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Research Article

Mechanical characterization of FDM-printed PLA: Role of infill geometry and build direction

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ABSTRACT

This study examines the mechanical behavior of polylactic acid (PLA) components produced via Fused Deposition Modeling (FDM), focusing on the effects of infill geometry and build orientation on tensile strength and deformation. Three infill patterns–Cubic Subdivision, Gyroid, and Tri-Hexagon–were combined with three build orientations (0°, 45°, and 90°) using an L9 Taguchi orthogonal array to systematically evaluate their influence and identify optimal configurations. ASTM D638 Type IV tensile specimens were fabricated and tested to assess performance. The results revealed that the Gyroid pattern at a 90° build orientation achieved the highest tensile strength (987.3 N), while the 45° build orientation exhibited the greatest ductility (3.39 mm), reflecting the anisotropic mechanical behavior inherent to FDM. The Tri-Hexagon pattern displayed brittle fracture characteristics, whereas the Cubic Subdivision offered intermediate performance. Analysis of variance (ANOVA) identified infill pattern as the most significant factor, accounting for 86.52% of the variation in mechanical properties, while build orientation contributed 6.29%. These findings emphasize that infill strategy plays a far more decisive role than build orientation in determining mechanical performance. Overall, the study provides practical insights into optimizing FDM-printed components by selecting appropriate infill patterns and build orientations to meet application-specific requirements, particularly where strength or energy absorption is critical. The results can serve as a reference for designers and engineers aiming to enhance the structural efficiency and reliability of 3D-printed PLA parts.

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1. Introduction

With the rapid evolution of modern technology and the accelerating transformation of industrial systems, significant progress has been achieved in both materials and manufacturing techniques to address the increasingly complex and diverse demands of industry. Among these innovations, additive manufacturing (AM) has gained widespread attention for its ability to produce three-dimensional components directly from computer-aided design (CAD) models, without the need for conventional molds or tooling. Unlike subtractive manufacturing methods that remove material to achieve the desired shape, AM builds parts layer by layer, offering significant advantages such as reduced material waste, enhanced design flexibility, and shortened production cycles (Huang et al. 2013; Zhou et al. 2024). These benefits have led to the rapid adoption of AM technologies across various sectors, including aerospace, automotive, biomedical engineering, architecture, and education, particularly in applications requiring complex geometries, rapid prototyping, and product customization.

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Among AM techniques, Fused Deposition Modeling (FDM) has emerged as one of the most prevalent methods, particularly for the fabrication of polymer-based components. Its widespread adoption is largely attributed to its operational simplicity, cost-effectiveness, and accessibility across both industrial and desktop-scale platforms. In this process, a thermoplastic filament—commonly PLA or acrylonitrile butadiene styrene (ABS)—is fed into a heated nozzle, melted, and extruded in a controlled manner along a predefined toolpath. The material is deposited layer by layer onto a build platform, where it solidifies and bonds with preceding layers to form the final three-dimensional structure. FDM technology offers several advantages over traditional subtractive techniques, including reduced material waste, shortened production lead times, and the ability to fabricate components with complex geometries, hollow sections, and customized internal infill patterns (Rajpurohit and Dave 2018; Solomon et al. 2020; Le et al. 2022; Equbal et al. 2024). Other FDM advantage is the elimination of dies and molds, which is an investment that needs to be made whenever the designs are changed. This makes FDM or AM a useful technique when high customization is necessary. FDM is still a novel technology that produces parts with a quality that is not currently comparable to the injection molding parts (Alafaghani and Qattawi 2018). These attributes make FDM particularly well-suited for rapid prototyping and low-volume manufacturing. Furthermore, materials such as PLA are frequently preferred due to their biodegradability, low warping behavior, and favorable strength-to-weight ratio (Equbal et al. 2024).

