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Experimental Analysis of Color Influence on Optimized FDM Parameters for PLA using the Taguchi Method

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ABSTRACT

This study examines the influence of filament color on optimizing FDM process parameters for PLA parts using the Taguchi method. Parameters such as layer thickness, print speed, and printing temperature were varied to identify optimal settings for white and black PLA filaments. The results demonstrate that the optimal parameters vary based on color: for white PLA, the best configuration involves a layer thickness of 0.35 mm, print speed of 50 mm/s, and a printing temperature of 210°C. For black PLA, the same layer thickness and print speed are optimal, but the printing temperature is lower at 200°C. Layer thickness was identified as the most significant factor affecting tensile strength across both filament types. However, the ideal printing temperature depended on the color of the filament. Notably, white PLA exhibited higher tensile strength than black PLA, with an increase ranging from 1.33% to 15.54%, attributed to the thermal properties of color pigments. These findings highlight the critical role of filament color in determining mechanical performance during FDM printing. Incorporating filament color into the optimization of FDM parameters can enhance the quality, strength, and reliability of 3D-printed components. This research provides valuable insights for improving additive manufacturing outcomes across a range of applications.

Keywords: FDM; PLA; Taguchi method; tensile strength; process optimization; material color

INTRODUCTION

Fused Deposition Modelling (FDM) technology is highly valued for its capability to produce both prototypes and functional parts. Achieving optimal outcomes requires the systematic adjustment of process parameters, such as layer thickness, print speed, and printing temperature. These parameters are key in determining the quality and durability of the final products, making their optimization vital across many industries. An often ignored factor is the impact of pigments in PLA materials, which can significantly alter the mechanical properties of the printed components. Understanding how color pigments affect the characteristics of PLA parts can enable more precise adjustments to the printing process, particularly when working with a diverse range of colors. The color of PLA filament can influence not only the structural integrity but also the surface quality and specific functionality of printed parts.

This study focuses on examining the influence of filament color, specifically white versus black, on the optimization of FDM printing parameters. To systematically explore this correlation, the Taguchi method is employed to optimize key parameters for white and black PLA components. The Taguchi method provides a structured approach to identifying and understanding the interactions between different configurations and their impact on the quality of fabricated parts. In this research, particular emphasis is placed on tensile strength, as it serves as a key indicator of the mechanical performance of the components. By conducting a systematic analysis of white and black

PLA parts, this study aims to determine the optimal settings for each color and uncover the underlying effects of color pigments on FDM outcomes. The goal is to demonstrate how filament color can influence the quality and performance of parts produced using FDM.

FDM is a commonly employed additive manufacturing technique known for its cost-effectiveness and flexibility in both prototyping and producing functional parts. By extruding thermoplastic materials layer by layer, FDM permits industries such as automotive, aerospace, and healthcare to efficiently produce components. Current studies highlight several aspects of FDM, including the thermal properties of different polymeric materials (Shanmugam et al. 2024) and the production of antibacterial PLA parts for medical applications (Nyabadza et al. 2024). Main process parameters like layer thickness, print speed, and printing temperature directly influence the quality and mechanical properties of printed parts. Research proves that optimizing these settings can improve characteristics such as compression resistance and tensile strength in PLA components (Passari et al. 2024; Wei et al. 2024). Innovations such as an alternate layer printing technique to reduce porosity (Naresh et al. 2024) and improvements in build orientation affecting flexural and tribological properties (Yaman et al. 2024) further contribute to improvements in FDM.

The focus on new materials and post-processing techniques, including PLA/Cu composites (Hamoud et al. 2024) and acetone vapor treatment for ABS prints (Demircali et al. 2024), shows the ongoing progress of FDM. Moreover, hardware innovations like multi-material printing and enhanced temperature control expand the technology's capabilities (Zisopol et al. 2024). Polylactic Acid (PLA) stands out as a favored thermoplastic in FDM, appreciated for its biodegradability, affordability, and user-friendliness, which makes it fit for various applications. Its mechanical strength and thermal stability, especially in composite forms, further increase its adaptability (Ulkir, 2024). However, PLA's temperature sensitivity can affect print quality, leading to issues like warping if parameters are not cautiously managed (Erdaş et al. 2024). Studies emphasize the importance of optimizing parameters such as nozzle diameter and speed to improve strength and decrease build time. Latest advancements in optimizing print settings include the application of Taguchi Grey Relational Analysis (Patela et al. 2024) and investigations into PLA degradation's effects on mechanical behavior (Hedayati et al. 2024), pushing the boundaries of PLA's competencies in numerous fields, including medical devices where antibacterial properties are crucial (Nyabadza et al. 2024).

