



Analysis of the Effect of Fused Deposition Modeling Process Parameters on the Tensile Strength of PLA Material

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ABSTRACT

Variations in process parameters in Fused Deposition Modeling (FDM) often lead to differences in the tensile strength of Poly(lactic acid) (PLA) materials. However, results reported in previous studies remain inconsistent and difficult to compare directly. This condition makes it challenging to identify which parameters have a truly significant effect on tensile strength. This study aims to analyze the influence of FDM process parameters on the tensile strength of PLA materials using secondary data consisting of 74 observations, which were organized into a structured dataset and analyzed using descriptive statistics and correlation analysis. The results show that print orientation has the strongest negative correlation, with a value of -0.51 , indicating that an increase in print orientation is associated with a decrease in tensile strength. Layer height also shows a negative correlation of -0.38 , where smaller layer thickness is associated with higher tensile strength. Nozzle temperature exhibits a positive correlation of 0.35 , while print speed does not show a significant effect on ultimate tensile strength (UTS). This approach enables a faster and more systematic identification of the most influential parameters compared to reviewing individual studies separately. Therefore, this study provides a clearer understanding of parameter prioritization in the FDM process, which can support more efficient decision-making to improve the tensile strength of PLA materials.

KEYWORDS *Fused Deposition Modeling, Ultimate Tensile Strength, Process Parameters, Layer Height, Build Angle.*

1. INTRODUCTION

The advancement of additive manufacturing technology, commonly known as three-dimensional (3D) printing, has transformed modern production methods. Among the various available techniques, Fused Deposition Modeling (FDM) has become one of the most widely used due to its ease of operation, relatively low cost, and compatibility with a wide range of thermoplastic materials [1]. The FDM process operates by extruding material layer by layer to form a three-dimensional object based on a digital design. These advantages have encouraged the adoption of FDM across various fields, ranging from prototyping in the automotive and aerospace industries to applications in the medical and educational sectors. Nevertheless, the quality of the final product is highly influenced by the process parameters employed. Therefore, understanding the effects of these parameters is essential to ensure optimal printing quality. Poly(lactic acid) (PLA) is one of the most commonly used bio-based thermoplastic materials in FDM processes. This material is widely favored due to its biodegradable nature, ease of processing at relatively low temperatures, and adequate mechanical properties for various applications. One of the key mechanical properties of PLA is tensile strength,

or Ultimate Tensile Strength (UTS), which represents the material's ability to withstand tensile loading before failure occurs. The UTS value is often used as a benchmark to evaluate the feasibility of FDM-printed components, particularly for applications requiring structural strength. Several studies have reported that the UTS of PLA produced through FDM ranges from 21 to 60 MPa. This variation indicates that printing conditions have a significant impact on the final mechanical performance of the material [2],[3].

The variation in Ultimate Tensile Strength (UTS) values of PLA materials produced through the FDM process is influenced by several printing parameters, such as layer height, nozzle temperature, print speed, and print orientation. Layer height determines the thickness of each printed layer, where excessively large values can reduce interlayer contact, resulting in weaker bonding strength [4]. Nozzle temperature affects the condition of the material during extrusion; inappropriate temperatures may lead to insufficient bonding between layers. Print orientation also plays a crucial role, as it determines the alignment of the material relative to the loading direction. If the orientation is not aligned with the tensile force, the material strength may decrease [5]. Print speed influences the printing outcome, particularly in terms of material deposition and interlayer bonding strength [6]. Variations in these parameter settings lead to differences in tensile strength results, indicating the need for proper parameter optimization to achieve optimal performance. Numerous studies have attempted to identify the most influential FDM process parameters on the tensile strength (UTS) of PLA materials; however, the findings remain inconsistent. Print orientation has been reported to contribute up to 45% to UTS variation [7], while infill density has been identified as having the largest contribution, approximately 39.1% [8]. A negative relationship between layer thickness and UTS has also been observed. Furthermore, a combination of 0.15 mm layer height and 100% infill density has been shown to produce the highest tensile strength. Some studies also indicate that tensile strength is the result of interactions among multiple parameters simultaneously [9]. These varying results suggest that there is still no fully consistent conclusion, and a gap remains in comprehensively understanding the influence of individual parameters.

This study analyzes the relationship between FDM process parameters and the Ultimate Tensile Strength of PLA materials using data collected from multiple studies. The data are organized into a structured dataset and analyzed quantitatively to identify relationships among process parameters and their influence on UTS variation. This approach enables the analysis of parameter interactions within a single integrated framework.