However, despite its many advantages, the mechanical integrity of FDM-printed parts is highly sensitive to various process parameters, including layer thickness, nozzle temperature, printing speed, infill density, and build orientation. Among these, build orientation and raster angle are particularly critical due to the anisotropic nature of the layer-by-layer deposition process. When the applied load is aligned either parallel or perpendicular to the printed layers, significant variations in tensile strength, ductility, and failure behavior can occur—primarily resulting from differences in interlayer bonding and internal stress distribution. Numerous studies have demonstrated that even slight changes in build orientation or raster angle can lead to substantial differences in mechanical performance, including elastic modulus and fracture behavior (Casavola et al. 2016; Yao et al. 2019; Taşdemir 2024). This anisotropic response presents a major challenge in functional applications where uniform mechanical properties are essential under complex loading conditions. Therefore, understanding and optimizing these build orientation-related parameters is crucial for enhancing the structural reliability and overall performance of FDM-printed components (Alafaghani and Qattawi 2018; Ambade et al. 2023).

Several recent studies have systematically explored the influence of FDM process parameters, internal structures, and deposition strategies on the mechanical performance and consistency of printed parts. Dezaki and Ariffin (2020) showed that combining infill patterns like grid and honeycomb can significantly improve mechanical integrity compared to single-pattern designs. In terms of fracture behavior, Marșavina et al. (2022) demonstrated that crack propagation paths vary significantly with build orientation, highlighting the strong anisotropy induced by the layer-wise process. Similarly, Zhao et al. (2019) focused on how internal geometry and wall thickness affect stress distribution and found that optimized internal designs can delay failure and increase energy absorption. Akhoundi and Behravesh (2019) further reported that concentric infill patterns outperformed other patterns such as rectilinear or honeycomb in tensile and flexural tests, indicating a pattern-dependent load distribution mechanism. Le et al. (2022) emphasized the importance of balancing mechanical performance with production efficiency, demonstrating that specific combinations of infill density, nozzle diameter, and shell count can reduce build time without significantly compromising strength. Laureto and Pearce (2018) provided quantitative insight into anisotropic mechanical behavior, noting a nearly 48% reduction in tensile strength for vertically printed PLA specimens compared to horizontal ones. Vălean et al. (2020) investigated the effects of spatial printing directions (0°, 45°, 90°) and specimen thickness on tensile properties, finding that orientation strongly influences tensile strength but has a lesser impact on Young's modulus, and also showed that key FDM parameters such as infill density, layer thickness, and print speed significantly affect tensile strength of PET-G parts. Ambade et al. (2025) demonstrated that optimized build orientation combined with specific infill geometries can significantly enhance tensile performance without increasing print time. Zhou et al. (2024) highlighted the role of advanced infill architectures, such as triply periodic minimal surfaces, in improving both load distribution and energy absorption in lightweight structural applications. These studies demonstrate that ensuring directional strength and structural consistency in FDM requires process-aware and multivariable optimization approaches. While several studies have individually optimized infill pattern or build orientation to enhance the mechanical properties of FDM-printed components, comprehensive investigations that address the combined and simultaneous optimization of both parameters remain limited. This gap is particularly evident for PLA-based applications, where anisotropic behavior and load distribution mechanisms are strongly influenced by the interaction between internal geometry and build orientation. The present study addresses this gap through a systematic Taguchi-based approach.

In this study, the mechanical behavior of FDM-printed PLA components was systematically investigated with respect to infill pattern and build orientation—two key parameters known to affect part strength and anisotropy. Standard tensile specimens were produced using three distinct infill geometries (Cubic Subdivision, Gyroid, and Tri-Hexagon) at three different printing angles (0°, 45°, and 90°), in accordance with ASTM D638 standards. An L9 Taguchi orthogonal array design was employed to efficiently explore the influence of these parameters on tensile strength and deformation characteristics. The objective is to identify optimal combinations of internal structure and build orientation that improve the mechanical performance of PLA-based FDM components. The findings of this study are expected to support parameter optimization in additive manufacturing processes, particularly for applications where dimensional accuracy, mechanical reliability, and load-bearing capacity are critical.

2. Experimental Methodology

This article analyzes the mechanical performance of parts manufactured using PLA as a filament. Table 1 shows the data provided by the manufacturer for the filament used. The additive manufacturing equipment to be used is the Creality Ender 3 V3 SE 3D printer using FDM technology (Fig. 1).