The effect of color pigmentation in PLA filaments on their properties during FDM printing is important. Pigments can modify thermal conductivity and heat absorption, affecting the filament's behavior during extrusion. Studies have shown that darker colors usually require different extrusion temperatures and can improve part finishing due to better heat absorption (Soares et al. 2018; Hanon et al. 2021). Mechanical properties, particularly tensile strength, are also impacted by color, with evidence demonstrating that black PLA may exhibit superior strength compared to lighter colors due to pigment additives that improve layer adhesion (Wittbrodt & Pearce, 2015; Frunzaverde et al. 2023). Research has discovered that darker filaments achieve better in terms of surface quality and dimensional stability (Valerga et al. 2017; Frunzaverde et al. 2022). PLA has a semi-crystalline structure and is a glossy, rigid, and colorless polymer with some, though limited, light transmission. Additives (pigments) are added to the material to color PLA, and they can change its various properties, mainly rheological (Rueda et al. 2017). Experimental studies were carried out on 13 types of PLA filaments obtained from a single manufacturer to determine how differences in pigment type affect the material properties of the products (Pandzic et al. 2014). The study found that color has a significant impact on the elastic modulus, yield strength, tensile strength, and toughness. Despite these findings, a gap exists in the literature regarding the optimization of 3D printing parameters based on filament color, as most studies focus on mechanical comparisons without addressing necessary alterations in process parameters.

Optimizing process parameters in FDM is essential for achieving high-quality prints, particularly for intricate shapes and critical components. Key parameters such as layer thickness, print speed, extrusion temperature, and cooling rate have a direct influence on the mechanical properties and surface finish of printed parts. Research highlights that optimizing these factors significantly improves print quality and consistency (Dey & Yodo, 2019). Approaches to parameter optimization comprise trial and error, statistical methods like the Taguchi approach, and simulation-based techniques. The Taguchi method is particularly accepted for its structured approach to improving material properties such as tensile strength and flexural resistance (Patel et al. 2012). Recent studies have compared the Taguchi method with other techniques, confirming its effectiveness in enhancing mechanical strength in FDM prints (Gao et al. 2022).

The Taguchi method is a robust statistical tool commonly used for optimizing FDM process parameters. By methodically varying key parameters to measure their impact on quality metrics, the method minimizes inconsistency and identifies optimal conditions with fewer experiments than traditional methods. Numerous studies have successfully applied the Taguchi method to enhance print quality and mechanical properties, showing its versatility and effectiveness in improving the characteristics of FDM components (Srivastava & Rathee, 2018; Hikmat et al. 2021).

However, there remains a gap in the literature regarding the specific effects of filament color on optimization results. Most studies have focused on enhancing mechanical properties without examining how color differences, particularly between common colors like white and black, influence these results. Future research should explore the implications of color on mechanical strength, thermal behavior, and surface quality, as well as how optimization techniques may need to be adapted for different filament colors to enhance part performance across various industrial applications.

This research is particularly substantial as it addresses the gap in understanding how filament color impacts FDM optimization. By applying the Taguchi method to explore color-specific parameter adjustments, the study aims to enhance the quality and reliability of colored PLA components. The findings could provide manufacturers with more accurate control over production processes, eventually leading to higher consistency and durability in colored 3D-printed parts used in various applications across automotive, aerospace, and consumer goods industries.

METHODOLOGY

TAGUCHI METHOD

The Taguchi method was formulated by Dr. Genichi Taguchi, a Japanese researcher (Pal et al. 2009). The technique aims to assist manufacturers in improving product quality while minimizing manufacturing costs. It is a technique that utilizes orthogonal arrays to systematically organize and analyze the impact of parameters on a process. By utilizing these arrays, industries are able to effectively determine the impact of different control factors on the outcome and subsequently optimize their process

SIGNAL-TO-NOISE RATIO

The experimental results are converted into a signal-to-noise (S/N) ratio, referred to as the objective function, which is logarithmic with respect to the desired output. The S/N ratio facilitates data analysis and aids in predicting the optimal outcome. Taguchi suggests utilizing a S/N ratio to assess the quality characteristic in relation to its desired value. The S/N ratio is determined for each combination of process parameter levels using S/N analysis. The analysis of S/N ratio typically involves categorizing quality characteristics into three types: smaller-the-better, larger-the-better, and nominal-the-better. This experimental design prioritizes the quality characteristic that improves as it becomes larger.