2. METHODOLOGY

This study employs a quantitative approach based on secondary data to analyze the influence of Fused Deposition Modeling (FDM) process parameters on the tensile strength of PLA materials [10]. The research workflow is presented in Figure 1.

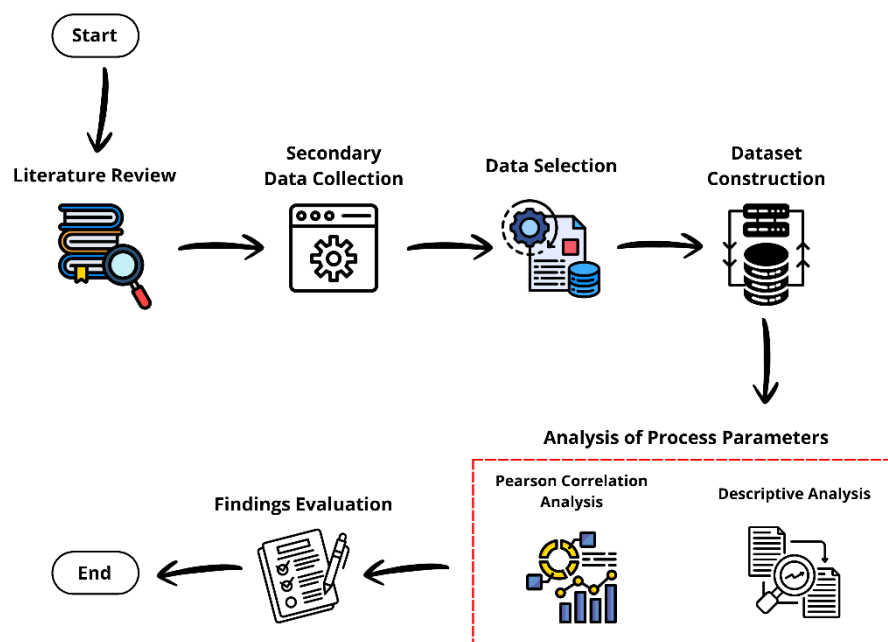


Figure 1. Research Methodology Flowchart

Data were collected through a literature review using scientific databases, specifically Google Scholar and ScienceDirect, covering publications from 2019 to 2026. Subsequently, a secondary data collection process was

conducted by compiling data from 11 relevant previous studies, resulting in a total of 74 data points used for analysis. The collected data include process parameters such as layer height, nozzle temperature, print speed, and print orientation, as well as the tensile strength values (Ultimate Tensile Strength, UTS). During the data selection stage, data were filtered based on inclusion criteria, which required complete primary process parameters, reported UTS values, and testing conducted in accordance with the ASTM D638 standard [11]. An illustration of the specimen is shown in Figure 2.

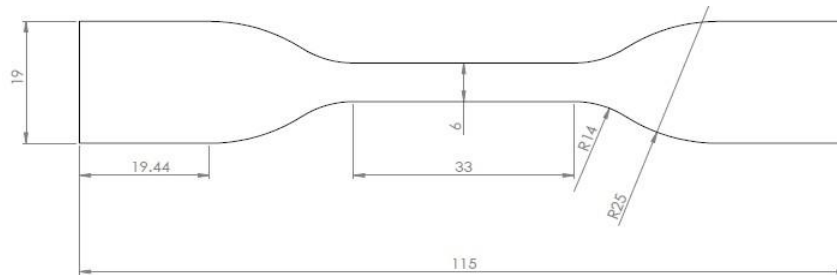


Figure 2. Illustration of ASTM D638 Type IV Tensile Test Specimen [16].

The tensile testing standard used refers to ASTM D638 Type IV, which is commonly applied in evaluating the mechanical properties of polymer materials. Data that met the criteria were then organized into a structured dataset. Exclusion criteria were applied by removing incomplete, inconsistent, or outlier data that fell outside the typical value range. All data were standardized into consistent units to ensure comparability across studies. Other parameters, such as infill density and raster angle, were not included in the analysis due to incomplete availability across all datasets, and therefore were not controlled in this study. Each data point was represented in terms of input and output variables. The input variables consist of layer height (mm), nozzle temperature ($^{\circ}\text{C}$), print speed (mm/s), and print orientation ($^{\circ}$), while the output variable is tensile strength (Ultimate Tensile Strength, UTS) in MPa. The dataset used in this study is presented in Table 1.

