

# Experimental analysis and predictive modeling of the tensile and flexural strength of FDM-printed PLA for clinical devices

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## Research Article

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# **Experimental analysis and predictive modeling of the tensile and flexural strength of FDM-printed PLA for clinical devices**

## **Abstract**

This article seeks to explore the effects of fused deposition modeling (FDM) technology's layer thickness (H), print speed (PS) and extrusion ratio (ER) on the tensile and flexural properties of polylactic acid (PLA)-based components. While the layer thickness and print speed have been well studied, the effect of the extrusion ratio, which influences interlayer bonding and deposition density, is less well understood. To do this, a full factorial design of experiments ( $3^3$ ) was used that resulted in 27 investigations each repeated 5 times to guarantee the accuracy of the tensile (ASTM D638) and flexural (ASTM D790) measurements. Second-order polynomial regression models were used to calculate mechanical responses, in addition to multi-objective optimization method used to obtain the necessary set of parameters. The results show that anisotropy is present because flexural characteristics are higher (34-51 MPa) than tensile strength (12-24 MPa).

In this article, the extrusion ratio was found to have the most significant effect on the strength of the PLA component, whereby an extrusion ratio of 110% significantly reduced the internal porosities of the component. The maximum stiffness and strength were achieved using the optimized layer thickness of 0.20 mm and the optimized extrusion ratio of 110%. The optimized parameters were validated using experimental results, which showed a high model accuracy with relative errors ranging from 1.89% to 6.32%. The optimized model can thus provide a predictive framework for the production of high-performance PLA-based components for use in demanding industries such as biomedical tooling, implants and rapid prototyping.

**Keywords:** AM, FDM, PLA, Mechanical properties, Three-point flexural tests, Tensile tests.

## **1. Introduction**

Additive manufacturing (AM), or 3D printing, involves the construction of a 3D object from a digital CAD file in layers. This has several advantages over conventional subtractive manufacturing. They include design freedom for complex shapes, reduced weight through hollow structures, faster time to market, reduced material usage, cost-

effectiveness for small batches, ability to produce customized products, and low human interface requirements [1, 2]. Additive manufacturing has several applications in the automotive industry, medicine, space exploration [3, 4] It exploits properties such as mechanical strength, flexibility, bio-compatibility, and biodegradability [5].

Compared to traditional manufacturing techniques, additive manufacturing (AM) specifically fused deposition modeling (FDM) has emerged as a highly promising approach for diverse biomedical applications [6, 7]. In medicine, it has applications in implants, scaffolding, and printed organs. This is in the early stages of development but has enormous potential [8]. Of the several 3D printing techniques, fused deposition modeling has become extremely popular in academia, space exploration, medicine, etc. This is because it is cost-effective, has a wide range of materials available (PLA, ABS, nylon, metallic-filled materials), is easy to use, has faster printing speeds than SLA machines, and is suitable for customized orthopedic applications [9, 10].

The healthcare sector increasingly emphasizes patient-specific customization, utilizing AM to scan and adapt medical equipment [11]. Literature identifies FDM as the preferred method for fabricating custom prostheses [12], implants [13, 14], orthoses [15, 16], and surgical instruments [17], producing dimensionally stable, clean, and cost-effective parts. FDM employs various polymers like ABS [15], PLA [18, 19], PETG [20], PEEK [13, 21], nylon [15], TPU [17] for rapid prototyping and specialized applications.

Among the wide range of materials available for FDM printers, PLA polymer remains the most commonly used due to its ease of use and bio-based nature, featuring key properties such as biocompatibility and biodegradability that make it useful for tissue engineering [22, 23], bone repair [4, 24] and medical aids [25, 26]. The scope of PLA applications continues to expand, particularly in the medical, instrumentation and surgical fields, where the number of PLA-based medical devices is rapidly increasing owing to their desirable physical and mechanical properties such as low melting point, ecological safety, transparency, printability, flexibility, tissue compatibility, rigidity, non-toxicity, durability, and ease of resorption with further growth anticipated in the near future [18].

The recent advancements do highlight that the direct impact from FDM process parameters is on printed PLA structures. Tensile properties, flexural behavior, fatigue resistance, and surface morphology depend on nozzle temperature, layer thickness, infill density, and print speed. Implants need this trait because those parts act as machines subject to bodily stresses [27, 28]. Mushtaq et al. [29] have optimized the parameters for the 3D printing of PLA materials for biomedical applications such as medical stents, dental prostheses, grafts, etc., with layer thickness as 0.26 mm, density as 84%, and speed as 68.87 mm/s. Despite the limitations in parts produced through FFF technology, such as surface finish, mechanical strength, and long printing time, the study used the entire central composite design with 20 samples validated with ANOVA to obtain the following results: Flexural strength = 70.1 MPa, tensile strength = 39.2

MPa, minimum surface roughness = 7.8  $\mu\text{m}$ , printing time = 47 min, energy consumption = 0.18 kWh.

This research fills an important gap in the literature by adopting an experimental approach to analyze the combined effect of three key parameters layer thickness, print speed, and extrusion ratio on the tensile and flexural mechanical properties of FDM parts. Although layer thickness and print speed are often explored, the extrusion ratio is rarely considered as a printing factor, despite its essential role in deposition density and interlayer bond quality. The objective is to identify the optimal FDM parameters that maximize tensile strength, Young's modulus (E), flexural strength, and flexural modulus of PLA components, while providing a robust predictive framework for demanding structural applications.

## **2. Material and Method**

This study includes: (i) selecting a lightweight biodegradable polymer, (ii) defining the printing parameters, (iii) manufacturing parts according to these parameters for tensile and flexural testing, (iv) optimizing the parameters using a full factorial design, (v) recommending the ideal set of variables and associated results.

### **2.1. Material Selection**

The biocompatible material used as filament in this research is a 1.75 mm diameter polylactic acid (PLA). PLA stands out for its ease of printing, lack of significant deformation, and relatively low filament temperature. PLA is an excellent choice for FDM 3D printers thanks to its attractive properties: a lower melting point than other filaments, making it easy and safe to use, and generally low toxicity. In recent years, it has found applications in various fields, particularly medicine (sutures, implants, drug delivery systems) [19, 30].

### **2.2. 3D Equipment and Design of Experiments**

To produce the specimens, a FlashForge 3D printer was utilized to fabricate the parts for both tensile and three-point flexural testing. The CAD models were designed using SolidWorks software and exported in STL format, which was subsequently sliced and converted into G-code using FlashPrint 5 software.

Although the properties of additive manufactured parts are directly influenced by the process parameters employed, according to the comprehensive literature review conducted, some combinations of parameters received insufficient attention in research. Thus, we chose three significant variables for the current research: layer thickness (mm), printing speed (mm/s), and extrusion ratio (%), with the purpose of determining their influence on the flexural properties of the

printed parts (Table 1).

**Table 1.** Variable settings that the FDM printer uses to create a samples.

| Parameters                        | Symbols | Level 1 | Level 2 | Level 3 |
|-----------------------------------|---------|---------|---------|---------|
| Layer thickness (mm)              | H       | 0.10    | 0.15    | 0.20    |
| Extrusion ratio (%)               | ER      | 90      | 100     | 110     |
| Print speed (mm.s <sup>-1</sup> ) | PS      | 40      | 50      | 60      |

The fixed 3D printing parameters and their corresponding values are detailed in Table 2.

**Table 2.** Fixed printing parameters.

| Parameter               | Recommended value |
|-------------------------|-------------------|
| Nozzle temperature (°C) | 220               |
| Cooling (%)             | 50                |
| Infill density (%)      | 60                |
| Shell thickness (mm)    | 1.2               |
| Number of shells        | 3                 |
| Filling type (Pattern)  | Grid              |
| Print orientation       | Horizontal        |
| Plate temperature (°C)  | 70                |

The total of 27 (3<sup>3</sup>) samples was designed and manufactured in accordance with the full-factorial experimental design, which is described in Table 3.

**Table 3.** Design of Experiments.

| Test | H (mm) | PS (mm.s <sup>-1</sup> ) | ER (%) |
|------|--------|--------------------------|--------|
| 1    | 0.1    | 40                       | 90     |
| 2    | 0.1    | 40                       | 100    |
| 3    | 0.1    | 40                       | 110    |
| 4    | 0.1    | 50                       | 90     |
| 5    | 0.1    | 50                       | 100    |
| 6    | 0.1    | 50                       | 110    |
| 7    | 0.1    | 60                       | 90     |
| 8    | 0.1    | 60                       | 100    |
| 9    | 0.1    | 60                       | 110    |
| 10   | 0.15   | 40                       | 90     |
| 11   | 0.15   | 40                       | 100    |
| 12   | 0.15   | 40                       | 110    |
| 13   | 0.15   | 50                       | 90     |
| 14   | 0.15   | 50                       | 100    |
| 15   | 0.15   | 50                       | 110    |
| 16   | 0.15   | 60                       | 90     |
| 17   | 0.15   | 60                       | 100    |
| 18   | 0.15   | 60                       | 110    |
| 19   | 0.2    | 40                       | 90     |
| 20   | 0.2    | 40                       | 100    |
| 21   | 0.2    | 40                       | 110    |
| 22   | 0.2    | 50                       | 90     |
| 23   | 0.2    | 50                       | 100    |
| 24   | 0.2    | 50                       | 110    |
| 25   | 0.2    | 60                       | 90     |
| 26   | 0.2    | 60                       | 100    |
| 27   | 0.2    | 60                       | 110    |

The research was focused on the three selected 3D printing parameters: layer thickness, extrusion ratio and printing speed. Each parameter was studied at three levels, which allowed us to carry out 27 experiments on the basis of all the possible combinations of the parameters. Five replicate tests were conducted for each configuration: tensile test dumbbell samples (ASTM D638 Type I) and rectangular samples for three-point flexural tests (ASTM D790). The mentioned specimens were tested for tensile and flexural strengths.

