scale is represented in Table 2 below. Upon testing, it was found that the hardness of the developed polymer blend with a combination of different 3D printing variables ranged between 73 and 91. The obtained ultimate hardness was found to be higher than the previously reported investigation on different polymer blends [10, 23, 24]. In prior studies, mainly pure polymer was studied, and that too with a single or two machine variables [23, 24]. This reduces the reliability of the study. Furthermore, studies on PLA/PETg composites were conducted with a low number of trials, which makes them less consistent [10]. By increasing the range of trials and with the three most influential variables, this assessment will be significant for industrial applications.

The trial data obtained for the hardness of samples prepared with PETg-PLA polymer blend were analyzed using Response Surface Methodology. The Sequential Model sum of square and fit assessments were undergone for assessing the appropriate model for describing the relations between the machine variables and hardness. Initially, the lack of fit test in Table 3 indicates the significance of the linear model as the probability value is less than 0.0001, whereas the two-factor interaction (2FI) is insignificant. However, model having a probability value of 0.0062, signifies the presence of curvature in the response. Further, the SMSS test in Table 4 confirms adequate fit of trials data with the quadratic model. Furthermore, the adjusted R^2 of 0.9737 and a forecast R^2 of 0.9065 imply excellent agreement between the trial and forecast values and confirm the model's reliability.

Table 2. Hardness of 3D Printed Samples

Exp No.	Thickness of Layer (mm)	Density of Infill (%)	Infill Pattern	Rockwell Hardness (R-Scale)
1	0.12	40	Grid	78
2	0.28	40	Grid	73
3	0.12	80	Grid	81
4	0.28	80	Grid	77
5	0.12	40	Cubic	88
6	0.28	40	Cubic	85
7	0.12	80	Cubic	91
8	0.28	80	Cubic	87
9	0.12	60	Triangle	83
10	0.28	60	Triangle	78
11	0.2	40	Triangle	80
12	0.2	80	Triangle	85
13	0.2	60	Grid	75
14	0.2	60	Cubic	86
15	0.2	60	Triangle	81
16	0.2	60	Triangle	82
17	0.2	60	Triangle	81
18	0.2	60	Triangle	81
19	0.2	60	Triangle	81
20	0.2	60	Triangle	82

Table 3. Lack of Fit Test for Hardness Analysis

Model Term	Consecutive p-value	Lack of Fit p-value	Adjusted R^2	Forecast R^2	
Linear	< 0.0001	0.0346	0.9430	0.9183	
2FI	0.8549	0.0214	0.9338	0.7664	
Quadratic	**0.0062**	**0.1368**	**0.9737**	**0.9065**	**Suggested**
Cubic	0.3046	0.0862	0.9783	-3.0109	**Aliased**

Table 4. SMSS Assessment for Hardness Analysis

Model Term	Sum of Squares	DOF	Mean Square	F-value	p-value	
Mean vs Total	1.337E+05	1	1.337E+05			
Linear vs Mean	353.90	3	117.97	105.74	< 0.0001	
2FI vs Linear	1.0000	3	0.3333	0.2572	0.8549	
Quadratic vs 2FI	**11.70**	**3**	**3.90**	**7.58**	**0.0062**	**Suggested**
Cubic vs Quadratic	2.60	4	0.6500	1.53	0.3046	Aliased
Residual	2.55	6	0.4242			
Total	1.340E+05	20	6701.65			

Table 5. Variance Analysis for Hardness

Model Term	Sum of Sq.	DOF	Mean Sq.	F-value	prob-value	
Model	366.60	9	40.73	79.16	< 0.0001	Recommended
Layer Thickness (A)	44.10	1	44.10	85.71	< 0.0001	
Infill Density (B)	28.90	1	28.90	56.17	< 0.0001	
Infill Pattern (C)	280.90	1	280.90	545.92	< 0.0001	
A-B	0.0000	1	0.0000	0.0000	1.0000	
A-C	0.5000	1	0.5000	0.9717	0.3475	
B-C	0.5000	1	0.5000	0.9717	0.3475	
A^2	0.1420	1	0.1420	0.2761	0.6107	
B^2	8.64	1	8.64	16.80	0.0022	
C^2	0.1420	1	0.1420	0.2761	0.6107	
Residual	5.15	10	0.5145			
Lack of Fit	3.81	5	0.7624	2.86	0.1368	not recommended
Pure Error	1.33	5	0.2667			
Cor Total	371.75	19				