Table 1. Technical specifications of the filament used.

Material	Color	Tensile strength (MPa)	Elongation at break (%)	Tensile modulus (MPa)	Density (g/cm^3 at 21.5 °C)
PLA+	White	40–50	7–8	750–910	1.24 ±0.1

Fig. 1. FDM 3D printer used in the production of experimental samples.

The Creality Print software is used to transfer the 3D models of the samples to G-code. The basic technical specifications of the FDM printer are described in Table 2.

The samples used in this study to evaluate the dimensional accuracy, repeatability, and mechanical properties were modeled according to the American Society for Testing and Materials ASTM D638 type IV standards for plastic tensile testing. Fig. 2 shows the dimensions used to create the CAD model.

Fig. 3 presents schematic representations of three filling patterns of Gyroid, Cubic Subdivision and Tri-Hexagonal structures. Gyroid pattern, a continuous wave-like 3D surface without flat planes, providing isotropic load distribution and improved interlayer adhesion. Its smooth curvature minimizes stress concentrations, potentially enhancing both strength and ductility (Khaderi et al. 2014; Silva et al. 2021). Cubic subdivision, a lattice-like cubic structure subdivided into smaller cells, offering balanced rigidity and weight reduction, with load transfer primarily along straight struts (Jasim et al. 2022; Rahman et al. 2023). Tri-Hexagon, a planar pattern composed of interlinked triangular and hexagonal cells, forming a stiff and lightweight grid. While this design provides high rigidity, stress concentrations at the vertices may reduce ductility (Tandon et al. 2021, 2025; Abdullah and Abbas 2023). After printing, dimensional accuracy of the specimens was verified using a digital caliper with ±0.01 mm resolution. Measurements were taken on critical features defined by the ASTM D638 Type IV standard, including overall length, gauge length, and width. All printed specimens were within ±0.2 mm of the nominal CAD dimensions, ensuring compliance with the standard's dimensional tolerance requirements.

Table 2. Technical specifications of the FDM 3D printer.

Printing technology	Fused deposition modelling
Build volume (mm)	220×220×250
Printing speed (typical – max) (mm/s)	180–250
Acceleration (mm/s^2)	2500
Layer height (mm)	0.1–0.35
Extruder type	"Sprite" direct extruder
Nozzle temperature (°C)	≤ 260
Heatbed temperature (°C)	≤ 100
Nozzle diameter (mm)	0.4

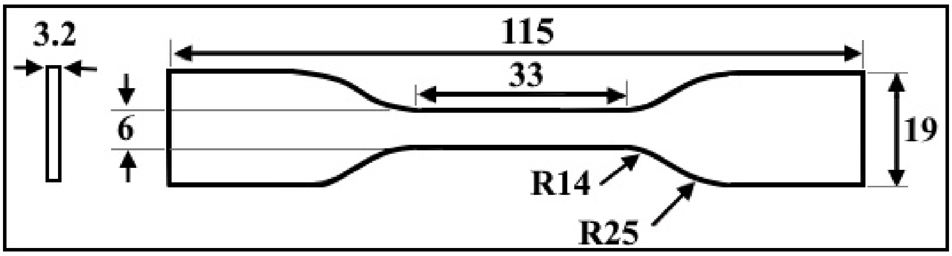

Fig 2. ASTM D638 type IV samples.