The physical specimens fabricated via the FDM process for both tensile (Fig. 1a) and flexural characterization (Fig. 1b) are illustrated in Fig. 1. This figure highlights the surface finish of the specimens, which were printed in strict accordance with the geometries specified by the respective ASTM standards.



**Fig. 1.** PLA printed samples images by FDM printer (a) tensile test (b) three-point flexural test.

## 2.3. Mechanical Testing

### 2.3.1. Tensile Testing

The LLOYD Instruments (AMETEK) universal testing machine was used to perform tensile tests on PLA samples produced by FDM printing. Figs. 2 and 3 show the dimensions of the test specimens used for these tests and the machine setup during testing, respectively. For this experimental study, the part models were created in SolidWorks CAD in accordance with the ASTM D638 standard before being converted to STL format for processing by the Cura slicer.

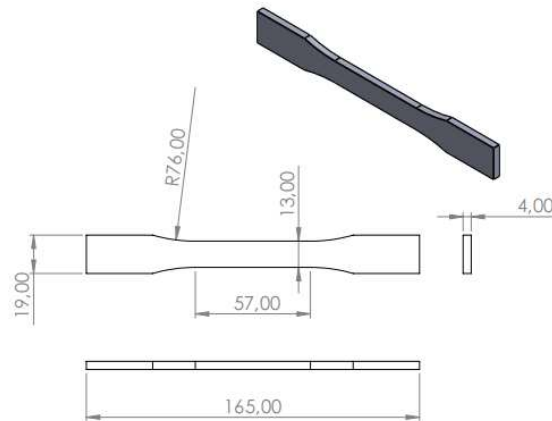


**Fig. 2.** Dimensions of the tensile test specimen according to ASTM D638, designed in SolidWorks.

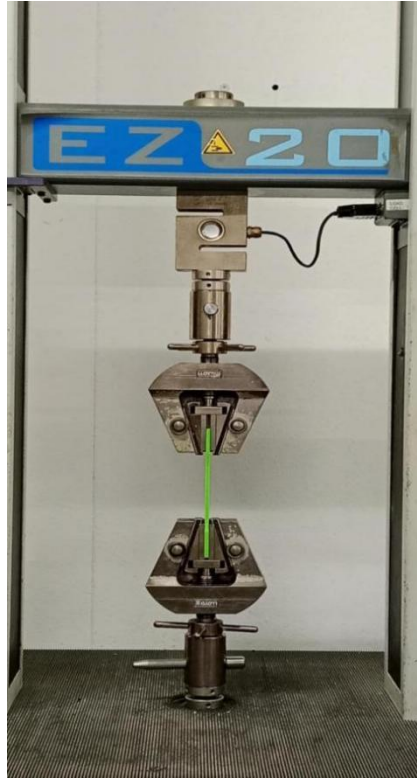


**Fig. 3.** Image of the universal testing machine (UTM) configuration during the tensile test.

The UTM (tensile testing) machine operated at a maximum speed of 2 mm/min. At room temperature, data was acquired directly on a PC connected to the device. Fig. 4 shows the PLA samples immediately after the tensile test.



**Fig. 4.** Image of PLA samples after tensile testing.

### 2.3.2. Tree-point flexural test

The three-point flexural test aims to characterize the linear behavior of a material when subjected to a vertical load perpendicular to its surface. It precisely quantifies the deflection induced by this force. Before each test, the dimensions of the samples were carefully measured. In accordance with ASTM D790, the tests were conducted on a LLOYD Instruments (AMETEK) universal testing machine at a crosshead speed of 2 mm/min, controlled by computer for

optimal data acquisition and control. A 500 N load cell was used to measure the forces applied, with the samples supported 64 mm apart and loaded perpendicularly at the center (Fig. 5 (a-b)). The data was collected in real-time at ambient conditions through the computer linked to the universal testing machine. The state of the samples after flexural test is shown in Figure 5c.

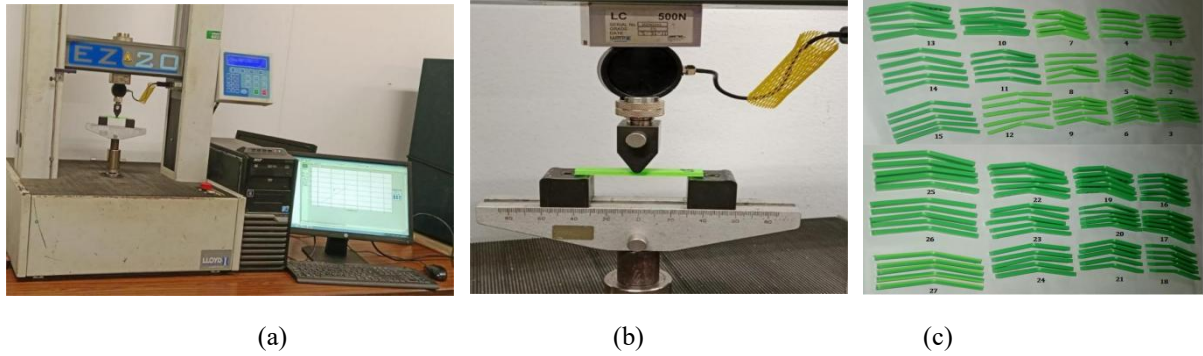


**Fig. 5.** (a) Installation of the sample on the three-point flexural test machine; (b) Detailed view of the installation showing the position of the sample between the supports and under the punch; (c) PLA samples after three-point flexural test.

### 3. Results and Discussion

#### 3.1. Tensile test results

Tensile testing was performed under displacement control using a constant crosshead speed of 2 mm/min. A full factorial experimental design ( $3^3$ ) was implemented with three factors each at three levels, generating 27 distinct parameter combinations. Five replicate specimens per configuration were tested and 135 samples for complete assessment of tensile properties. This rigorous method provides both statistical robustness and enables detailed evaluation of the effects of individual factors and the interaction of individual factors. Average peak tensile stress and average Young's modulus values for all 27 configurations are presented as histograms in Figs. 6 and 7.

It is apparent that there is remarkable variability in the tensile properties based on the printing parameters used. In regard to maximum tensile stress (Fig. 6), the average values range from 12.09 MPa up to 23.83 MPa. The smallest values of tensile stress occur at 12.09 MPa in case there is a low extrusion ratio of 90% coupled with a thin layer of 0.10 mm; hence, there is high likelihood of interlayer defects. On the other hand, the highest tensile strengths are always observed at an extrusion ratio of 110%, especially when moderate printing speeds such as 40 to 50 mm/s are considered, implying that material flow is very essential in determining the tensile strength. Indeed, the findings of this study correlate highly with the experimental data provided by Fernandes et al. [31] regarding PLA tensile strength of 17.67 to 30.22 MPa. As in the two studies, optimizing interlayer bonding in terms of enhanced material flow or factors

such as thinner layer thickness of 0.1 mm and high extrusion temperature of 220°C is highly desirable in order to achieve Ultimate Tensile Strength.

Tensile Young's moduli of average values shown in Fig. 7 vary from 567.29 MPa to 872.87 MPa, or from 0.57 to 0.87 GPa. Tensile stiffer behavior occurs at higher values, specifically 872.87 MPa, when using thicker layers at 0.20 mm thickness, together with a high value of extrusion ratios. On the contrary, the least moduli (i.e., 567.29 MPa) are registered in cases where thin layers are coupled with low extrusion ratios, since the presence of numerous interfaces and insufficient consolidation result in increased compliance of the samples under stress. In terms of numerical values, this trend correlates perfectly with the range of modulus of elasticity (0.72 to 1.32 GPa) determined by Fernandes et al. [31]. Thus, it can be assumed that the results are fairly consistent with previous studies regarding the mechanical characteristics of FDM-printed PLA. Both works point out to the same physical factor affecting stiffness, namely, the geometric continuity and absence of internal voids.

These physical observations regarding the importance of material flow and the reduction of interface defects are rigorously confirmed by the statistical analysis conducted by Kumar et al. [32] Indeed, their study, based on a Taguchi L<sub>9</sub> design of experiments, demonstrates via analysis of variance (ANOVA) that layer height is the ultra-dominant parameter affecting tensile strength, with a critical contribution of 78.26%. The raster angle and print speed account for only 17.55% and 2.37% of the total variance, respectively. In our work, achieving maximum stress at a high extrusion rate (110%) and a moderate speed (40–50 mm/s) perfectly corroborates the trend observed by Kumar et al. [32], who identified the combination (deposition angle of 45°, a speed of 50 mm/s, and a maximum layer height of 0.50 mm) as optimal for achieving a strength of 21.85 MPa. This convergence shows that a greater layer height, combined with an optimized dynamic speed, promotes greater material continuity and limits the formation of internal microscopic voids.