For larger the better:

$$\frac{S}{N} = -10log\left(\frac{1}{n}\sum_{i=0}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

where; MSD = mean square deviation, y = observations, n=no. of tests in a trial. Taguchi established a standardized methodology for optimizing process parameters. The steps are outlined in Figure 1.

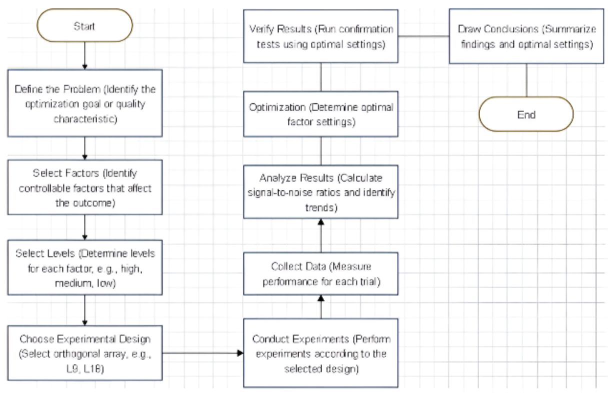

FIGURE 1. Taguchi steps

MATERIAL, PARAMETERS AND ORTHOGONAL ARRAY

This study employed white and black PLA filaments with a density of 1.25 g/cm³ and a diameter of 1.75 mm. The filaments were provided by Creality authorized reseller and are of the same quality, but vary in color. The Taguchi method, a reliable statistical technique, was employed to optimize the parameters of the FDM process. Minimizing variation enhances the quality and simplifies the experimental procedures.

In order to conduct a thorough investigation and determine the most effective combination of process parameters, three key control parameters were identified: layer thickness, print speed, and temperature. Each factor was evaluated at three distinct levels. The layer thickness was assessed at 0.15 mm, 0.25 mm, and 0.35 mm. The print speed was examined at 50 mm/s, 60 mm/s, and 70 mm/s while the printing temperature was examined at 190°C, 200°C, and 210°C. The experiments were conducted systematically using an L9 orthogonal array , which included three factors at three levels. This resulted in a total of nine experimental runs. This cost-effective design reduced the number of experiments and material consumption while still yielding satisfactory data for determining the most favorable parameter configurations. Table 1 displays the configuration of the L9 orthogonal array.

TABLE 1. L9 Orthogonal array design

Run	Input factors		
	Layer thickness (mm)	Print speed (mm/s)	Printing temperature (°C)
1	0.15	50	190
2	0.15	60	200
3	0.15	70	210
4	0.25	50	200
5	0.25	60	210
6	0.25	70	190
7	0.35	50	210
8	0.35	60	190
9	0.35	70	200

SPECIMEN FABRICATION

The test specimens were produced using a conventional desktop FDM printer, as depicted in Figure 2. The device employed was a Creality CR-5 Pro H 3D Printer with printing size 300 x 225 x 380 mm, renowned for its reliability and precision. Before conducting the experiments, the printer's printer bed was levelled and its nozzle was cleaned to prevent contamination. By keeping certain parameters constant throughout all experiments, only the effects of the control parameters were observed. Specifically, the bed temperature was adjusted to 60°C to promote strong bonding of the initial layer, while the infill density was set to 100% to achieve optimal density and uniform internal structure in the printed objects.

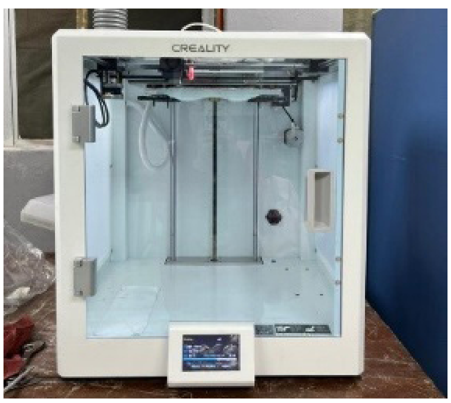

FIGURE 2. Creality CR-5 Pro H 3D printer

Nine distinct combinations of control parameters were employed to produce the tensile test specimens, which were specifically designed according to the standards outlined in ASTM D638 Type I as in Figure 3. Tensile tests were performed to determine the mechanical properties of the printed specimens. The tensile test specimens were carefully extracted from the printer bed, as illustrated in. The specimens were subjected to a 24-hour conditioning period at ambient temperature. The procedure guaranteed that all the specimens would be subjected to uniform conditions during testing.