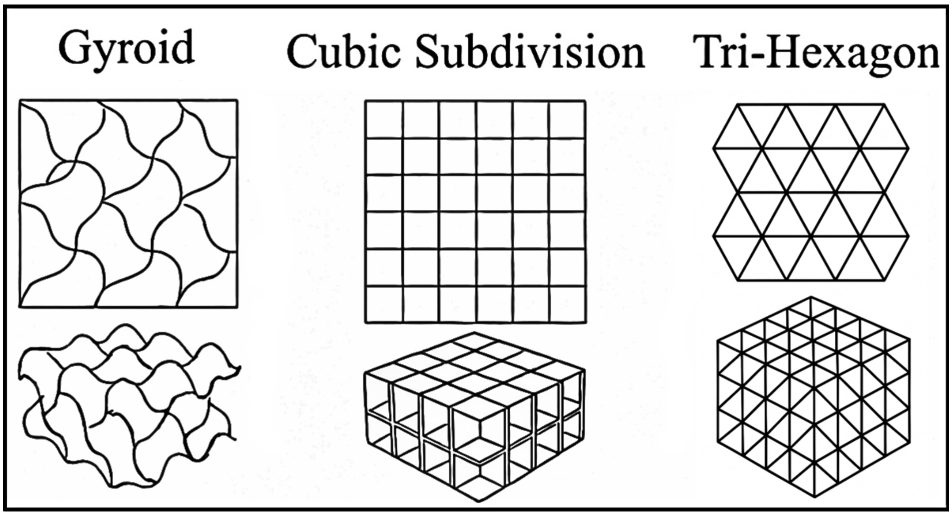

Fig. 3. The schematic representations of three filling patterns of Gyroid, Cubic Subdivision and Triple Hexagonal structures.

This 3D model was then transferred to the Creality Print slicing software to generate the appropriate G-code for printing, as illustrated in Fig. 4. After slicing, the printer settings were optimized. The fixed printing parameters were as follows: nozzle temperature (200 °C), heatbed temperature (60 °C), print speed (180 mm/s), layer height (0.2 mm), and nozzle diameter (0.4 mm). Variable parameters infill pattern and build orientation were selected as controllable factors in this study and are listed in Table 3. Each parameter was tested at multiple levels using a L9 orthogonal Taguchi Design of Experiments (DoE) approach to ensure robust statistical evaluation. The results were analyzed by signal-to-noise ratio (S/N), mean values and standard deviations. In addition, the statistical significance of the factors was evaluated by ANOVA. All statistical analyses were performed using Minitab® Statistical Software (version 21.1.1). Both the ANOVA and signal-to-noise (S/N) ratio calculations were conducted using parametric methods.

Prior to analysis, the Anderson–Darling test confirmed that residuals followed a normal distribution ($p>0.05$), and Levene's test verified homogeneity of variances ($p>0.05$), meeting the assumptions required for valid parametric inference. The Taguchi L9 orthogonal array was selected to evaluate the effects of two control factors—infill pattern (Cubic Subdivision, Gyroid, Tri-Hexagon) and build orientation (0°, 45°, 90°)—each at three levels. According to Taguchi design principles, an L9 array provides a balanced comparison of factor levels while reducing the total number of experiments from 27 (full factorial) to 9, thereby conserving material, time, and experimental resources without sacrificing statistical validity for main effects analysis. The choice of these two parameters was guided by prior literature identifying them as the most influential on the anisotropic tensile performance of FDM-printed PLA parts. Other process variables, including layer height, nozzle temperature, print speed, and infill density, were held constant to isolate the effects of the selected factors. The main limitation of this approach lies in its inability to fully capture higher-order interaction effects or responses under different environmental conditions. Furthermore, the analysis was restricted to PLA material and a specific set of geometries, which may limit direct generalization to other materials or process settings.

Table 3. Variable parameters for all specimens.

Process parameters	Level 1	Level 2	Level 3
Infill pattern	Cubic Subdivision	Gyroid	Tri-Hexagon
Build orientation	0°	45°	90°