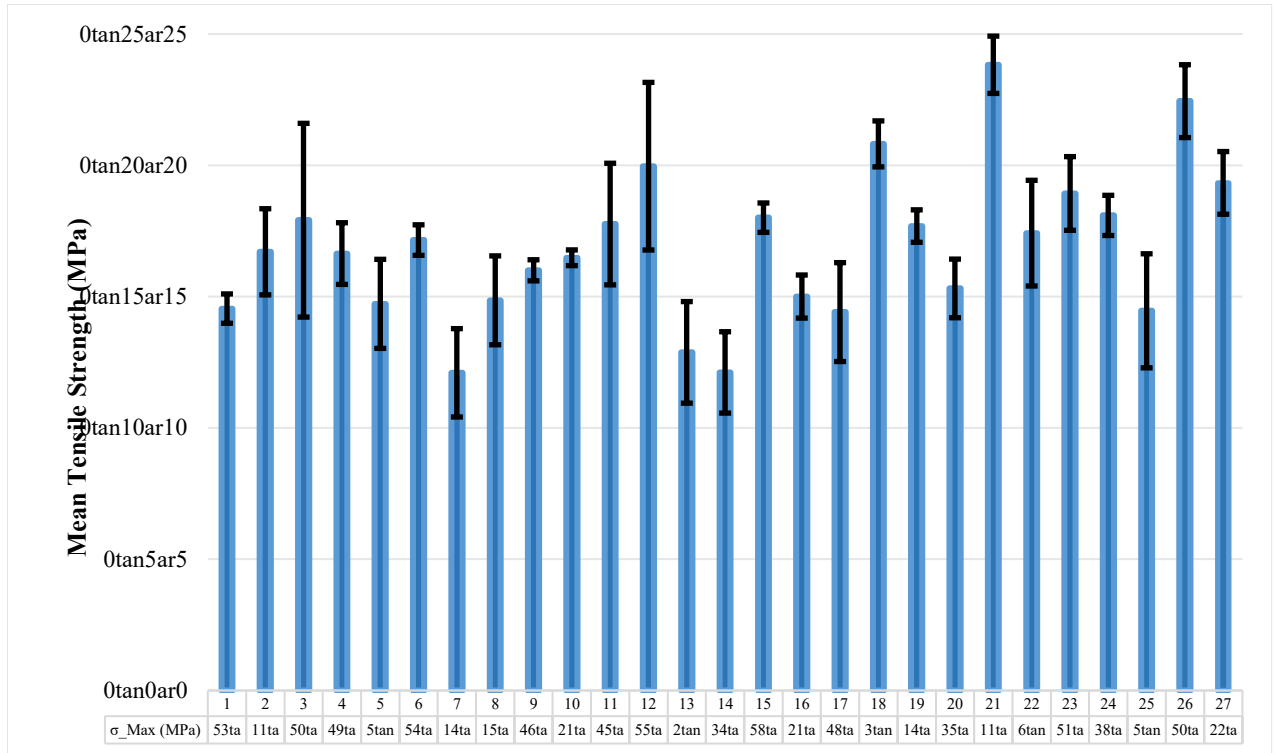


Fig. 6. Average Tensile Stress for PLA.

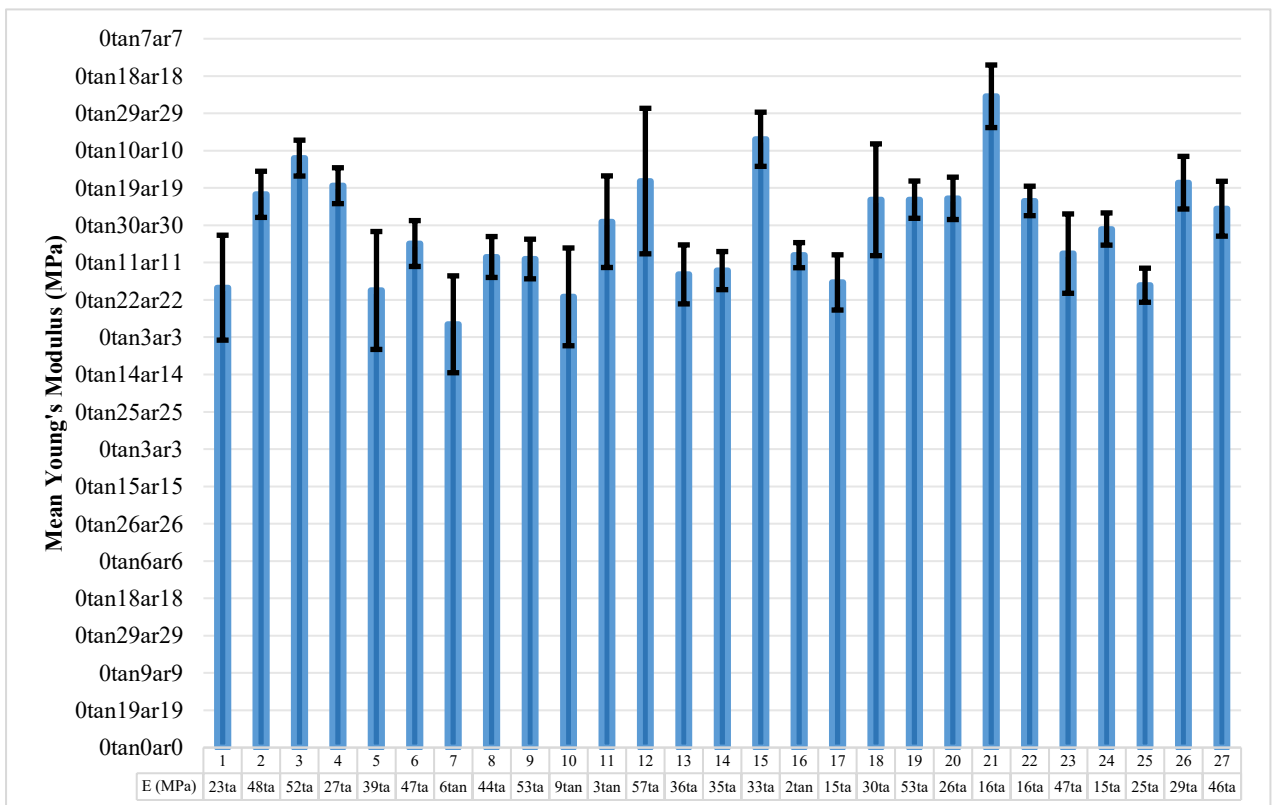


Fig. 7. Average Young's Modulus for PLA.

### 3.1.1. Maximum stress

The main effects plot (Fig. 8a) shows that the extrusion ratio (ER) is the most dominant factor that influences the tensile strength. The increase in ER from 90% to 110% increases the maximum stress from approximately 12 MPa to 24 MPa. This improvement can largely be attributed to a sharp reduction in internal porosity from 5.82% down to 0.05% as reported by Lendvai et al. [33]. This finding is further supported by Lou et al. [34], who emphasized that extrusion ratios above 105% significantly enhance interlayer bonding.

The interaction plot (Fig. 8b) shows that the positive effect of a high extrusion ratio is most pronounced when combined with thin layers (0.10 mm). In such configurations, a moderate printing speed in the range of 40–50 mm/s is recommended to ensure controlled thermal fusion between layers. This observation aligns with the optimal speed of 40 mm/s identified by Yılan et al. [35], and is also consistent with the guidelines proposed by Syrlybayev et al. [36]. Rota et al. [37] further emphasized that optimizing printing parameters is fundamental for achieving the best performance of PLA-based composites for patient-specific medical devices, including guided bone regeneration membranes and fixation screws for maxillofacial applications.

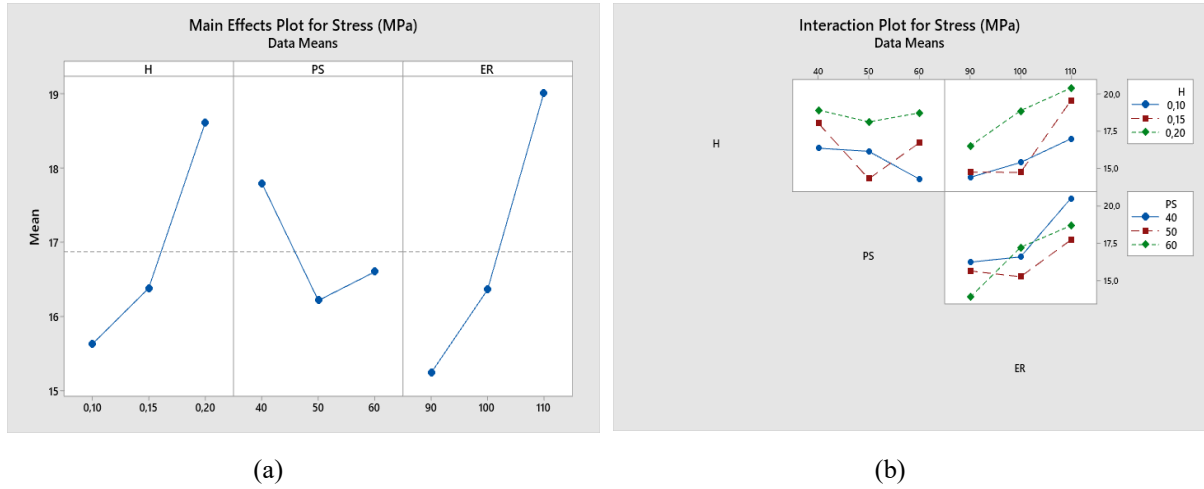


Fig. 8. Main effects of (a) means and (b) interactions on Tensile Stress.

### 3.1.2. Young's Modulus

As shown in Fig. 9a, the evolution of the tensile modulus follows a pattern comparable to that observed under flexural loading. The measured values range from 567.29 MPa to 872.87 MPa. Although the extrusion ratio contributes significantly to the overall stiffness, layer thickness appears to be the predominant factor under tensile conditions. Specimens printed with a layer thickness of 0.20 mm exhibit the highest modulus values, reaching up to 872.87 MPa.

The interaction plot presented in Fig. 9b highlights a clear synergy between layer thickness and extrusion ratio. As previously noted by Lendvai et al. [33], the reduction in porosity and the improvement in structural integrity (validated by thermal conductivity gains) explain why stiffness is optimal when a high extrusion ratio is paired with thicker layers.

Furthermore, Kafshgar et al. [38] confirmed through multi-objective optimization that the combination of appropriate layer thickness and optimized extrusion conditions produces the best mechanical performance, supporting our observation that thicker layers (0.20 mm) combined with high extrusion ratios yield maximum modulus values.