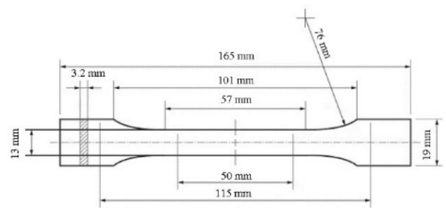

FIGURE 3. ASTM D638 type 1 specimen dimension.

TENSILE TEST AND DATA COLLECTION

The tensile testing was performed using an Instron 8872 universal testing machine with dynamic load capacity 25kN, as depicted in Figure 4, with fixtures that securely held the specimens. The UTM was calibrated to ensure precision in force and displacement measurements. The specimen was subjected to a uniaxial tensile load at a constant strain rate of 4 mm/min until it reached failure. The mechanical properties were measured and recorded, including tensile strength, modulus of elasticity, and elongation at break. Figure 5 depicts a sample of white and black PLA printed specimen.

Analyzed data was used to determine the optimal combination of FDM process parameters for both white and black PLA filaments. A comparative analysis was performed to determine the impact of color on the mechanical properties and to verify if the Taguchi method successfully identifies the optimal combination of parameters in FDM. Table 2 presents a comparison of the tensile strength measurements for white and black PLA components.

CONFIRMATION TEST

The confirmation test is necessary when the experimental run does not include the parameters necessary to attain the maximum tensile strength. In this study, the confirmation test was carried out only for white PLA.

FIGURE 4. Instron 8872 universal tensile testing machine.

FIGURE 5. Sample of white and black PLA printed specimen.

RESULTS

COMPARISON OF WHITE AND BLACK PLA PARTS

Table 2 presents a summary of the tensile strengths and S/N ratios of the white and black PLA samples across nine experiments. The tensile strengths of white PLA range from 21.267 MPa to 33.536 MPa, and the corresponding S/N ratio is between 26.548 dB and 30.512 dB. The tensile strength, measured at 33.536 MPa, exhibited the highest S/N ratio of 30.512 dB, indicating a robust and dependable performance. The mean tensile strength of White PLA is 26.563 MPa, with a standard deviation of 4.275 MPa. The mean S/N ratio is 28.668 dB, with a standard deviation of 1.330 dB.

The tensile strengths of Black PLA range from 19.204 MPa to 32.354 MPa, while the S/N ratios range from 25.666 dB to 30.198 dB. Similarly, the maximum tensile strength, which measures approximately 32.354 MPa, exhibits the highest S/N ratio of 30.198 dB, indicating excellent performance. The mean tensile strength of Black PLA is 25.227 MPa, with a standard deviation of 4.723 MPa. The mean S/N is 27.755 dB, with a standard deviation of 1.550 dB. Therefore, it is anticipated that the White PLA would possess a higher tensile strength compared to the Black PLA, primarily due to the variations in their thermal properties influenced by colorants. Black pigments have a higher heat absorption capacity compared to white pigments. This can result in different cooling rates and thermal stresses during printing, which may ultimately impact interlayer adhesion and overall mechanical properties. The results demonstrate the impact of filament color on the mechanical performance of FDM parts. It is recommended to take color into account when optimizing process parameters for producing high-strength and durable parts.

SIGNAL-TO-NOISE (S/N) RATIO AND MEANS

The Taguchi method employs the S/N ratio as a metric to quantify the impact of various process parameters on performance characteristics. The purpose of this analysis is to determine the optimal levels of the parameters that will minimize variability or noise, while maximizing the desired outcome or signal. The estimation of effects plots for the signal-to-noise ratio, delta, and rank value was performed using Minitab 19 software. Formula (1) was used to calculate the S/N ratio for tensile strength in this research, based on the larger-the-better criterion.