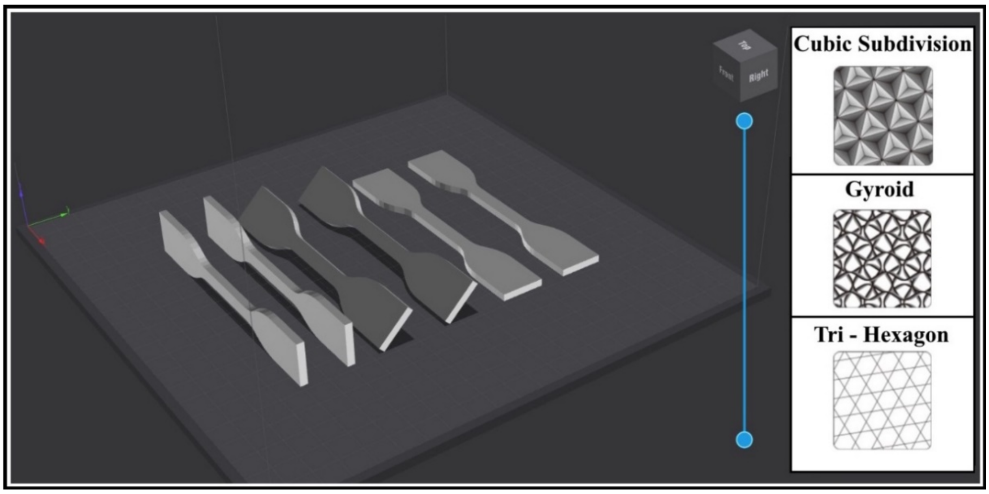

Fig. 4. Slicing in flash print software tensile model.

An experimental matrix consisting of nine test conditions was developed, incorporating three different build orientations (0°, 45°, and 90°) and three infill patterns (Cubic Subdivision, Gyroid, and Tri-Hexagon). As shown in Table 4, for each of the nine experimental conditions defined in the L9 Taguchi orthogonal array, two identical specimens were fabricated and tested to assess repeatability and minimize experimental error. The number of repetitions was limited to two to preserve the efficiency of the Taguchi design. Statistical analyses, including ANOVA and S/N ratio evaluation, were performed to verify the consistency of the results. Images of samples with different infill pattern after production are shows in Fig. 5.

Table 4. Taguchi experiment L9 matrix**.**

Exp. no.	Nomenclature samples	Infill pattern	Build orientation
1	C0	Cubic Subdivision	0°
2	C45	Cubic Subdivision	45°
3	C90	Cubic Subdivision	90°
4	G0	Gyroid	0°
5	G45	Gyroid	45°
6	G90	Gyroid	90°
7	T0	Tri-Hexagon	0°
8	T45	Tri-Hexagon	45°
9	T90	Tri-Hexagon	90°

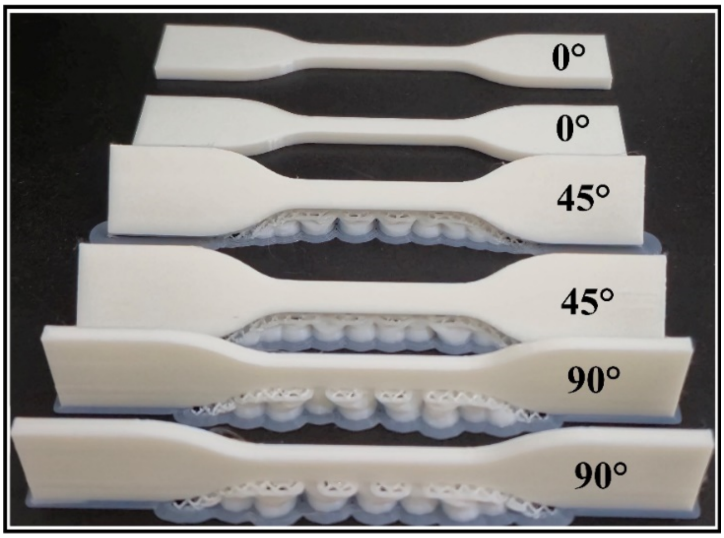

Fig. 5. Tensile test samples produced in different orientations.

After fabrication, the samples were subjected to tensile testing using an INSTRON 5982 universal testing machine to evaluate their mechanical performance tensile strength and elongation at break. As illustrated in Fig. 6, the tests were conducted at room temperature on a static testing machine with a constant crosshead speed of 5 mm/min, in accordance with ASTM D638 Type IV standards for FDM-fabricated specimens.

Fig. 6. The image of experimental samples in the tensile test device.