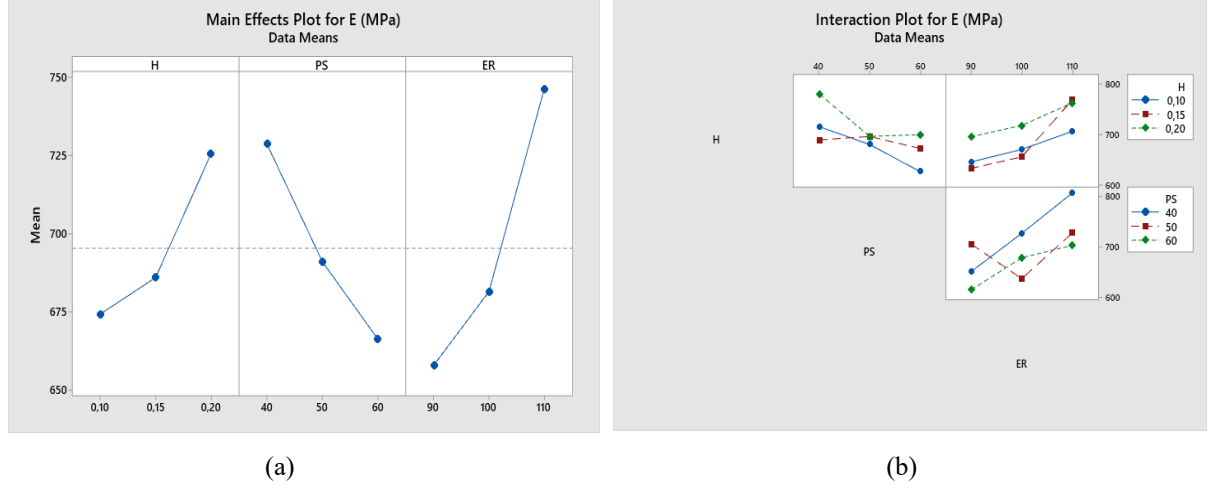


**Fig. 9.** Main effects of (a) means and (b) interactions on Young's Modulus.

### 3.1.3. Regression modeling

Based on the trends observed in the graphs of main effects and interactions (Figs. 8 and 9), a regression analysis was performed to mathematically model the relationship between the printing parameters and the mechanical tensile response. A second-order polynomial equation was developed to incorporate the main effects, quadratic terms, and complex interactions between layer height (H), print speed (PS), and extrusion rate (ER). The regression models for tensile Young's modulus (E) and maximum tensile stress provide a predictive framework for the experimental space.

The mechanical performance of the FDM-printed PLA specimens under uniaxial tension was evaluated using simplified linear regression models for both tensile strength and elastic modulus (E), establishing a highly robust error structure (DF = 23) across both responses. The global regression frameworks prove to be highly significant, yielding reliable predictive capacities with p-values of 0.001 ( $F = 8.10$ ,  $R^2 = 51.39\%$ ,  $R^2_{Adj} = 45.05\%$ ) for tensile strength and 0.002 ( $F = 6.94$ ,  $R^2 = 47.52\%$ ,  $R^2_{Adj} = 40.68\%$ ) for the elastic modulus (Tables 4 and 5).

**Table 4.** ANOVA table of tensile stress.

| Source     | DF | Adj SS  | Adj MS | F-Value | P-Value |
|------------|----|---------|--------|---------|---------|
| Regression | 3  | 110,370 | 36,790 | 8,10    | 0,001   |
| H          | 1  | 40,082  | 40,082 | 8,83    | 0,007   |
| PS         | 1  | 6,447   | 6,447  | 1,42    | 0,246   |
| ER         | 1  | 63,841  | 63,841 | 14,06   | 0,001   |
| Error      | 23 | 104,401 | 4,539  |         |         |
| Total      | 26 | 214,772 |        |         |         |

**Table 5.** ANOVA table of tensile modulus.

| Source     | DF | Adj SS | Adj MS | F-Value | P-Value |
|------------|----|--------|--------|---------|---------|
| Regression | 3  | 64884  | 21628  | 6,94    | 0,002   |
| H          | 1  | 11921  | 11921  | 3,83    | 0,063   |
| PS         | 1  | 17626  | 17626  | 5,66    | 0,026   |
| ER         | 1  | 35337  | 35337  | 11,34   | 0,003   |
| Error      | 23 | 71647  | 3115   |         |         |
| Total      | 26 | 136532 |        |         |         |

These moderate coefficients of determination are physically consistent with FDM polymeric structures, where a portion of the mechanical variance is naturally driven by process-induced micro-structural phenomena, such as local cooling fluctuations and micro-void configurations. Individual factor evaluation reveals that the extrusion ratio (ER) is the primary governing parameter for both resistance ( $p = 0.001$ ,  $F = 14.06$ ) and elastic stiffness ( $p = 0.003$ ,  $F = 11.34$ ), as a higher material flow optimizes internal compaction and expands the effective load-bearing cross-sectional area of the PLA grid. However, their secondary mechanical drivers diverge significantly; the tensile strength is strongly dependent on the layer thickness (H,  $p = 0.007$ ,  $F = 8.83$ ) because a higher layer height reduces the density of critical inter-layer weld lines that act as defect sites during macro-cracking, whereas layer thickness remains non-significant for the elastic modulus ( $p = 0.063$ ). Conversely, the initial elastic stiffness is significantly driven by the printing speed (PS,  $p = 0.026$ ,  $F = 5.66$ ), which alters nozzle residence times and cooling kinetics to modulate polymer chain relaxation and local crystallinity, whereas speed does not influence the structural failure ( $p = 0.246$ ).

The regression equations, incorporating the complexity of the interactions, are presented below:

$$\sigma \text{ (MPa)} = -3,45 + 29,8 H - 0,0598 PS + 0,1883 ER \quad (1)$$

$$E \text{ (MPa)} = 332 + 515 H - 3,13 PS + 4,43 ER \quad (2)$$

Probability plots (Fig. 9) were used to determine the fit of the experimental results to a theoretical normal distribution model. In these plots, the experimental results are considered normally distributed if the values fall along the centerline. Tensile stress (Fig. 10a): The experimental results are found to be lying along the center line with a mean of 16.87 MPa and a standard deviation of 2.874. The p-value of 0.646 is much higher than the limit of 0.05, validating

the normality condition. Young's modulus (Fig. 10b): Similarly, for the tensile modulus, the experimental results are found to be lying well along the mean of 695.4 MPa and the standard deviation of 72.47. The p-value of 0.416 confirms the validity of using this dataset for statistical modeling and parameter optimization.

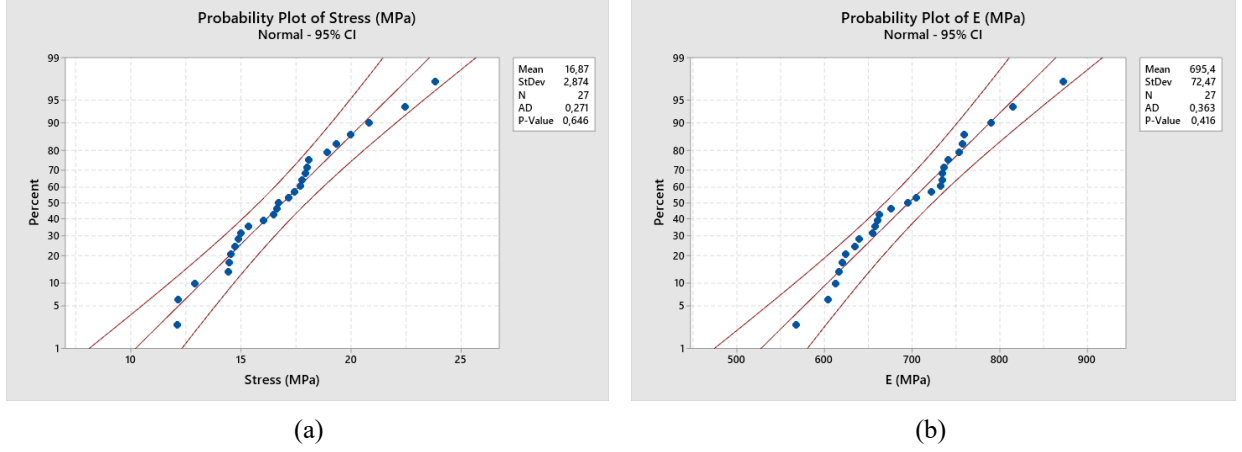


**Fig. 10.** Probability plots: (a) Tensile stress; (b) Tensile modulus.

### 3.2. Three-point flexural test results

Following the tensile characterization, three-point flexural tests were performed on specimens printed under identical conditions to evaluate flexural behavior. The same full factorial design ( $3^3$ ) was applied, comprising the same 27 unique configurations with five repetitions each, resulting in another 135 specimens for flexural characterization. The histograms grouping the 27 tests, shown in Figs. 11 and 12, were used to derive two essential mechanical quantities: the maximum flexural stress (averages of 34.46 to 50.44 MPa, minimum in test 10 and maximum in test 27), and Young's modulus (E) calculated from the flexural stress-strain curves (averages ranging from 1714.81 MPa to 2604.81 MPa, minimum in test 1 and maximum in test 27). Analysis of these histograms reveals a high dispersion for the maximum stress (34–51 MPa), with high values systematically obtained at an extrusion rate of 110%, confirming its dominant effect on strength (Fig. 11), and an even more marked dispersion for Young's modulus (1700–2600 MPa), reflecting the combined effect of the extrusion rate and layer thickness, highlighting a compromise between stiffness and strength (Fig. 12).