Tables 3 and 4 display the S/N ratio at various levels for the three process parameters: layer thickness, printing speed, and printing temperature. The calculations are based on the larger-the-better criterion, meaning that a higher S/N ratio indicates a better tensile strength. Among the parameters examined, it is evident that the thickness of the layer has had the greatest impact on both the white and black PLA specimens. For example, when using white PLA, the S/N ratio increases from 26.74 at Level 1 to 30.08 at Level 3, with a significant difference of 3.34. Black PLA exhibits a S/N ratio that varies from 26.16 at Level 1 to 29.66 at Level 3, with a substantial delta value of 3.50. This indicates a notable impact on the material's tensile strength. On the other hand, the speed at which the printing is done has a moderate impact. The signal-to-noise ratios for all materials are quite similar, with small differences: 0.52 for white PLA and 0.08 for black PLA. As a result, the effect of this factor on the tensile strength would be less significant. The printing temperature has a negligible impact, as indicated by the very similar S/N ratio levels and the smallest delta values of 0.28 for the white PLA and 0.60 for the black PLA. This suggests that, compared to the other parameters, the printing temperature has a minimal effect. The results clearly demonstrate that the primary determinant of tensile strength in FDM-printed parts is layer thickness, followed by printing speed, and lastly, printing temperature, irrespective of the PLA color.

TABLE 2. Tensile strength comparison between white and black PLA parts

Run	White PLA Tensile strength (MPa)	White PLA S/N ratio (dB)	Black PLA Tensile strength (MPa)	Black PLA S/N ratio (dB)	Percentage Difference of Tensile strength (%)
1	22.371	26.992	20.562	26.257	8.80
2	21.558	26.667	21.275	26.550	1.33
3	21.267	26.548	19.204	25.666	10.74
4	27.307	28.727	26.046	28.314	4.84
5	27.146	28.676	25.483	28.127	6.53
6	25.564	28.156	22.126	26.897	15.54
7	33.536	30.512	32.354	30.198	3.65
8	30.774	29.761	28.930	29.225	6.37
9	31.540	29.973	30.068	29.560	4.90
Mean	26.563	28.668	25.227	27.755	6.97
Standard deviation	4.275	1.330	4.723	1.550	4.23

TABLE 3. Response table for S/N ratio of white PLA.

Level	Layer thickness	Printing speed	Printing temperature
1	26.74	28.74	28.30
2	28.52	28.37	28.46
3	30.08	28.23	28.58
Delta	3.34	0.52	0.28
Rank	1	2	3

TABLE 4. Response table for S/N ration of black PLA

Level	Layer thickness	Printing speed	Printing temperature
1	26.16	28.26	27.46
2	27.78	27.97	28.14
3	29.66	27.38	28.00
Delta	3.50	0.88	0.68
Rank	1	2	3

The mean response table for layer thickness demonstrates that it is the primary factor that significantly impacts the tensile strengths of 3D printed parts as depicted in Table 5 and 6. When the thickness of the layers is increased, the tensile strength of both white and black PLA increases significantly. The tensile strength for white PLA increases from 21.73 to 31.95, while for black PLA it increases from 20.35 to 30.45. The delta values, which indicate the change in tensile strength, are highly positive at 10.22 and 10.1 for white and black PLA, respectively. This demonstrates that increasing the thickness of the layers results in a more robust component. On the other hand, the speed at which the printing is done has a moderate impact.

The tensile strength of white PLA decreases slightly from 27.74 to 26.12, a difference of 1.61, while the tensile strength of black PLA decreases from 26.32 to 23.80, a difference of 2.52. It demonstrates that while printing speed can impact strength, its influence is less significant compared to layer thickness. Among these factors, temperature has the least significant impact. The increase in tensile strength is the smallest, with white PLA increasing from 26.24 to 27.32 and black PLA increasing from 23.87 to 25.68. The smallest differences, or deltas, are 1.08 and 1.92, respectively. In order to optimize tensile strength, it is crucial to consider the layer thickness and strive for the highest quality possible. However, variations in printing speed and temperature may not have a significant impact on the final outcome.