The analysis of variance results of the model shown in Table 5 revealed that it is noteworthy as depicted through the F-value of 79.16 and probability value of <0.0001. This also depicts the significant influence of the deposition thickness, density of infill, and pattern on the polymer hardness. Among the selected parameters, infill pattern has major dominance over the hardness, followed by the density of infill and deposition thickness. The mechanical performance is crucially influenced by the internal structure pattern and the print variables. All the interaction terms were found to be insignificant, and the combined effect of the two variables does not affect the hardness. Among the quadratic terms, only the infill density square term had a significant role, indicating its non-linear effect on hardness. The other square terms of layer thickness and infill pattern weren't significant.

A low residual error, having a sum of squares of 5.15, shows the precision of the trials. An insignificant lack of fit illustrates adequately fitting the trail data of the model. The obtained quadratic model efficiently depicts the relation between the machine variables and the hardness of the PETg-PLA polymer blend. The variation in the hardness of samples can be attributed to the impact of printing variables on interlayer bonding and material density.

Table 6. Fit Data for Hardness

Standard Deviation	0.7173	**R^2**	0.9862
Mean	81.75	**Adj. R^2**	0.9737
Coeff. of Var. %	0.8775	**Forecasted R^2**	0.9065
		Adequate Precision	35.8818

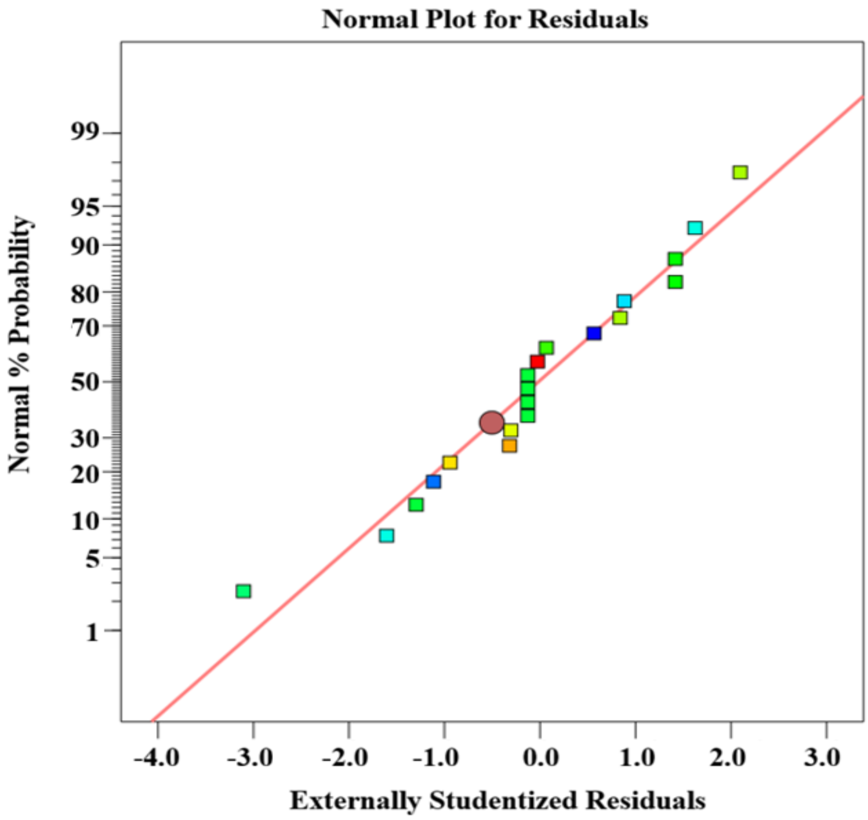

Figure 4. Normal Plot for Hardness of Polymer Blend

An increase in deposition thickness tends to reduce number of deposited layers per unit height, which leads to low interlayer adhesion and microstructural uniformity, which reduces the hardness. Conversely, thin layer improves bonding and surface finish, leading to better hardness. The number of deposited layers increases with thin-layer deposition that promotes more frequent interlayer interfaces with enhanced consolidation. The interfacial bonding and molecular diffusion across the adjacent layers increase with the thin layer. A thinner layer will also lower the risk of internal voids and reduce the porosity that will result in better hardness.