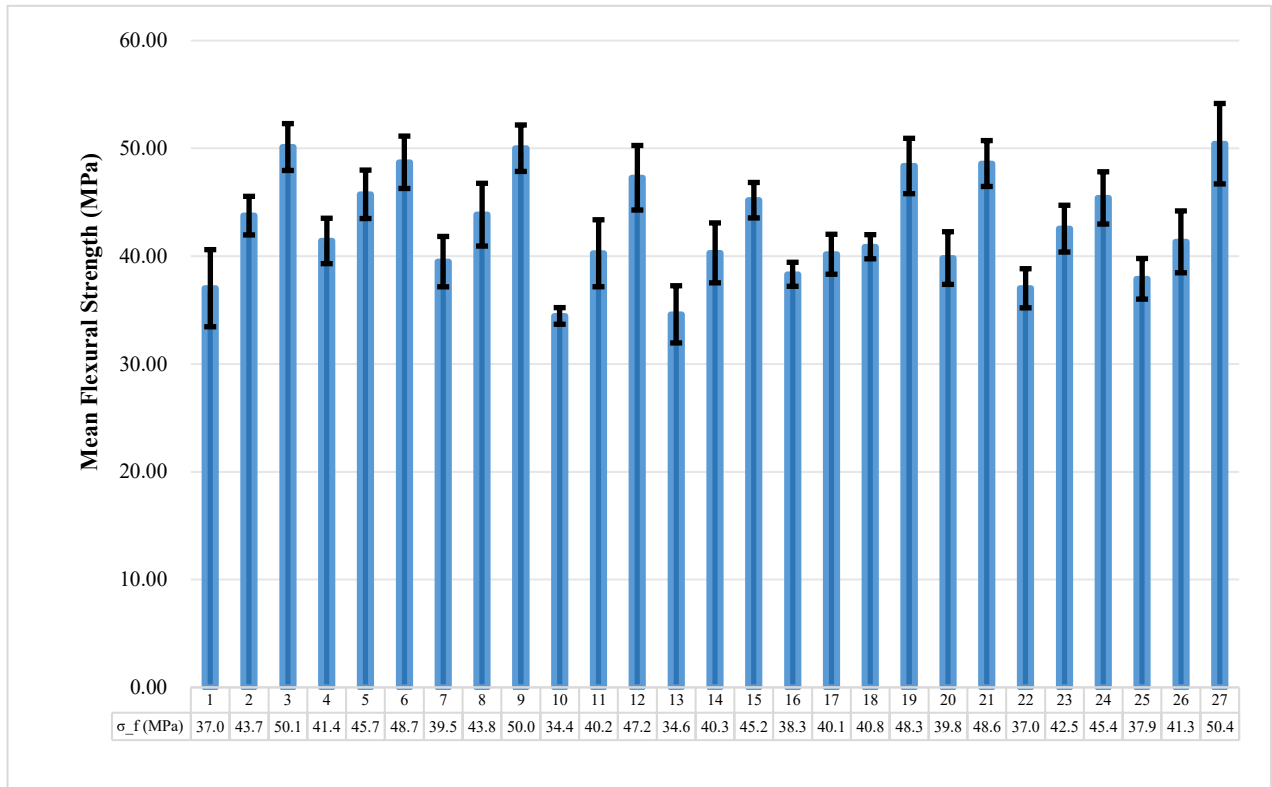


**Fig. 11.** Average Flexural Stress for PLA.

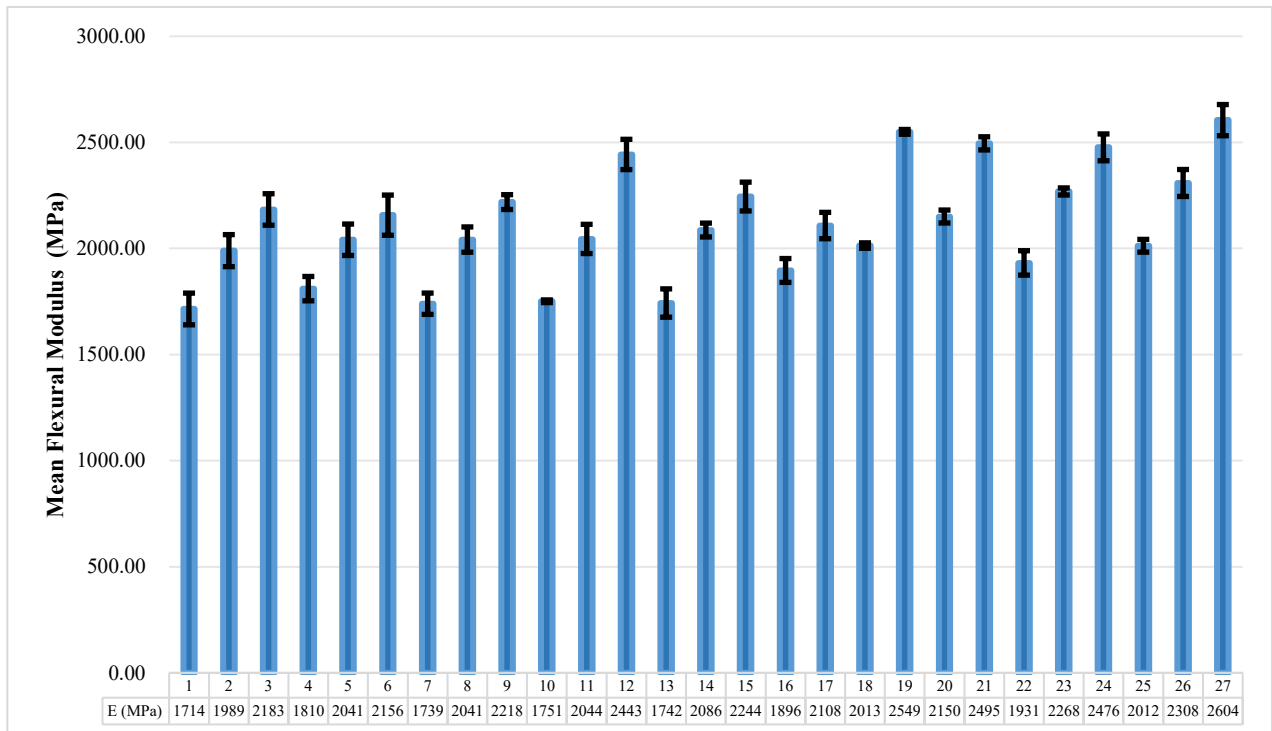


**Fig. 12.** Flexural Modulus for PLA.

It is pertinent to note that the values of flexural properties (stress: 34-51 MPa, modulus: 1700-2600 MPa) are much higher compared to the tensile properties (stress: 12-24 MPa, modulus: 567-873 MPa). This is also a common observation for PLA specimens printed using the FDM process, as the material is known to be anisotropic in nature. In the case of flexural

loading, the outer layers experience the maximum stresses, and these layers are also expected to be more compact compared to the core layer. This results in higher values of strength and modulus. It has been observed that the anisotropy of the material should be taken into account while designing a part for a particular loading condition, especially in biomedical applications where both tensile and flexural loads are expected. These results are in agreement with the results obtained by Pastor-Artigues et al. [39], who concluded that the tensile, compressive, and flexural properties of PLA specimens printed using the FDM process are not consistent with each other, thereby confirming that the test method itself affects the mechanical properties due to the inherent anisotropy of the material.

The factorial study emphasizes the decisive role played by FDM process parameters on the mechanical behavior of PLA samples, whereas the statistical analysis accurately measures the effects both individually and in combination of layer thickness, extrusion rate, and speed of printing on the flexural behavior of the samples.

### 3.2.1. Maximum flexural stress

Under flexural loading, the extrusion ratio remains the dominant factor (Fig. 13), with the average stress increasing from 39 MPa to 48 MPa. The highest value, 50.44 MPa, is obtained with a layer thickness of 0.20 mm. Unlike in tension, the benefit of a high extrusion ratio is here more pronounced for thicker layers (0.20 mm). This finding is consistent with Shergill et al. [40], who reported that while increasing layer thickness may reduce tensile strength, it often enhances flexural performance by providing greater geometric resistance.

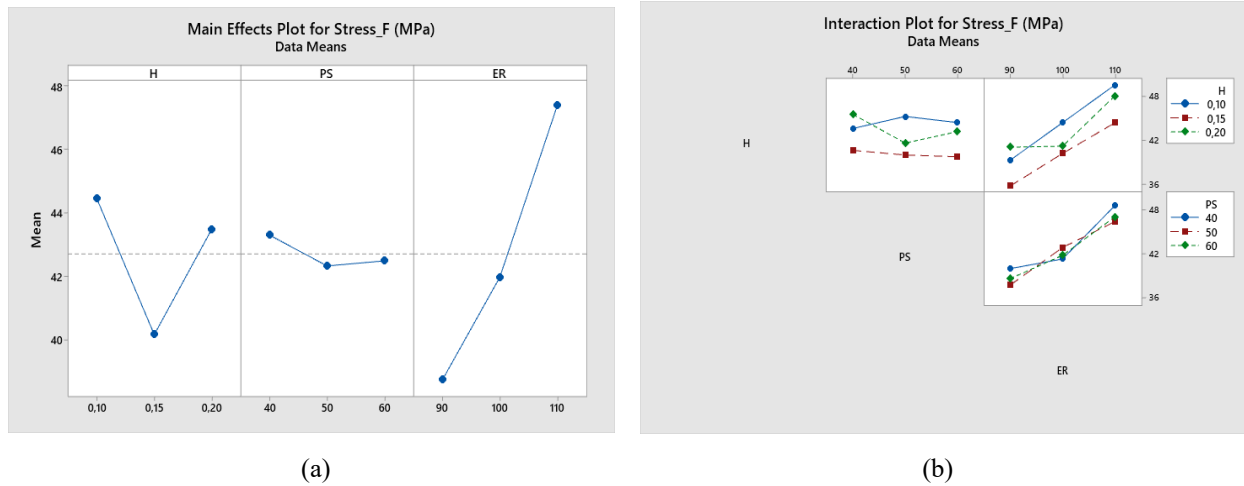


**Fig. 13.** Main effects of (a) means and (b) interactions on Flexural Stress.

### 3.2.2. Flexural Modulus

The evaluation of flexural modulus (Figure 14 a and b) indicates that rigidity is influenced by thickness of layers and extrusion ratio. An improvement of the modulus by 16% is registered at increasing the thickness of the layer from 0.10 mm to 0.20 mm. These two factors also show a large synergistic impact on the stiffness of the material, as the

interaction graph (Figure 14b) shows that the great extrusion ratio together with thicker layer of 0.20 mm is of maximum influence on the stiffness obtaining the maximum values of 2604.81 MPa. The observation correlates with the results of Shergill et al. [40], who state that while increasing thickness of the layer has negative impact on the tensile strength, it positively influences the flexural characteristics due to stronger geometric resistance and stiffness of the material. Also, the ability to obtain maximum modulus due to the synergy of parameters proves the correctness of the multi-objective optimizing techniques of Kafshgar et al. [38] and Kumar et al. [41], confirming that optimal mechanical properties in FDM result from the balanced interaction of printing parameters rather than isolated adjustments.