TABLE 5. Response table for means for white PLA

Level	Layer Thickness	Printing Speed	Printing Temperature
1	21.73	27.74	26.24
2	26.67	26.49	26.80
3	31.95	26.12	27.32
Delta	10.22	1.61	1.08
Rank	1	2	3

TABLE 6. Response table for means for black PLA

Level	Layer Thickness	Printing Speed	Printing Temperature
1	20.35	26.32	23.87
2	24.55	25.23	25.80
3	30.45	23.80	25.68
Delta	10.10	2.52	1.92
Rank	1	2	3

CORRELATION ANALYSIS

The correlation analysis was performed using Pearson correlation between printing temperature and the difference tensile strength of black and white PLA. Pearson correlation coefficient r is calculate using the following formula.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (2)$$

x and y are the individual data points for the two variables (temperature and tensile strength difference.
n is the number of data points
r=+1: Perfect positive correlation (temperature increases with tensile strength difference)
r=−1: Perfect negative correlation (temperature decreases with tensile strength difference)
r=0: No correlation (temperature and tensile strength difference are independent).

A Pearson correlation coefficient (r) of -0.334 obtained indicates a moderate negative correlation between temperature and PLA color with respect to tensile strength. This means that as the temperature increases, the tensile strength tends to decrease (or vice versa) when comparing different colors of PLA. The negative sign suggests that this relationship is inversely proportional, implying that temperature and tensile strength are not positively associated when considering PLA color variations.

OPTIMIZATION OF PROCESS PARAMETERS

The study has identified the process parameter levels that would optimize the tensile strength. Regardless of the category of quality features, a higher value of the signal-to-noise ratio (S/N ratio) corresponds to enhanced quality features. According to the main effect plot in Figure 6 and 7, increasing the S/N ratio leads to higher values for tensile. The linear graphs provide information regarding the optimal values and levels of process parameters, which are presented in Table 7. The experimentation demonstrated that the most effective process conditions for producing white PLA were a layer thickness of 0.35 mm, a print speed of 50 mm/s, and a nozzle temperature of 210°C. On the other hand, the most suitable settings for black PLA were as follows: a layer thickness of 0.35 mm, a print speed of 50 mm/s, and an extruder temperature of 200°C. These differences once again emphasize the significance of filament color in the processing conditions to achieve the best possible quality of the part, as indicated in Table 7. The results indicate that there is an interaction between the color of PLA and the printing temperature, which affects the tensile strength. However, this interaction has a relatively small impact on the tensile strength. The confirmation test for white PLA indicates that the tensile strength obtained is 33.585kN, which is greater than the value of 33.536kN obtained in run 7. This confirms that the combination of parameters established for white PLA is accurate.

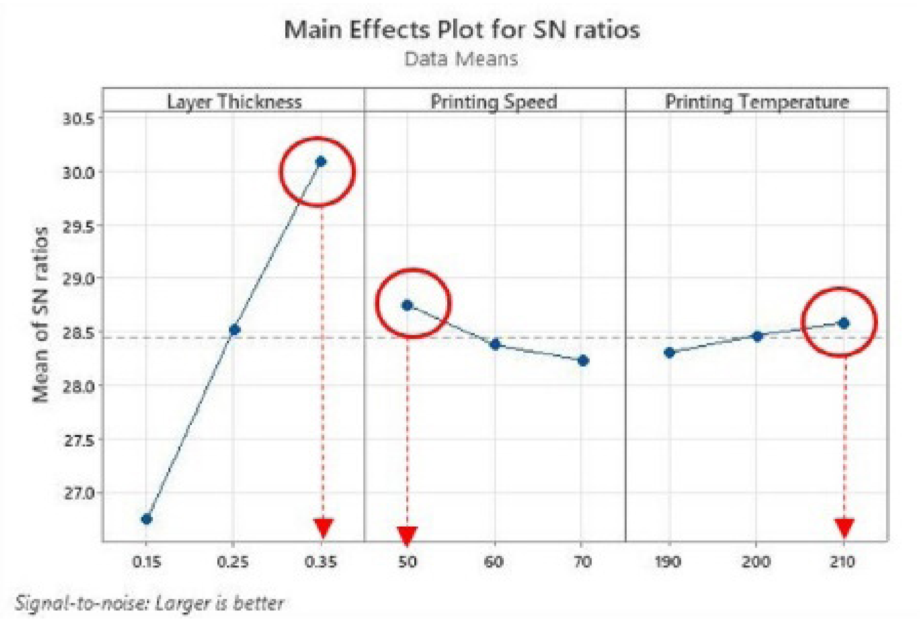

FIGURE 6. Main effect plot for S/N ratio for white PLA.