Table 1. Research Variables Used in This Study

No.	Parameter	Variable Type
1	Layer Thickness	Input
2	Nozzle Temperature	Input
3	Print Speed	Input
4	Build Angle	Input
5	UTS	Output

This analysis is conducted to understand the distribution and variation of the data before proceeding to further analysis. The second stage involves Pearson correlation analysis to identify the relationship between each process parameter and the tensile strength of PLA materials. This analysis is used to determine both the direction and the strength of the relationship between input and output variables. The correlation coefficient is calculated using Equation 1.

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (1)$$

In this equation, the value of r represents the strength and direction of the relationship between variables. The variable x_i represents the process parameter data, while y_i represents the tensile strength (UTS) values. The terms \bar{x} and \bar{y} denote the mean values of the process parameters and UTS, respectively. The correlation coefficient ranges from -1 to $+1$, where a positive value indicates a direct relationship, a negative value indicates an inverse relationship, and a value close to zero indicates a weak relationship [13],[14].

The final stage involves evaluation to validate the findings by comparing them with relevant previous studies. This evaluation aims to assess the consistency of the observed relationships between process parameters and the tensile strength of PLA materials, as well as to strengthen the validity of the results. Through this analysis, the most dominant parameters influencing variations in tensile strength can be identified. In addition, the results are supported by data visualization to clearly illustrate the relationships among variables.

3. RESULTS AND DISCUSSION

1. Characteristics of FDM Process Parameter Data

The data used in this study consist of secondary data obtained from various previous studies related to the Fused Deposition Modeling (FDM) process using PLA material. The dataset includes process parameters such as layer height, nozzle temperature, print speed, and print orientation as input variables, as well as tensile strength (Ultimate Tensile Strength/UTS) as the output variable. In total, 74 data points from 11 different studies were analyzed. The variation in parameter values reflects differences in printing conditions across studies, providing sufficient data diversity for further analysis. To provide an initial overview of the data characteristics, descriptive statistical analysis was performed, including minimum, maximum, mean, and standard deviation values for each parameter. The results of the descriptive statistical analysis are presented in Table 2.

Table 2. Descriptive Statistics of Process Parameters and UTS Values

Parameter	Min	Max	Mean	Std. Dev.
Layer Height (mm)	0.060	0.400	0.18	0.08
Nozzle Temperature (°C)	180.000	260.000	210.95	11.75
Print Speed (mm/s)	30.000	600.000	63.24	78.39
Build Angle (°)	0.000	90.000	15.81	31.98
UTS (MPa)	21.800	59.800	39.27	7.55

The descriptive statistical results of the data used in this study are presented in Table 2. The analyzed parameters include layer height, nozzle temperature, print speed, print orientation, and tensile strength (UTS). Based on the results, layer height ranges from 0.060 mm to 0.400 mm, with an average value of 0.18 mm. Nozzle temperature ranges from 180°C to 260°C, with an average of 210.95°C. Print speed exhibits considerable variation, ranging from 30 mm/s to 600 mm/s, with an average of 63.24 mm/s. Print orientation varies from 0° to 90°, with a mean value of 15.81°. Meanwhile, the tensile strength (UTS) ranges from 21.80 MPa to 59.80 MPa, with an average of 39.27 MPa. The variation in these parameter values indicates that the dataset has a relatively high level of diversity, enabling further analysis to investigate the influence of process parameters on the tensile strength of PLA materials.

2. Analysis of Process Parameters on Tensile Strength

The results of the correlation analysis between FDM process parameters and tensile strength (UTS) are presented in Figure 3. In general, the correlation values indicate that each parameter exhibits a different level of relationship with UTS, either positive or negative.