3. Results and Discussion

The Taguchi optimization technique, employed in process improvement, follows an eight-step methodology involving the design, execution, and evaluation of matrix experiments to determine the ranking and optimal levels of control factors (Arora et al. 2023). The Taguchi method was applied to systematically evaluate the effects of infill pattern and build orientation on the tensile strength and elongation at break of PLA-based FDM specimens. An L9 orthogonal array design was selected to reduce the number of experiments while maintaining statistical validity. The experimental results were then analyzed to determine the optimal levels of control factors and their relative influence on mechanical properties.

3.1. Analysis of experimental tensile tests

In this section, the results of all tensile tests are presented by systematically grouping the data according to constant infill patterns and build orientations. The mechanical performance of each group is evaluated under distinct headings to facilitate a clearer comparison of the effects of individual parameters. Fig. 7 presents the post-tensile test appearance of specimens fabricated via FDM using different infill patterns (Gyroid, Cubic Subdivision, Tri-Hexagon) and build orientations (0°, 45°, 90°). It is observed that fractures predominantly occurred in the central region, with fracture surfaces varying depending on the infill pattern and build orientation. Specimens printed at 90° exhibited greater deformation, indicating a more ductile fracture behavior, whereas those printed at 0° showed sharper and more brittle fracture characteristics. In the 45° oriented specimens, inclined and irregular fracture surfaces suggest that interlayer interactions had a significant influence on the failure behavior. The slight drop in force observed around 200 N in the all tensile curves can be attributed to early micro-failure at interlayer zones or void collapse in transition regions between outer shell and internal infill. Adragna et al. (2021) and Marşavina et al. (2022) reported similar behavior in PLA specimens with complex infill geometries, where local instabilities caused a momentary force reduction, followed by stress redistribution across the infill, allowing for a secondary rise in force prior to failure.

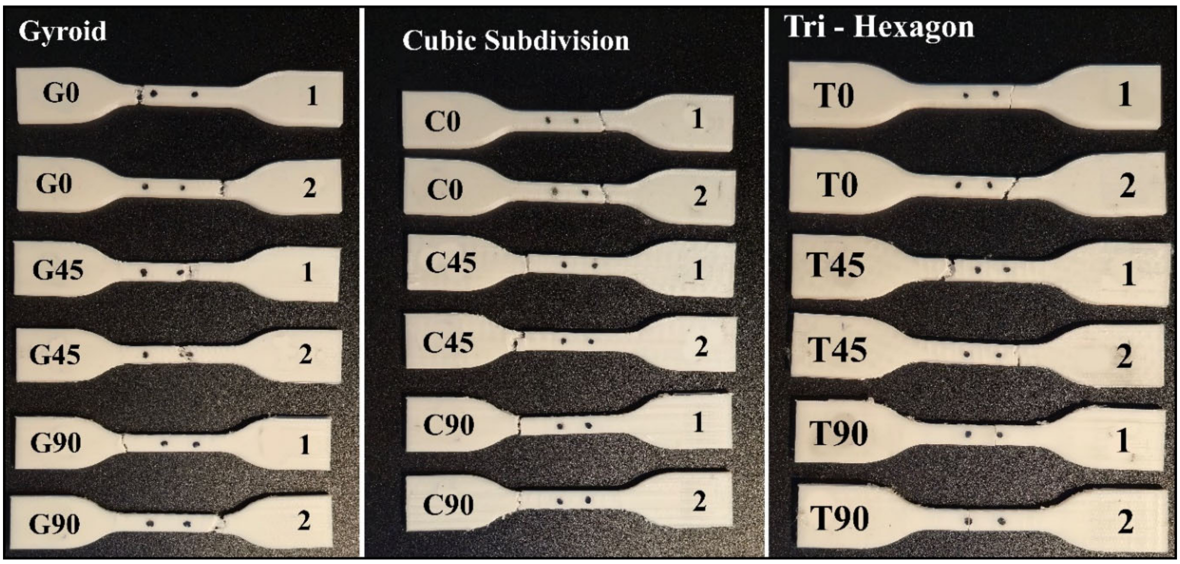

Fig. 7. Images of samples after tensile testing.