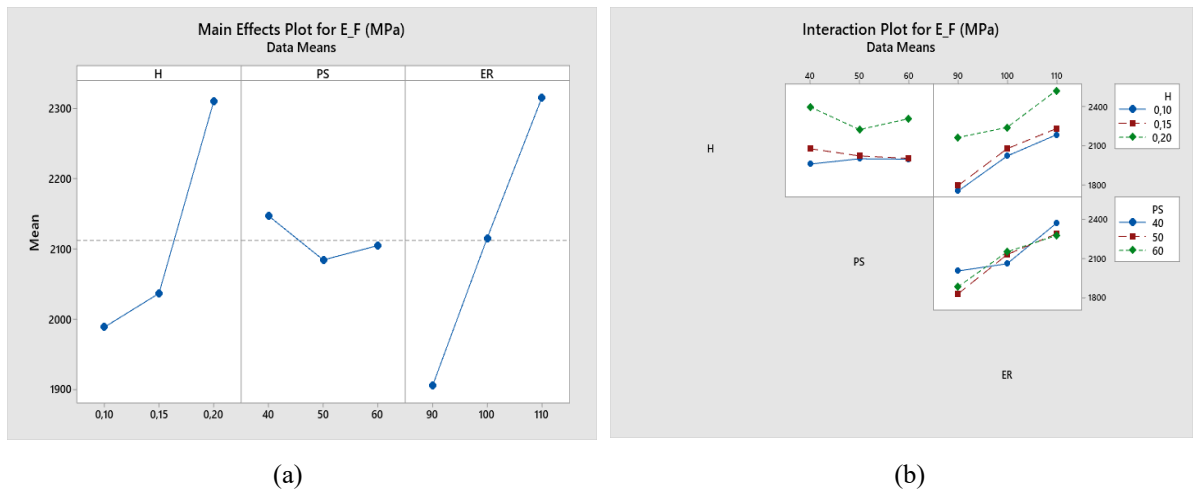


**Fig. 14.** Main effects of (a) means and (b) interactions on Flexural Modulus.

### 3.2.3. Regression modeling

Based on the trends observed in the main effects and interaction plots (Figs. 13 and 14), a regression analysis was performed to mathematically model the relationship between the printing parameters and the flexural response.

The mechanical performance of the FDM-printed PLA specimens under three-point flexural loading was modeled using an advanced, high-order response surface regression framework incorporating quadratic, cubic, and quartic interaction terms to capture the complex, multi-axial stress states inherent to flexural deformation (Tables 6 and 7).

**Table 6.** ANOVA table of flexural strength.

| Source                | DF | Adj SS  | Adj MS | F-Value | P-Value |
|-----------------------|----|---------|--------|---------|---------|
| Regression            | 19 | 569,252 | 29,961 | 6,57    | 0,008   |
| H                     | 1  | 1,152   | 1,152  | 0,25    | 0,631   |
| PS                    | 1  | 6,465   | 6,465  | 1,42    | 0,272   |
| ER                    | 1  | 6,080   | 6,080  | 1,33    | 0,286   |
| H <sup>2</sup>        | 1  | 38,245  | 38,245 | 8,39    | 0,023   |
| PS <sup>2</sup>       | 1  | 7,874   | 7,874  | 1,73    | 0,230   |
| ER <sup>2</sup>       | 1  | 6,686   | 6,686  | 1,47    | 0,265   |
| H.PS                  | 1  | 2,445   | 2,445  | 0,54    | 0,488   |
| H.ER                  | 1  | 4,605   | 4,605  | 1,01    | 0,348   |
| PS.ER                 | 1  | 6,132   | 6,132  | 1,35    | 0,284   |
| H <sup>2</sup> .PS    | 1  | 37,770  | 37,770 | 8,29    | 0,024   |
| H <sup>2</sup> .ER    | 1  | 37,085  | 37,085 | 8,14    | 0,025   |
| H.PS <sup>2</sup>     | 1  | 8,848   | 8,848  | 1,94    | 0,206   |
| H.PS.ER               | 1  | 4,469   | 4,469  | 0,98    | 0,355   |
| H.ER <sup>2</sup>     | 1  | 11,058  | 11,058 | 2,43    | 0,163   |
| PS <sup>2</sup> .ER   | 1  | 6,405   | 6,405  | 1,41    | 0,274   |
| PS.ER <sup>2</sup>    | 1  | 4,856   | 4,856  | 1,07    | 0,336   |
| H <sup>2</sup> .PS.ER | 1  | 38,120  | 38,120 | 8,37    | 0,023   |
| H.PS <sup>2</sup> .ER | 1  | 7,068   | 7,068  | 1,55    | 0,253   |
| H.PS.ER <sup>2</sup>  | 1  | 7,947   | 7,947  | 1,74    | 0,228   |
| Error                 | 7  | 31,899  | 4,557  |         |         |
| Total                 | 26 | 601,150 |        |         |         |

**Table 7.** ANOVA table of flexural modulus.

| Source                | DF | Adj SS  | Adj MS | F-Value | P-Value |
|-----------------------|----|---------|--------|---------|---------|
| Regression            | 19 | 1665670 | 87667  | 14,94   | 0,001   |
| H                     | 1  | 1126    | 1126   | 0,19    | 0,675   |
| PS                    | 1  | 10382   | 10382  | 1,77    | 0,225   |
| ER                    | 1  | 9229    | 9229   | 1,57    | 0,250   |
| H <sup>2</sup>        | 1  | 136050  | 136050 | 23,18   | 0,002   |
| PS <sup>2</sup>       | 1  | 21486   | 21486  | 3,66    | 0,097   |
| ER <sup>2</sup>       | 1  | 11866   | 11866  | 2,02    | 0,198   |
| H.PS                  | 1  | 5453    | 5453   | 0,93    | 0,367   |
| H.ER                  | 1  | 8913    | 8913   | 1,52    | 0,258   |
| PS.ER                 | 1  | 9654    | 9654   | 1,65    | 0,240   |
| H <sup>2</sup> .PS    | 1  | 132066  | 132066 | 22,50   | 0,002   |
| H <sup>2</sup> .ER    | 1  | 137093  | 137093 | 23,36   | 0,002   |
| H.PS <sup>2</sup>     | 1  | 31097   | 31097  | 5,30    | 0,055   |
| H.PS.ER               | 1  | 10922   | 10922  | 1,86    | 0,215   |
| H.ER <sup>2</sup>     | 1  | 27555   | 27555  | 4,70    | 0,067   |
| PS <sup>2</sup> .ER   | 1  | 18902   | 18902  | 3,22    | 0,116   |
| PS.ER <sup>2</sup>    | 1  | 7264    | 7264   | 1,24    | 0,303   |
| H <sup>2</sup> .PS.ER | 1  | 135787  | 135787 | 23,14   | 0,002   |
| H.PS <sup>2</sup> .ER | 1  | 27138   | 27138  | 4,62    | 0,069   |
| H.PS.ER <sup>2</sup>  | 1  | 20364   | 20364  | 3,47    | 0,105   |
| Error                 | 7  | 41079   | 5868   |         |         |
| Total                 | 26 | 1706749 |        |         |         |

The global ANOVA results display outstanding statistical significance, yielding a p-value of 0.008 ( $F = 6.57$ ) for flexural strength and 0.001 ( $F = 14.94$ ) for the flexural modulus. The models demonstrate exceptional predictive power, with remarkably high coefficients of determination for both flexural strength ( $R^2 = 94.69\%$ ,  $R^2_{Adj} = 80.29\%$ ) and flexural modulus ( $R^2 = 97.59\%$ ,  $R^2_{Adj} = 91.06\%$ ), proving that almost the entirety of the flexural experimental variance is captured by this advanced polynomial framework. While uniaxial tension highlighted direct linear dependencies, the flexural response uncovers, the individual factor evaluation reveals a highly localized statistical significance centered entirely on the non-linear configurations of layer thickness (H). Specifically, the pure quadratic effect of layer thickness ( $H^2$ ) is highly significant for both flexural strength ( $p = 0.023$ ) and flexural modulus ( $p = 0.002$ ). This non-linear behavior is further amplified by specific higher-order couplings; the three-way interactions  $H^2$ .PS ( $p = 0.024$  for flexural strength ( $\sigma_F$ ),  $p = 0.002$  for flexural modulus ( $E_F$ )) and  $H^2$ .ER ( $p = 0.025$  for flexural strength ( $\sigma_F$ ),  $p = 0.002$  for flexural modulus ( $E_F$ )), alongside the comprehensive four-way interaction  $H^2$ .ER ( $p = 0.023$  for flexural strength ( $\sigma_F$ ),  $p = 0.002$  for flexural modulus ( $E_F$ )), all achieve strong statistical significance. Physically, these results reveal that

under three-point flexural test where the specimen undergoes a combined state of upper-surface compression, neutral-axis shear, and lower-surface tension the structural integrity is fundamentally governed by a non-linear geometric and thermal threshold related to the layer height. The high critical significance of the  $H^2$  terms demonstrates that internal void geometry, bead-to-bead necking growth, and interlaminar weld lines do not scale linearly. Instead, there is an optimal processing window where specific combinations of layer thickness, flow dynamics governed by the extrusion ratio (ER), and thermal tracking speeds (PS) collectively minimize internal structural defects, thereby maximizing the cross-sectional moment of inertia and preventing premature delamination under complex flexural stress states.