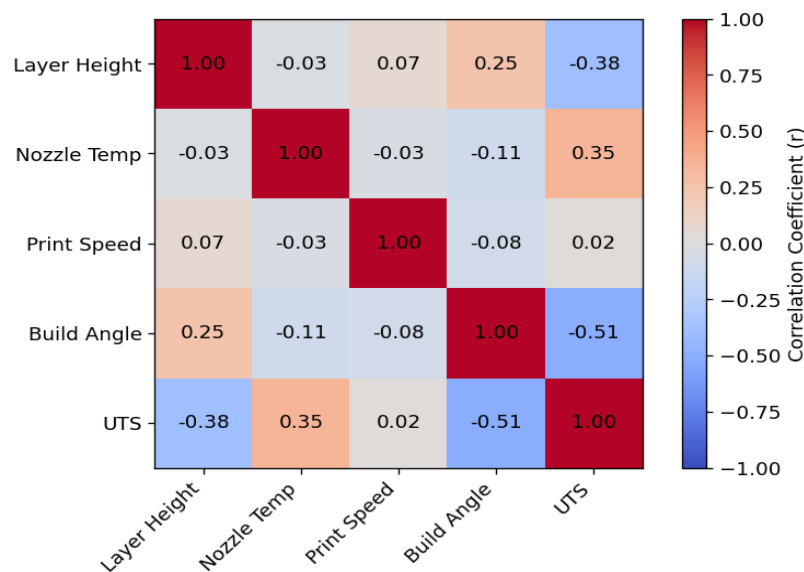


Figure 3. Correlation Matrix of FDM Process Parameters and Tensile Strength (UTS)

The build angle parameter exhibits the strongest negative relationship with UTS, with a correlation value of -0.51 . This indicates that as the print orientation increases, the tensile strength tends to decrease. This phenomenon is related to the alignment of layers with respect to the loading direction, where orientations that are not aligned with the

tensile force result in weaker interlayer bonding. This finding is consistent with previous studies stating that print orientation is a dominant factor in determining the mechanical properties of FDM-produced materials, as it significantly affects interlayer bonding quality [15]. The layer height parameter also shows a negative relationship with UTS, with a correlation value of -0.38 . This suggests that increasing layer height tends to reduce tensile strength. Physically, a larger layer height leads to a reduced number of layers and decreased interlayer contact area, resulting in weaker bonding strength. This result is consistent with studies indicating that smaller layer heights can enhance tensile strength due to increased density and improved interlayer adhesion [16].

Nozzle temperature demonstrates a positive relationship with UTS, with a correlation coefficient of 0.35 . This indicates that increasing the nozzle temperature tends to improve the tensile strength of PLA material. This occurs because higher temperatures promote more complete material melting, enhancing interlayer diffusion and strengthening the bonding between layers. This finding aligns with several studies that identify nozzle temperature as a key parameter in improving the mechanical quality of FDM-printed parts [17]. In contrast to the other parameters, print speed shows a very weak relationship with UTS, with a correlation value of 0.02 . This suggests that variations in print speed within the observed data range do not have a significant effect on tensile strength, making it a less influential factor compared to the other parameters. These findings are further supported by the visualization of relationships among variables, as shown in Figure 3. The visualization illustrates the trend patterns between each process parameter and UTS values more clearly.