The infill density has a significant influence on the hardness of the material. When the percentage of infill is increased from 40% to 80%, the quantity of filament lines deposited per layer increases, thus enhancing the load-bearing capacity and reducing the internal voids. Therefore, the resistance to indentation is improved, and better hardness is achieved. However, due to the quadratic effect of infill density, beyond an optimal level, the attained hardness becomes marginal because of material shrinkage and thermal stresses. The infill pattern exhibits the most dominant effect, and the cubic or triangular pattern provides better load distribution and strength as compared to the grid pattern. The geometric preparation of the deposited filament plays an important part in enhancing the stiffness and providing resistance to deformation.

Table 6 represents the fit statistics for the present model, and here the forecasted R^2 of 0.9065 complies with the adjusted R^2 of 0.9737. A ratio of 35.8818 of the adequate precision is adequate. Thus, through this table, it is found that the present model is adequate and can assess the trial design. Following the fit summary, the below mentioned eq. 1 represents the equation which is in terms of actual variables utilized to predict the hardness for the provided extent of every variable. The extent of each variable is stated in actual units and the coefficients are scaled in order to accommodate units of every variable and the intercept is not centred with the design space.

$$\boldsymbol{Hardness} = 95.775 - 12.045 \times A - 0.447 \times B + 5.425 \times C + 2.342E - 15 \times A \times B + 3.125 \times A \times C - 0.013 \times B \times C - 35.511 \times A^2 + 0.004 \times B^2 - 0.227 \times C^2 \ldots \ldots . Eq. 1$$

Where A is Layer Thickness, B is Infill Density and C is Infill Pattern.

Figure 4 depicts the normal plot of residuals for hardness, where the superficially studentized residuals are plotted contrary to the anticipated normal probability. The majority of data points lie near the diagonal reference line, which indicates the normal distribution of the residuals. This also confirms that the errors in the model are random and not systematically biased. No significant deviation is observed, which suggests that the developed model effectively represents the trial data without any transformation. Only a few deviations are observed at the extremes, but they also fall within the acceptable range and do not represent abnormality. Therefore, the normality assumption for variance analysis is satisfied and authenticates the suitability of the response model in forecasting the hardness of 3D Printed PETg-PLA polymer blend.

Figure 5 represents the Box-Cox graph for hardness, which is utilized to analyze appropriate power transformation for parameters to stabilize variance and improve the regularity of residuals in the regression model. The plot shows that, for hardness, the value of lambda is one, and the confidence interval for lambda includes this value. As this lambda value corresponds to untransformed data, no transformation is required. Therefore, the developed model for hardness prediction is statistically adequate in its original form, and the trial data are stable. The present quadratic model also effectively describes the relation between the machine variables and the assessed hardness of the polymer blend.

Figure 6 illustrates the predicted versus actual plot, which illustrates the correlation between trial hardness of the polymer blend and the predicted hardness developed by the RSM model. All the data points lie near the diagonal, which elucidates that the predicted values perfectly match the trial values. Hence, the accuracy and predictive reliability of the developed quadratic model for hardness are confirmed. The residuals are minimal due to the absence of major deviations from the diagonal line. This further supports the model adequacy and validates that the selected machine factors are properly modelled to predict the hardness of the polymer blend of PETg-PLA.

Further, Figure 7 (a) represents the contour plot for the combined effect of the deposition thickness and the infill density on the hardness of the polymer blend. It is observed that the hardness increases with higher infill density and thinner layers.