The regression equations, incorporating main effects, quadratic terms, and complex interactions, are presented below:

$$\begin{aligned} \sigma_{fMax} \text{ (MPa)} &= -2493 + 8382 H + 69,6 PS + 49,4 ER + 77000 H^2 - 0,536 PS^2 - 0,249 ER^2 - 294 H.PS - (3) \\ &\quad 285 H.ER - 1,062 PS.ER - 1510 H^2.PS - 756 H^2.ER + 3,66 H.PS^2 + 6,00 H.PS.ER + 2,06 H.ER^2 \\ &\quad + 0,00482 PS^2.ER + 0,00420 PS.ER^2 + 15,12 H^2.PS.ER - 0,0326 H.PS^2.ER - 0,0345 H.PS.ER^2 \\ E_f \text{ (MPa)} &= -89742 + 262117 H + 2791 PS + 1923 ER + 4592537 H^2 - 28,0 PS^2 - 10,51 ER^2 - 13891 H.PS - (4) \\ &\quad 12555 H.ER - 42,1 PS.ER - 89313 H^2.PS - 45948 H^2.ER + 216,7 H.PS^2 + 296 H.PS.ER \\ &\quad + 103,0 H.ER^2 + 0,262 PS^2.ER + 0,162 PS.ER^2 + 903 H^2.PS.ER - 2,018 H.PS^2.ER - \\ &\quad 1,748 H.PS.ER^2 \end{aligned}$$

The complexity of these equations, particularly the presence of significant interaction terms (H, PS, ER), highlights the synergistic nature of the FDM process. For the flexural modulus, although the individual factors have higher p-values, the overall significance of the model ( $P=0.006$ ) confirms that the combined interaction of layer thickness and extrusion rate is the true driver of the material's stiffness.

Normal probability plots (Fig. 15) were utilized to assess the goodness of fit of the experimental data to a theoretical normal distribution. In these plots, the experimental data points are considered normally distributed if they align closely along the diagonal reference line. As illustrated for the flexural strength (Fig. 13a), the experimental data points fall well along this reference line, exhibiting a mean of 42.71 MPa and a standard deviation of 4.808 MPa. Similarly, for the flexural modulus (Fig. 13b), the experimental data points are tightly distributed around the mean of 2112 MPa with a standard deviation of 256.2 MPa. The obtained p-values 0.348 for the flexural strength and 0.554 for the flexural modulus are significantly greater than the standard 0.05 significance threshold, thereby failing to reject the null hypothesis and supporting the assumption of normality. This statistical evidence confirms the validity of using this specific dataset for subsequent statistical modeling, regression analysis, and multi-objective parameter optimization [42], ensuring a robust predictive framework for FDM-printed PLA.

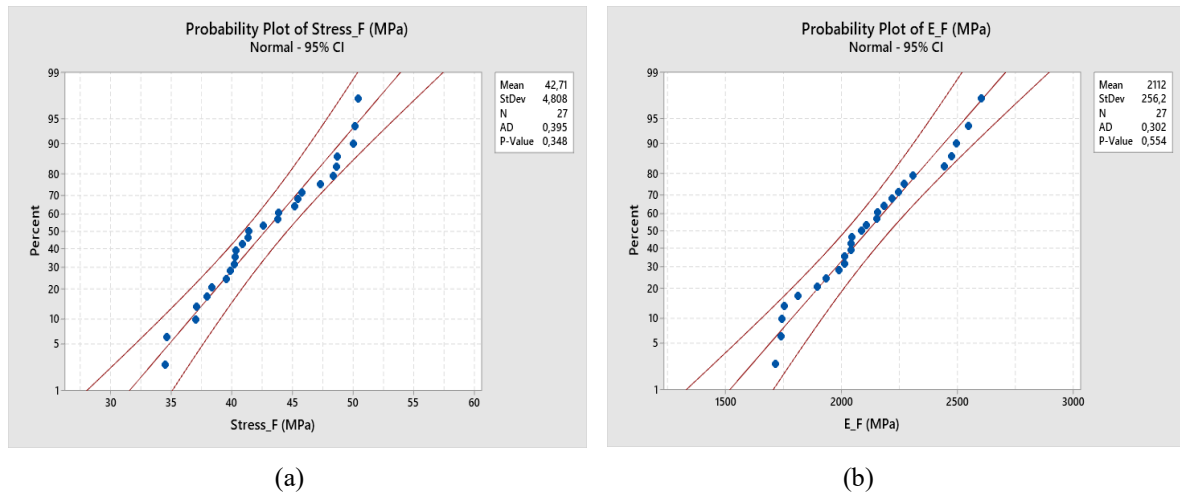


Fig. 15. Probability plots: (a) Flexural stress; (b) Flexural modulus.

#### 4. Multi-objective optimization and experimental validation

Following the modeling phase, a multi-objective optimization was implemented to determine the Pareto-optimal trade-off for maximizing both tensile and flexural properties. The optimized FDM processing parameters identified through this multi-objective framework are a layer thickness (H) of 0.20 mm, a printing speed (PS) of 40 mm/s, and an extrusion ratio (ER) of 110%.

The predictive model's performance was verified via conducting experimental tests with the improved process parameters. The experimental results were analyzed in comparison with the expected theoretical ones in Table 8. The results show highly positive results with the deviations from the expected data at the levels of 2.61% and 6.21%. The strong correlation among all the resulting data shows the efficiency of the suggested prediction model for the use of PLA materials generated through the FDM process. Thus, the results of the research give important recommendations on how to adjust the FDM process for better mechanical characteristics of the produced parts.

**Table 8.** Results of the predictive model validation (Prediction vs. Experience).

| Property                      | Predicted | Measured | Error (%) |
|-------------------------------|-----------|----------|-----------|
| Maximum Flexural Stress (MPa) | 47.25     | 50.44    | 6.32      |
| Flexural Modulus (MPa)        | 2452.87   | 2604.81  | 5.83      |
| Maximum Tensile Stress (MPa)  | 22.84     | 23.83    | 4.15      |
| Young's Modulus (MPa)         | 856.40    | 872.87   | 1.89      |

#### 5. Conclusion

This paper presents a critical analysis of the effects of the three parameters in FDM printing: the layer thickness

(0.10, 0.15, and 0.20 mm), the printing speed (40, 50, and 60 mm.s<sup>-1</sup>), and the extrusion ratio (90, 100, and 110 %), on flexural and tensile characteristics of PLA.

This research has successfully established a comprehensive understanding of how key FDM process parameters dictate the mechanical integrity of PLA structures. Based on a methodical exploratory and statistical model, several important conclusions were made. The extrusion ratio (ER) is determined to be the most affecting factor of tensile and flexural strength properties, since an increase in the ER to 110% ensures proper bonding between the layers and the almost complete absence of internal porosity of the material, which is important for the structural applications. Though each of the factors is important, it is primarily the interaction between the layer thickness and the extrusion ratio that is of great importance for Young's modulus, as the layer thickness of 0.20 mm allows achieving the highest rigidity when combined with high extrusion ratios, especially during bending tests. Multi-objective optimization has identified the optimum configuration as follows: H = 0.20mm, PS = 40mm/s, and ER = 110%, and experimental validation showed excellent agreement with the predictive models, with errors not exceeding 6.32%. Ultimately, the predictive framework and optimized parameters developed in this work provide a reliable guide for researchers and engineers.

As this work was specifically conducted to advance the development of patient-specific medical devices such as finger orthoses designed to correct finger deformities and deficits future research will focus on directly applying these optimal printing parameters to the FDM fabrication of functional finger splints. Furthermore, visions entail extending this optimization concept by using machine learning methodologies, including neural networks and genetic algorithms.