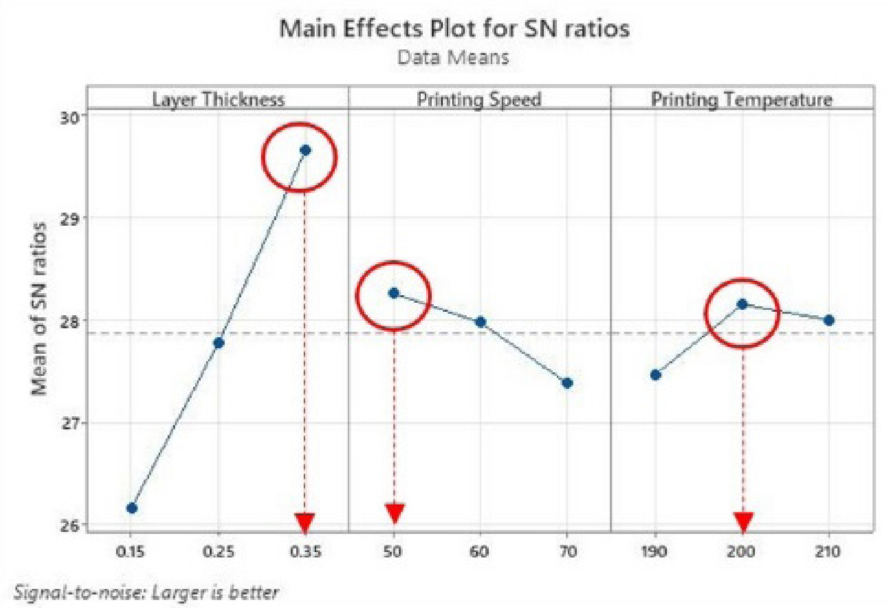

FIGURE 7. Main effect plot for S/N ratio for black PLA.

TABLE 7. Optimized process parameters for white and black PLA parts

Color	Layer thickness (mm)	Print speed (mm/s)	Printing temperature (°C)
White	0.35	50	210
Black	0.35	50	200

The optimized process parameters for white and black PLA parts exhibit distinct variations, primarily in printing temperature, while the layer thickness and print speed remain unchanged. Both of these parameters, the layer thickness of 0.35 mm and the print speed of 50 mm/s, do not significantly affect the optimization for different colors within the tested range. The primary distinction lies in the printing temperature settings required for white and black

PLA. White PLA is optimized for a temperature of 210°C, whereas black PLA is suitable at 200°C. This observation implies that there may be variations in the thermal properties or the presence of different additives among the different colors used in the PLA formulations (Soares et al. 2018). At elevated temperatures, the white PLA exhibits enhanced flowability and layer bonding, leading to a more polished surface finish and improved dimensional accuracy. Conversely, the black PLA's lower temperature setting effectively reduces issues like overheating and stringing, thereby guaranteeing consistent print quality (Hanon et al. 2021). These findings suggest that in order to achieve optimal outcomes in various colors, it is crucial to make color-specific adjustments to the printing temperature. Further research can expand the range of parameters by incorporating additional variables, such as infill density, cooling configurations, and others, in order to investigate their impact on color-specific performance. In addition, it can attempt to retrieve a narrower range for those parameters in order to further refine the process.

CONCLUSIONS

The analysis of the optimized process parameters for white and black PLA parts reveals that, although the layer thickness and print speed remain the same for both colors, there is a significant disparity in nozzle temperature. White PLA can be optimized by using nozzles with higher temperature settings, specifically around 210°C. This helps to enhance the flow of the material and improve the bonding between layers, resulting in a better surface finish and more accurate dimensions. In contrast, black PLA exhibits optimal performance at a slightly reduced temperature of 200°C. This is crucial for preventing overheating and ensuring stable printing. This leads to the conclusion, which emphasizes once again: in order to achieve the optimal printing outcome, the process parameters must be adjusted based on the color of the filament. The study suggests that the uniformity of layer thickness and print speed does not play a crucial role in the optimization of color-specific outcomes. The nozzle temperature is crucial in preventing the thermal behavior of different PLA formulations. Additional factors such as infill density and cooling settings, as well as a wider range of colors and temperatures, should be investigated in future research to further optimize the process. Implementing this will enhance the overall caliber and dependability of PLA parts produced through 3D printing, catering to a diverse array of applications with specific material characteristics.

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DECLARATION OF COMPETING INTEREST

None

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