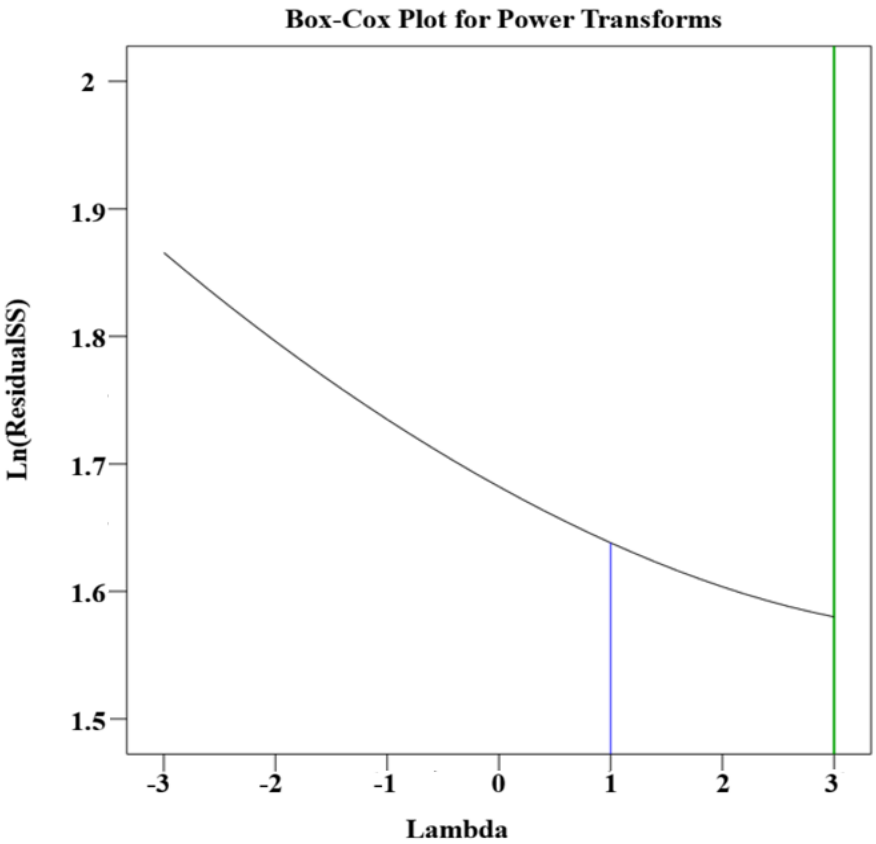

Figure 5. Box-Cox Plot for Hardness

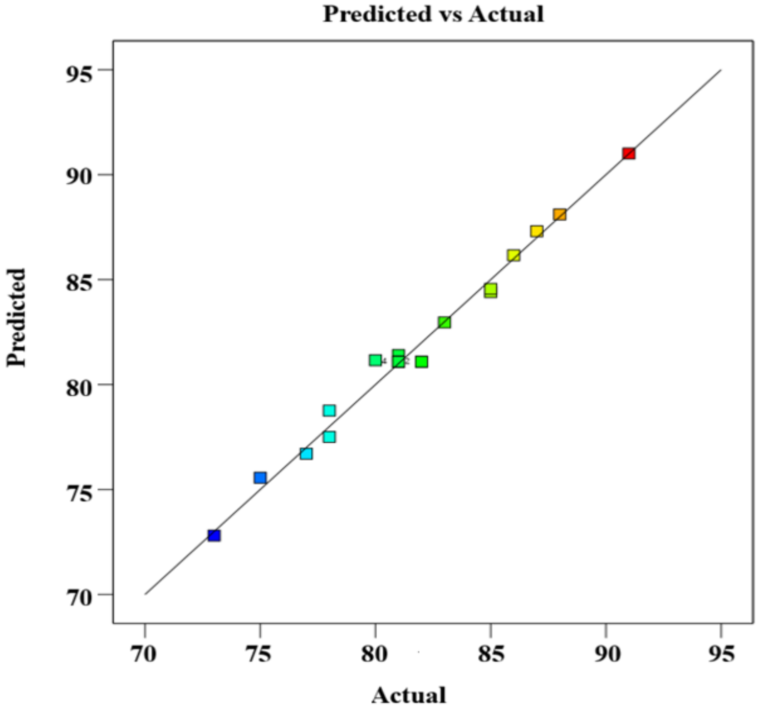

Figure 6. Predicted vs Actual Plot for Hardness