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## **Declarations**

**Consent to participate** Not applicable.

**Consent for publication** The manuscript was approved by all authors for publication.

**Conflict of Interest** The authors declare no competing interests.

## References

1. Kumar, R., M. Kumar, and J.S. Chohan (2021) Material-specific properties and applications of additive manufacturing techniques: a comprehensive review. *Bulletin of Materials Science*. 44(3): p. 181. <https://doi.org/10.1007/s12034-021-02364-y>.
2. Karakurt, I. and L. Lin (2020) 3D printing technologies: techniques, materials, and post-processing. *Current Opinion in Chemical Engineering*. 28: p. 134-143. <https://doi.org/10.1016/j.coche.2020.04.001>.
3. Mohanavel, V., et al. (2021) The roles and applications of additive manufacturing in the aerospace and automobile sector. *Materials Today: Proceedings*. 47: p. 405-409. <https://doi.org/10.1016/j.matpr.2021.04.596>.
4. Han, S.H., et al. (2021) BMP-2 and hMSC dual delivery onto 3D printed PLA-Biogel scaffold for critical-size bone defect regeneration in rabbit tibia. *Biomedical Materials*. 16(1): p. 015019. <https://doi.org/10.1088/1748-605X/aba879>.
5. Vardhan, H., R. Kumar, and J.S. Chohan (2020) Investigation of tensile properties of sprayed aluminium based PLA composites fabricated by FDM technology. *Materials Today: Proceedings*. 33: p. 1599-1604. <https://doi.org/10.1016/j.matpr.2020.05.335>.
6. Kouhi, M., et al. (2024) Recent advances in additive manufacturing of patient-specific devices for dental and maxillofacial rehabilitation. *Dental Materials*. 40(4): p. 700-715. <https://doi.org/10.1016/j.dental.2024.02.006>.
7. Petersmann, S., et al. (2020) Mechanical properties of polymeric implant materials produced by extrusion-based additive manufacturing. *Journal of the mechanical behavior of biomedical materials*. 104: p. 103611. <https://doi.org/10.1016/j.jmbbm.2019.103611>.
8. Kumar, R., M. Kumar, and J.S. Chohan (2021) The role of additive manufacturing for biomedical applications: A critical review. *Journal of Manufacturing Processes*. 64: p. 828-850. <https://doi.org/10.1016/j.jmapro.2021.02.022>.
9. Ngo, T.D., et al. (2018) Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*. 143: p. 172-196. <https://doi.org/10.1016/j.compositesb.2018.02.012>.
10. Srivastava, M., et al. (2022) A review of various materials for additive manufacturing: Recent trends and processing issues. *Journal of Materials Research and Technology*. 21: p. 2612-2641. <https://doi.org/10.1016/j.jmrt.2022.10.015>.
11. Choi, W.J., et al. (2020) Rapid development of dual porous poly (lactic acid) foam using fused deposition modeling (FDM) 3D printing for medical scaffold application. *Materials Science and Engineering: C*. 110: p. 110693. <https://doi.org/10.1016/j.msec.2020.110693>.
12. Raj, T., et al. (2025) Investigation of impact and compression behaviour of polymer composites for foot prosthesis through fused filament fabrication. *Plastics, Rubber and Composites*. 54(6-7): p. 261-278. <https://doi.org/10.1177/14658011251344990>.
13. Dua, R., et al. (2021) Applications of 3D-printed PEEK via fused filament fabrication: a systematic review. *Polymers*. 13(22): p. 4046. <https://doi.org/10.3390/polym13224046>.
14. Buj-Corral, I., A. Tejo-Otero, and F. Fenollosa-Artés (2021) Use of FDM technology in healthcare applications: recent advances. *Fused Deposition Modeling Based 3D Printing*. p. 277-297. [https://doi.org/10.1007/978-3-030-68024-4\\_15](https://doi.org/10.1007/978-3-030-68024-4_15).
15. Górski, F., et al. (2020) Experimental studies on 3D printing of automatically designed customized wrist-hand orthoses. *Materials*. 13(18): p. 4091. <https://doi.org/10.3390/ma13184091>.
16. Ben Amor, K., et al. (2025) Design and 3D printing of a customised wrist-hand orthosis. *Progress in Additive Manufacturing*. 10(4): p. 2715-2731. <https://doi.org/10.1007/s40964-024-00779-7>.

17. Jandyal, A., et al. (2022) 3D printing—A review of processes, materials and applications in industry 4.0. *Sustainable Operations and Computers*. 3: p. 33-42. <https://doi.org/10.1016/j.susoc.2021.09.004>.
18. Ranakoti, L., et al. (2023) Promising role of polylactic acid as an ingenious biomaterial in scaffolds, drug delivery, tissue engineering, and medical implants: research developments, and prospective applications. *Molecules*. 28(2): p. 485. <https://doi.org/10.3390/molecules28020485>.
19. Naghieh, S., et al. (2016) Numerical investigation of the mechanical properties of the additive manufactured bone scaffolds fabricated by FDM: The effect of layer penetration and post-heating. *Journal of the mechanical behavior of biomedical materials*. 59: p. 241-250. <https://doi.org/10.1016/j.jmbbm.2016.01.031>.
20. Belhadj, A., et al. (2023) Effect of printing process parameters on the tensile behavior of FDM-built parts. in *Advances In Additive Manufacturing Conference*. Springer. [https://doi.org/10.1007/978-3-031-47784-3\\_26](https://doi.org/10.1007/978-3-031-47784-3_26).
21. Wang, Y., et al. (2021) Mechanical properties of fused filament fabricated PEEK for biomedical applications depending on additive manufacturing parameters. *Journal of the mechanical behavior of biomedical materials*. 115: p. 104250. <https://doi.org/10.1016/j.jmbbm.2020.104250>.
22. Razzaq, M.H., et al. (2025) Additive manufacturing for biomedical bone implants: Shaping the future of bones. *Materials Science and Engineering: R: Reports*. 163: p. 100931. <https://doi.org/10.1016/j.mser.2025.100931>.
23. Layeb, N., et al. (2025) Improving the strength properties of PLA acetabular liners by optimizing FDM 3D printing: Taguchi approach and finite element analysis validation. *The International Journal of Advanced Manufacturing Technology*. 137(5): p. 2649-2664. <https://doi.org/10.1007/s00170-025-15314-3>.
24. Sölmann, S., et al. (2021) Mammalian cell adhesion on different 3D printed polymers with varying sterilization methods and acidic treatment. *AIMS Bioengineering*. 8(1). 10.3934/bioeng.2021004.
25. Moreno, R., et al. (2021) Statistical models for the mechanical properties of 3D printed external medical aids. *Rapid Prototyping Journal*. 27(1): p. 176-186. <https://doi.org/10.1108/RPJ-02-2020-0033>.
26. Ahrendt, D. and A. Romero Karam (2020) Development of a computer-aided engineering–supported process for the manufacturing of customized orthopaedic devices by three-dimensional printing onto textile surfaces. *Journal of Engineered Fibers and Fabrics*. 15: p. 1558925020917627. <https://doi.org/10.1177/1558925020917627>.
27. Reddy, S., et al. (2025) Optimization of Mechanical Properties in Biomedical-Grade Polylactic Acid (PLA) Components Fabricated Via Fused Filament Fabrication (FFF). *Advances in Polymer Technology*. 2025(1): p. 9156905. <https://doi.org/10.1155/adv/9156905>.
28. Amor, K.B., S. Chatti, and B. Louhichi (2024) Material investigation and effect of printing orientation, tensile speed, and density on the mechanical behaviour of 3d printed parts. *Annals of “Dunarea de Jos” University of Galati. Fascicle XII, Welding Equipment and Technology*. 35: p. 109-118. <https://doi.org/10.35219/awet.2024.10>.
29. Mushtaq, R.T., et al. (2024) Maximizing performance and efficiency in 3D printing of polylactic acid biomaterials: unveiling of microstructural morphology, and implications of process parameters and modeling of the mechanical strength, surface roughness, print time, and print energy for fused filament fabricated (FFF) bioparts. *International Journal of Biological Macromolecules*. 259: p. 129201. <https://doi.org/10.1016/j.ijbiomac.2024.129201>.
30. Risad, R.H., et al. (2024) FDM printing process and its biomedical application. *Chemical Research and Technology*. 1(3): p. 138-149. <https://doi.org/10.22034/chemrestec.2024.467346.1021>.
31. Leite, M., et al. (2018) Study of the influence of 3D printing parameters on the mechanical properties of PLA. <https://doi.org/10.25341/D4988C>.

32. Rakesh Kumar, M.K., Naveen Singh, Ravi Bhardwaj, Gaurav Luthra (2025) Optimizing FDM Parameters for Reliable and Efficient Production of Biomedical Parts. *Journal of Materials and Engineering school*. 03(3): p. 247-258. <https://doi.org/10.61552/JME.2025.03.001>.
33. Lendvai, L., et al. (2025) Experimental study on the effect of filament-extrusion rate on the structural, mechanical and thermal properties of material extrusion 3D-printed polylactic acid (PLA) products. *Progress in Additive Manufacturing*. 10(1): p. 619-629. <https://doi.org/10.1007/s40964-024-00646-5>.
34. Lou, X., et al. (2025) Influence of layer thickness and extrusion ratio on strand morphology, porosity, surface roughness, and anisotropic mechanical properties in FDM. *Scientific Reports*. 15(1): p. 42351. <https://doi.org/10.1038/s41598-025-26253-0>.
35. Yılan, F., et al. (2023) The effects of different process parameters of PLA+ on tensile strengths in 3D printer produced by fused deposition modeling. *El-Cezeri*. 10(1): p. 160-174. <https://doi.org/10.31202/ecjse.1179492>.
36. Syrlybayev, D., et al. (2021) Optimisation of Strength Properties of FDM Printed Parts—A Critical Review. *Polymers*. 13(10): p. 1587. <https://doi.org/10.3390/polym13101587>.
37. Rota, I., D. Bertolo, and D. Gastaldi (2025) Printing fidelity assessment and micro-mechanical characterization of FDM-printed PLA/HA composite for maxillofacial and oral applications. *Journal of the Mechanical Behavior of Biomedical Materials*. 168: p. 106987. <https://doi.org/10.1016/j.jmbbm.2025.106987>.
38. Kafshgar, A.R., et al. (2021) Optimization of properties for 3D printed PLA material using Taguchi, ANOVA and multi-objective methodologies. *Procedia Structural Integrity*. 34: p. 71-77. <https://doi.org/10.1016/j.prostr.2021.12.011>.
39. Pastor-Artigues, M.-M., et al. (2019) Elastic asymmetry of PLA material in FDM-printed parts: Considerations concerning experimental characterisation for use in numerical simulations. *Materials*. 13(1): p. 15. <https://doi.org/10.3390/ma13010015>.
40. Shergill, K., Y. Chen, and S. Bull (2023) What controls layer thickness effects on the mechanical properties of additive manufactured polymers. *Surface and Coatings Technology*. 475: p. 130131. <https://doi.org/10.1016/j.surfcoat.2023.130131>.
41. Kumar, K. and H. Singh (2023) Multi-objective optimization of fused deposition modeling for mechanical properties of biopolymer parts using the Grey-Taguchi method. *Chinese Journal of Mechanical Engineering*. 36(1): p. 30. <https://doi.org/10.1186/s10033-023-00847-z>.
42. Hasanzadeh, R., et al. (2023) Optimization of process parameters of fused filament fabrication of polylactic acid composites reinforced by aluminum using Taguchi approach. *Metals*. 13(6): p. 1013. <https://doi.org/10.3390/met13061013>.