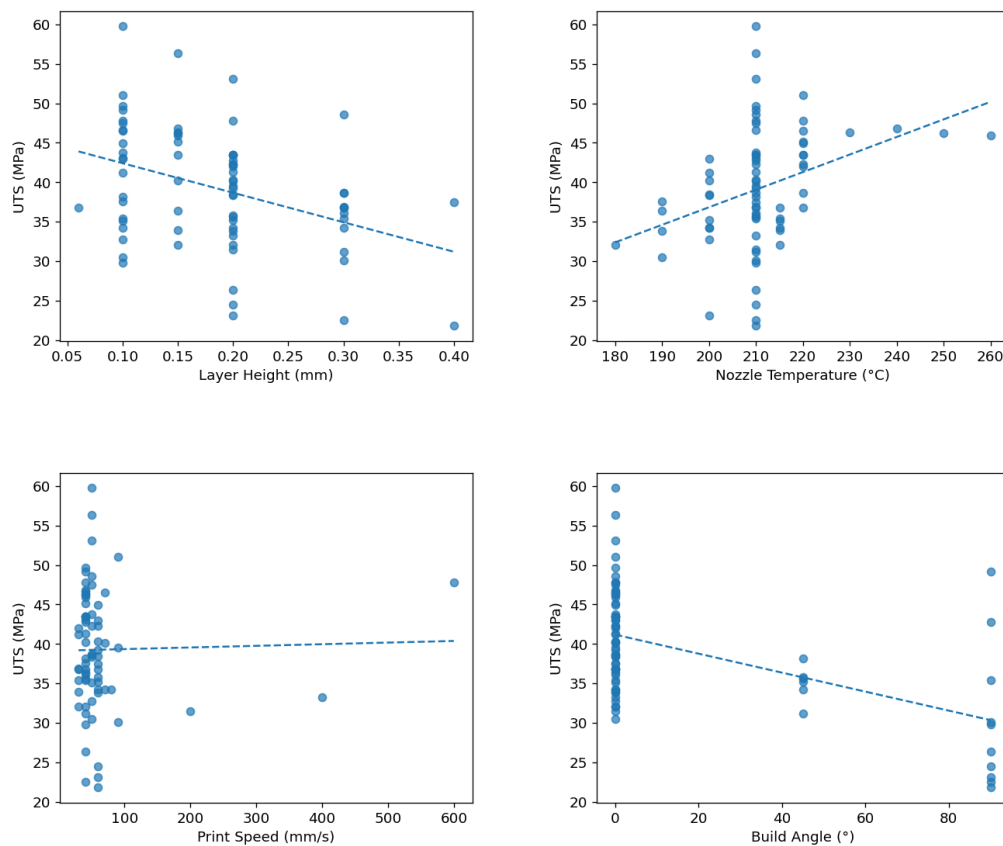


Figure 3. Visualization of the Relationship between FDM Process Parameters and UTS

The relationship between FDM process parameters and tensile strength is not uniform across all parameters. The figure illustrates differences in trend patterns for each parameter with respect to UTS values, indicating that not all parameters contribute equally to the mechanical performance of the material. From the observed patterns, parameters related to layer structure and orientation show a more pronounced influence compared to others. Layer height demonstrates a trend in which increasing layer thickness is associated with a decrease in tensile strength. This indicates that thicker layers limit the quality of interlayer bonding. In this context, tensile strength is more strongly governed by the quality of interlayer adhesion rather than the amount of material deposited. In contrast, nozzle temperature exhibits an opposite trend, where increasing temperature is associated with higher tensile strength. This suggests that the melting process plays a crucial role in enhancing interlayer bonding. However, the relatively high data variability indicates that this effect does not act independently, but is influenced by the interaction with other process parameters.

Unlike these parameters, print speed does not show a consistent pattern with respect to changes in UTS values. This suggests that, within the observed range, print speed is not a dominant factor in determining tensile strength. As long as the printing process remains stable, variations in speed do not significantly affect the quality of the printed output. On the other hand, print orientation exhibits the most consistent trend, where an increase in angle is followed by a decrease in tensile strength. This highlights the importance of orientation in determining how the applied load is distributed within the material. When the layer direction is not aligned with the tensile force, the structure becomes more susceptible to failure. Conversely, aligned orientations allow for more uniform load distribution, resulting in higher tensile strength. Overall, these results indicate that factors related to the direction and quality of layer deposition play a more dominant role than parameters associated solely with processing conditions. Therefore, improving the tensile strength of PLA materials is more effectively achieved by optimizing print orientation and layer height, rather than solely adjusting parameters such as print speed. The distribution of tensile strength values is further illustrated in Figure 4, which presents the frequency-based distribution of UTS data.

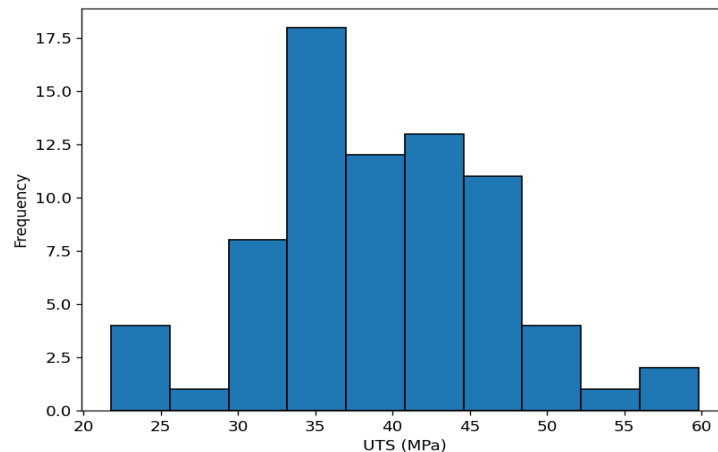


Figure 4. Distribution of Tensile Strength (UTS)

Based on the figure, the distribution of tensile strength values for PLA materials indicates that most of the data fall within a moderate range, approximately 35–45 MPa. This suggests that the majority of printing conditions result in tensile strength within this mid-range level. On the other hand, several data points exhibit values lower or higher than this range, indicating variations in processing conditions that influence tensile strength. To further understand the factors contributing to this variation, an analysis based on process parameter categories is presented in Figure 5.