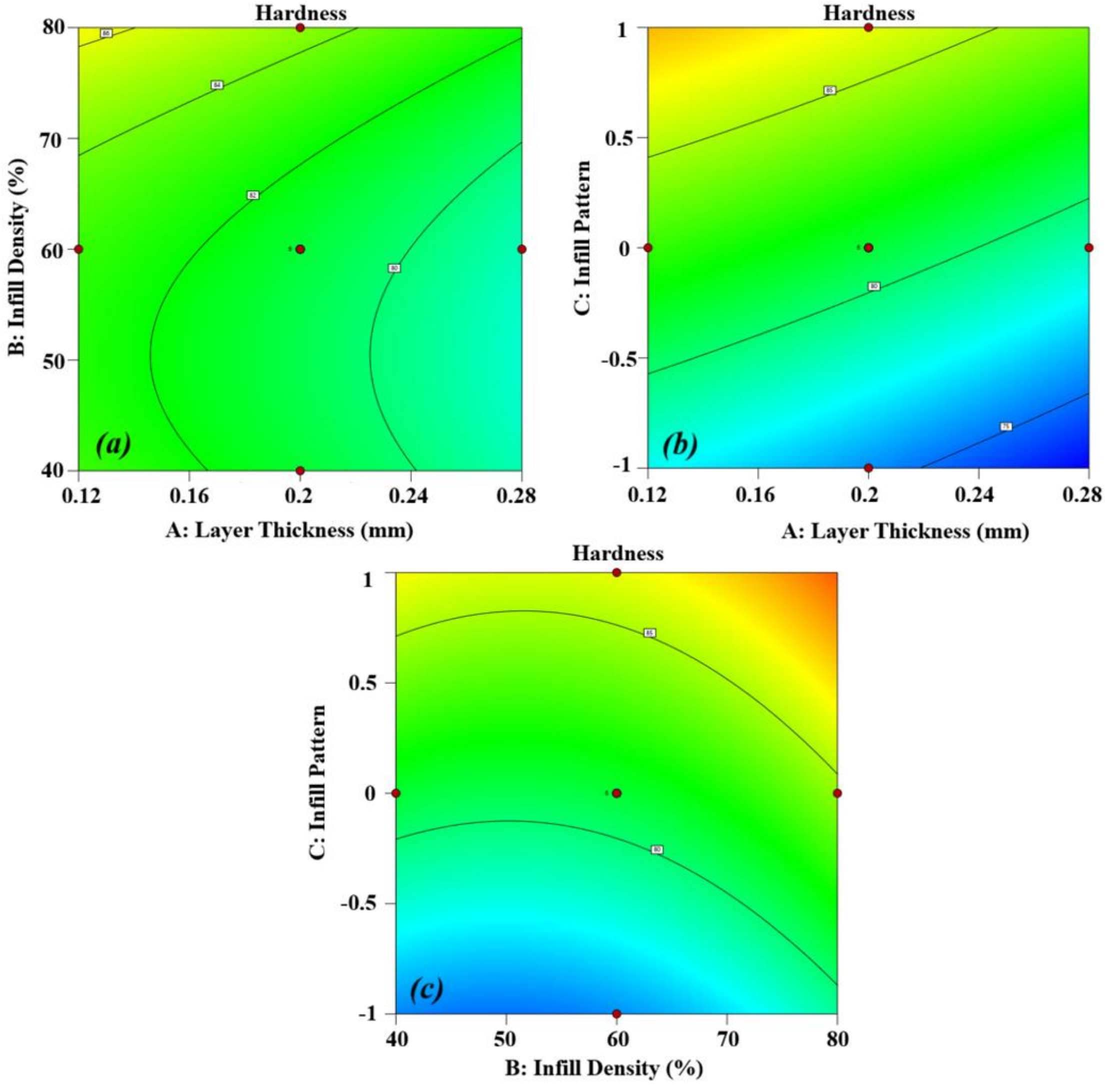

Figure 7. Contour Plot for Hardness with (a) Thickness of Layer and Density of Infill, (b) Thickness of Layer and Pattern type, and (c) Infill Density and Pattern