3.1.1. Effect of infill pattern on mechanical properties

The tensile graphs of different infill patterns, keeping the build orientation constant as 0°, are presented in Fig. 8. The maximum load and maximum elongation of the samples in different infill patterns of this figure were evaluated. The load-displacement curves obtained as a result of the tensile tests clearly reveal the effects of different internal structure patterns on mechanical performance. Samples with G0, T0 and C0 patterns were produced with the same build orientation (0°) and showed significant differences in terms of their load carrying capacities and ductility during deformation. The T 0 sample with the Tri-hexagon pattern reached the highest maximum load value of approximately 800 N, indicating that this pattern was the most advantageous structure in terms of strength. However, this sample exhibited a sudden load loss after reaching the peak point and fractured at a lower displacement; this situation suggests that the structure exhibited a relatively brittle behavior. On the other hand, the G0 sample with the Gyroid pattern reached a similar load level but showed a longer deformation zone before rupture. This situation reveals that the Gyroid structure has high ductility and energy absorption capacity. The cubic patterned C0 sample exhibited a moderate performance in terms of both maximum load and ductility.

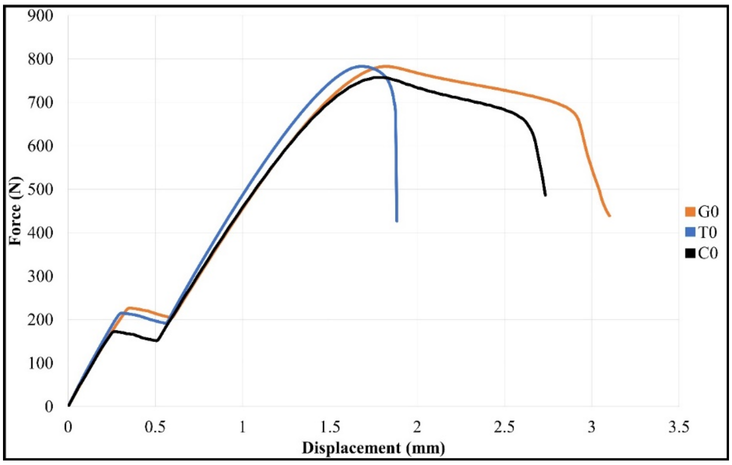

Fig. 8. Effect of infill geometry on tensile behavior at 0° orientation.

Fig. 9 shows the tensile force–displacement behavior of specimens manufactured with a Gyroid infill pattern under 45° build orientation. The load-displacement curves of the samples with 45° built-up orientation once again revealed the effect of infill patterns on the mechanical behavior. When the G45, T45 and C45 patterns were compared, the Gyroid structure had the highest maximum load capacity (~840 N) and the largest deformation area. This shows that the Gyroid pattern maintained its high ductility and toughness properties even at the 45° built-up orientation. The T45 and Cubic C45 patterns reached lower peak loads around 740–760 N and showed earlier fracture. Especially the T45 sample exhibited a relatively brittle behavior with a sudden load drop. The Cubic C45 patterned sample exhibited a more stable behavior, but was limited in terms of ductility. It is also understood that the 45° orientation changes the bond strength between layers and affects the direction of load transfer, thus differentiating the mechanical response. In this context, it is seen that the Gyroid pattern stands out with both its high load carrying capacity and its ability to absorb energy during the deformation process, and that it can maintain its structural integrity even in the 45° build orientation. Jasim et al. (2022) reported that the choice of infill pattern alone can change PLA tensile strength by more than 25% and that gyroscopic type patterns consistently outperform linear and honeycomb designs in terms of strength-to-weight ratio.