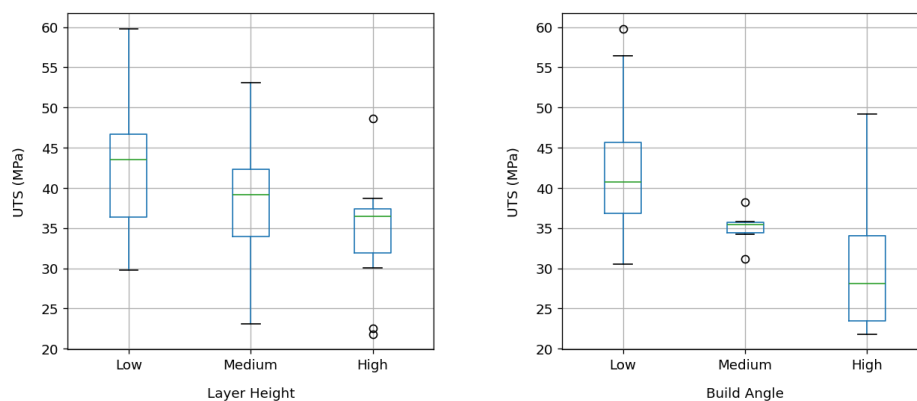


Figure 5. Distribution of UTS Based on Process Parameters

The analysis based on process parameter categories indicates that layer height and print orientation exhibit consistent patterns with respect to changes in the tensile strength of PLA materials. Both parameters suggest that variations in layer structure and orientation are directly associated with changes in UTS values. At lower layer heights, UTS values tend to be higher with a wider variation, indicating the potential to achieve maximum tensile strength under certain conditions. In contrast, increasing layer height is associated with a decrease in UTS values and a narrower data distribution, suggesting limitations in achieving high tensile strength. A clearer pattern is observed in print orientation, where UTS values tend to decrease as the print angle increases. At lower angles, UTS values are relatively higher and more varied, whereas at higher angles, UTS values tend to be lower and more concentrated. This indicates that print

orientation plays a crucial role in determining how the layered structure responds to applied loads. Overall, these two parameters exhibit a similar trend, highlighting that the quality of layer deposition is a key factor in determining tensile strength. Lower layer heights and smaller print angles provide more favorable conditions for stronger interlayer bonding, resulting in higher tensile strength.

The analysis results indicate that not all Fused Deposition Modeling (FDM) process parameters have the same level of influence on the tensile strength of PLA materials. Print orientation exhibits the strongest relationship with UTS, followed by layer height and nozzle temperature, while print speed has a relatively minor effect. These findings are consistent with previous studies summarized in Table 3. This is further supported by descriptive analysis, which shows that UTS values tend to be higher under conditions of low print orientation and small layer height. Conversely, increasing these parameters is associated with a decrease in tensile strength. This pattern highlights that the quality of layer arrangement and orientation plays a crucial role in determining the tensile strength of printed materials. The data used in this study were obtained from various previous studies published in recent years. A summary of these studies is presented in Table 3 to provide an overview of the findings reported in earlier research.

Table 3. Summary of Previous Studies on FDM Process Parameters and the Tensile Strength of PLA