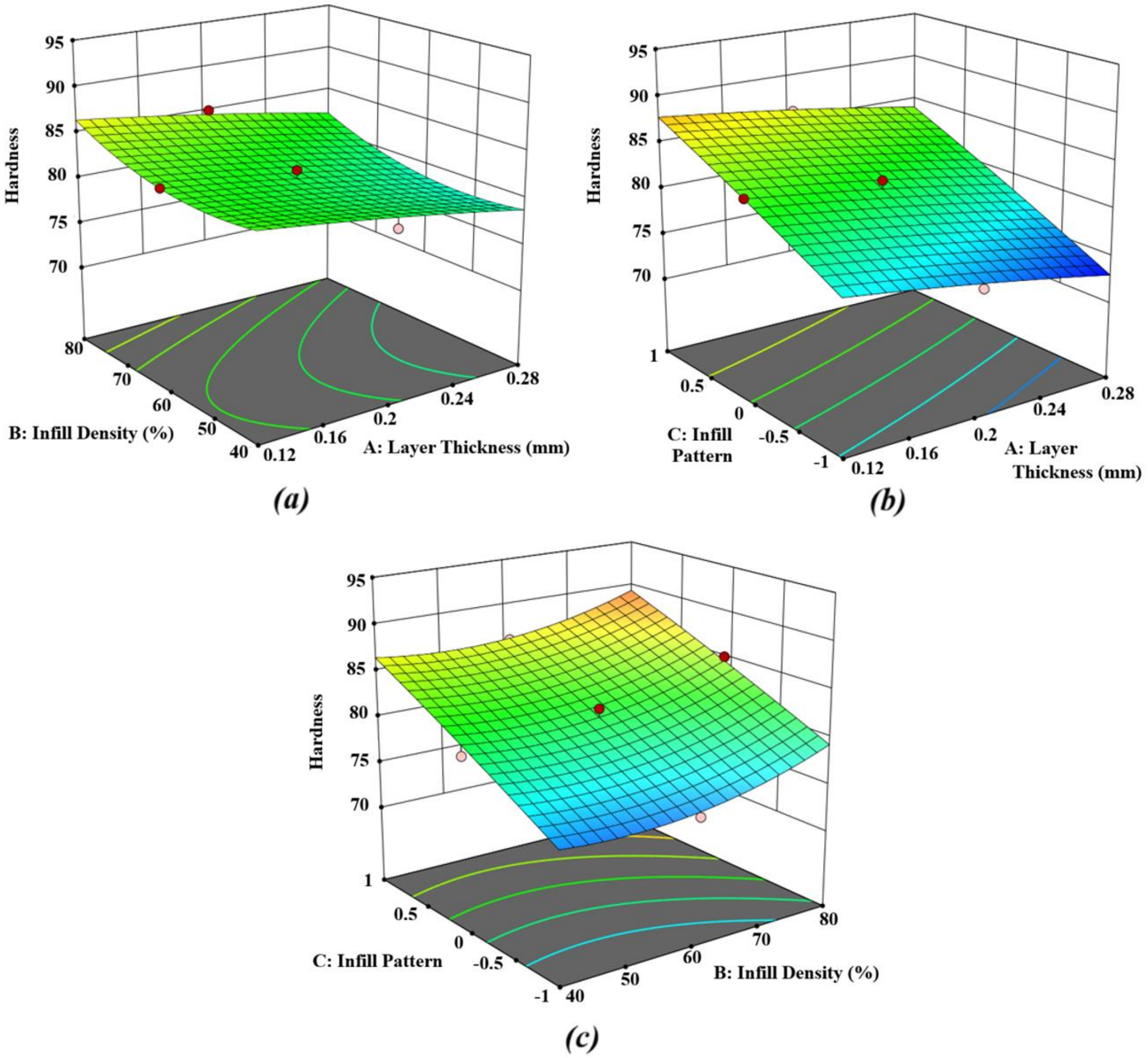

Figure 8. Response Surface Plot for hardness of PETg-PLA polymer blend with (a) Thickness of Layer and Infill Density, (b) Thickness of Layer and Pattern type, and (c) Infill Density and Pattern

With a thinner layer and higher infill density, higher hardness is observed. As the deposition thickness is set to 0.28 mm, a gradual decrease in hardness is observed, even when the infill density is high. Similarly, with lower infill density, the hardness remains relatively low across the thickness of the layer. The density of infill has a more positive impact than layer thickness. Higher infill density reduces internal voids, whereas higher layer thickness weakens interlayer bonding. The contour plot for hardness with infill pattern and layer thickness is depicted in Figure 7 (b). The plot clearly indicates that the hardness increases with the use of a cubic infill pattern. The highest hardness of the polymer blend is observed with lower thickness and a cubic pattern. The cubic pattern provides better load distribution as compared to the triangular and grid patterns. Moreover, Figure 7 (c) shows the contour plot for hardness with infill density and infill pattern. It is observed that both these variables have a noteworthy influence on the hardness of the PETg-PLA polymer blend, and a higher density with a cubic pattern must be used for better hardness.

The 3D surface plot for the hardness of PETg-PLA polymer blend to analyze the combined influence of thickness of layer, density of infill, and the pattern type is depicted in Figure 8. From Figures 8(a) and 8(b), it is elucidated that as the deposition thickness increases, the hardness decreases. Thinner layers allow better inter-layer bonding and more uniform fusion, thus enhancing the surface integrity and the hardness of the polymer blend. On the other hand, a thicker layer led to increased voids and weaker bonding, thus reducing the hardness. Figure 8(a) and 8(c) illustrate that the hardness of the polymer blend increases with higher infill density. The more material deposition, the lower the internal porosity and the denser the printed part. This will result in higher hardness values. The curved response surface confirms the non-linear influence of infill density.