No	Author(s) (Year)	Title	Parameters Investigated	Key Findings
1	Megersa et al. (2024)	Investigation of the Influence of FDM 3D Printing Process Parameters on Tensile Properties of PLA Parts Using the Taguchi Method	Build orientation, raster angle, nozzle diameter, infill density	The highest UTS was 58.05 MPa. Build orientation (45%), nozzle diameter (25%), and infill density (19%) were the most significant factors. On-edge orientation produced the highest strength.
2	Marşavina et al. (2022)	Effect of the Manufacturing Parameters on the Tensile and Fracture Properties of FDM 3D-Printed PLA Specimens	Printing direction, build orientation (0°/45°/90°), printer type, layer thickness (0.15 & 0.40 mm), filament color	UTS ranged from 30–52 MPa. Filament color and printing direction significantly influenced results. A layer thickness of 0.15 mm produced higher UTS than 0.40 mm.
3	Ambade et al. (2023)	Influence of FDM Process Parameters on Tensile Strength of Parts Printed by PLA Material	Air gap, extruder temperature, layer thickness, infill density, raster angle	Infill density and raster angle were the most dominant parameters. Optimal conditions included extruder temperature of 230°C, layer thickness of 0.15 mm, 100% infill, and raster angle of 0°.
4	Bembenek et al. (2022)	Research on the Influence of Processing Parameters on the Specific Tensile Strength of FDM Additive Manufactured PET-G and PLA Materials	Print speed, layer thickness, infill density, printing temperature	PLA exhibited higher UTS than PET-G under the same conditions. 100% infill and thinner layers consistently improved UTS in both materials.
5	Tünçay (2024)	An Investigation of 3D Printing Parameters on Tensile Strength of PLA Using Response Surface Method	Layer thickness, infill density, print speed	The highest UTS (48.22 MPa) was achieved with 100% infill, 0.15 mm layer height, and 40 mm/s print speed. Infill density showed the strongest contribution.
6	Jatti et al. (2024)	Optimization of Tensile Strength in 3D Printed PLA Parts via Meta-	Infill density, build orientation, layer thickness, raster angle, print speed	GA and PSO produced optimal parameter configurations with UTS values 8–12% higher than conventional Taguchi methods. On-edge orientation

		Heuristic Approaches: A Comparative Study		and 100% infill were consistently optimal.
7	Cojocar et al. (2022)	The Influence of the Process Parameters on the Mechanical Properties of PLA Specimens Produced by Fused Filament Fabrication A Review	Layer thickness, infill density, build orientation, raster angle, nozzle temperature, print speed	Layer thickness and infill density were the most widely studied and most influential parameters. Nozzle temperature significantly affected interlayer bonding. UTS of PLA typically ranged from 28–60 MPa.
8	Hong Vi et al. (2024)	Effects of Infill Density, Layer Thickness and Raster Angle on Weight and Tensile Strength of PLA Products Fabricated by FDM	Layer height, infill density, raster angle	Infill density contributed 39.1% to UTS and 88.7% to weight. A layer height of 0.1 mm and 80% infill produced optimal strength within the tested range.

Based on previous studies, most research indicates that parameters related to layer structure have a significant influence on the tensile strength of PLA materials. Print orientation (build orientation) has been reported as one of the key factors in determining tensile strength [18]. This result is consistent with the findings of this study, where print angle shows a strong influence on variations in tensile strength. The effect of layer height observed in this study is also supported by previous research, which demonstrates a relationship between layer thickness and the tensile strength of PLA materials [19]. Smaller layer thickness tends to produce higher tensile strength due to improved interlayer bonding quality. Several studies have shown that infill density has a significant impact on tensile strength [20]. However, this parameter was not included in the present analysis due to incomplete and inconsistent availability across the dataset. Additionally, the variation in infill density values among studies is relatively large, making it difficult to compare within a unified analytical framework. The influence of nozzle temperature identified in this study is in agreement with previous findings [21], which indicate that temperature plays a role in enhancing interlayer bonding quality. Overall, the results of this study suggest that the tensile strength of PLA materials is influenced by the interaction of multiple process parameters, with those related to material structure and orientation playing a more prominent role in determining the mechanical performance of FDM-printed parts.

4. CONCLUSION

Based on the analysis results, FDM process parameters exhibit varying influences on the Ultimate Tensile Strength (UTS) of PLA materials. Print orientation shows the strongest negative effect, with a correlation value of -0.51 , indicating that an increase in print angle is associated with a decrease in tensile strength. Layer height also demonstrates a negative relationship (-0.38), suggesting that smaller layer thickness tends to produce higher tensile strength. Nozzle temperature shows a positive relationship, with a correlation coefficient of 0.35 , indicating that increasing temperature within the observed range is associated with improved interlayer bonding quality. Meanwhile, print speed does not exhibit a significant influence on UTS. These findings indicate that parameters related to layer structure and orientation have a more pronounced effect on tensile strength compared to other process parameters.

AUTHORS' CONTRIBUTIONS

DL, YR, and **YP** contributed to the conceptualization of the study, methodology development, supervision, formal analysis, data validation, writing of the original draft, and reviewing and editing the manuscript. **RM** and **ES** were responsible for investigation, data curation, formal analysis, data visualization, and preparation of the original draft. Meanwhile, **DL, YR,** and **YP** also contributed to conceptualization, methodology development, supervision, project administration, and manuscript review and editing.

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