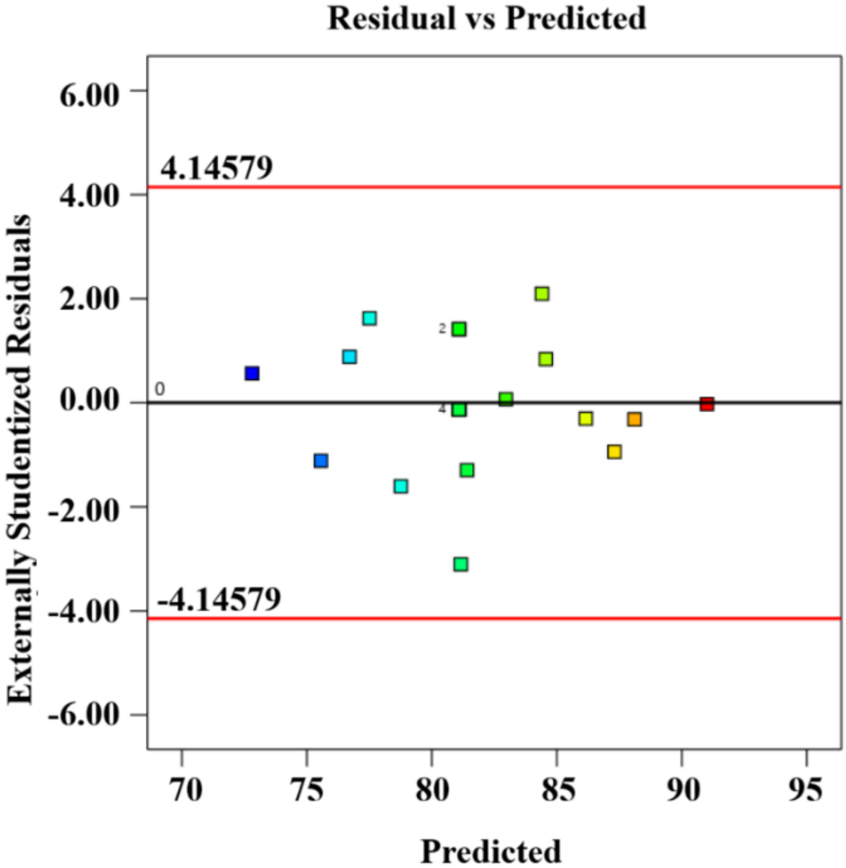

Figure 9. Residual vs predicted plot for Hardness

Table 7. Validation of the Quadratic Model for Hardness of PET-PLA Polymer Blend Filament

S.No.	3D Printing Variables	Hardness (R-Scale)		Residual Error
		Predicted Value	Observed Value	
1	Thickness of layer: 0.2 mm Density of infill: 60% Pattern type: Triangle	81.0909	82	1.11%

Figure 8(b) shows the nearly planar response surface, which confirms that the two factors influence hardness mainly in a linear manner, consistent with the variance analysis results depicting negligible interaction effects. The cubic infill pattern results in better hardness as compared to the grid and triangular patterns because of its superior 3D load-supporting geometry.

The residual vs predicted plot depicted in Figure 9 shows the externally studentized residual distribution, which is random around the zero line without any noticeable pattern. All the residuals lie in the acceptable range (± 4.14579), which indicates the absence of outliers and confirms the model adequacy. This demonstrates that the RSM model is reliable in predicting the hardness of 3D printed polymer blends.

4. Validation of the Model

The authentication of the model was performed through the point-forecast technique of RSM as depicted in Table 7. It is accomplished to validate the data of the model and to forecast whether it is accurate in predicting the hardness within the range of studied variables. The forecasted value of the hardness is compared with the observed value. The predicted value was 81.09 on the R-scale, while the observed value was 82 on the R-scale. The residual error of 1.11% indicates the close agreement between the trial values and the model. A very small deviation demonstrates the high predictivity and reliability of the developed model. Thus, the model can be considered valid and accurate and is suitable for predicting the hardness of the polymer blend within the range of studied variables.

5. Conclusion

The present study optimized the hardness of a 70 wt% PLA/30 wt% PETG filament fabricated via injection moulding and processed by FDM using response surface methodology. Twenty experimental runs were designed by RSM by varying layer thickness, infill density, and infill pattern. The measured Rockwell hardness ranged from 73 to 91 HRR, confirming a strong dependence on printing parameters. ANOVA showed that the quadratic model was statistically significant ($F = 79.16$, $p < 0.0001$), with a significant curvature effect indicated by the lack-of-fit result. Among the selected variables, infill pattern exerted the strongest influence on hardness, followed by infill density and layer thickness. A lower layer thickness improved interlayer adhesion and microstructural uniformity, resulting in higher hardness, whereas thicker layers reduced bonding quality and hardness. Increasing infill density from 40% to 80% enhanced hardness by increasing the number of deposited roads, improving load-bearing capacity, and reducing internal voids. Infill pattern also played a decisive role; cubic and triangular architectures provided better stress distribution and deformation resistance than the grid pattern, with the cubic pattern yielding the highest hardness. The best hardness response was obtained at lower layer thickness, higher infill density, and cubic infill geometry. Model validation showed a prediction error of only 1.11%, demonstrating excellent agreement between experimental and predicted values and confirming the reliability of the developed RSM model. This work establishes a practical framework for hardness optimization of PLA/PETG blend filaments, while future studies may extend the approach to other blend ratios and additional process variables such as nozzle temperature, bed temperature, raster angle, and printing speed.

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Authors Contribution Statement

Basant Lal: Conceptualization, Methodology, Writing – Original Draft. Mohd. Reyaz Ur Rahim: Data Curation, Formal Analysis. Prem Kumar Bharti: Validation, Writing review and editing. Syed Asghar Husain Rizvi: Formal analysis, resources, Supervision. All the authors read and approved the final version of the manuscript.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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