Fig. 10 shows the tensile force–displacement behavior of specimens manufactured with a Gyroid infill pattern under 90° build orientation. The load-displacement curves of the samples produced in 90° build orientation made the effect of infill patterns on mechanical performance more evident. The sample with G90 pattern reached the highest maximum load value of approximately 1000 N and maintained its superiority in terms of strength at this orientation angle. In addition, the G90 sample not only carried high loads but also showed a longer deformation until the point of failure. This shows that the Gyroid structure exhibits both ductile and tough behavior. The samples with Tri-hexagon T90 and Cubic C90 patterns reached a maximum load carrying capacity of approximately 850–880 N. These patterns showed higher strength at 90° compared to the previous orientations, but the deformation time was shorter compared to the Gyroid pattern. In particular, the T90 sample exhibited a more brittle fracture behavior characterized by a sudden drop. The Cubic patterned C90 sample has a relatively more balanced fracture profile and shows a more positive behavior in terms of ductility than T90. However, these results obtained along the 90° build orientation reveal that aligning the layers perpendicular to the load direction increases the load carrying capacity and especially the Gyroid pattern is the most advantageous structure mechanically under this orientation. Consistent with the present findings, recent work on TPMS-based gyroid structures confirmed their superior isotropic load distribution and higher specific strength compared to lattice or grid designs, particularly under multi-axial loading (Alemayehu and Todoh 2024).

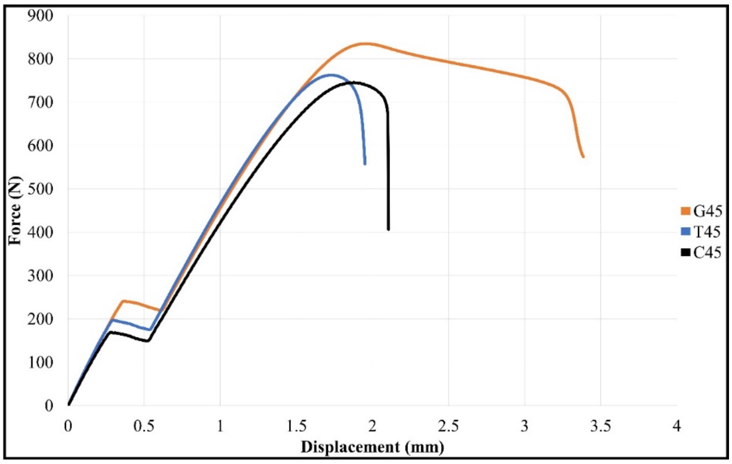

Fig. 9. Effect of infill geometry on tensile behavior at 45° orientation.

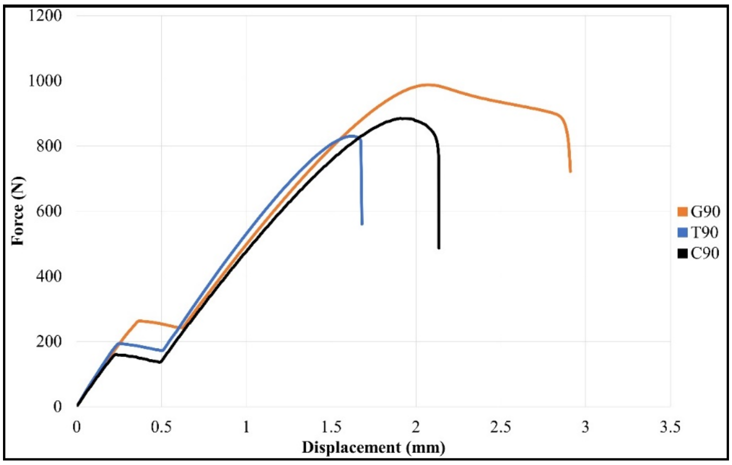

Fig. 10. Effect of infill geometry on tensile behavior at 90° orientation.

3.1.2. Effect of build orientations on mechanical properties

Fig. 11 shows the tensile force–displacement behavior of specimens manufactured with a Gyroid infill pattern under three different build orientations: 0°, 45°, and 90°. The results clearly demonstrate the significant influence of build orientation on mechanical performance. The G90 specimen exhibited the highest tensile strength, reaching approximately 1000 N, along with the greatest displacement before failure. This indicates a more ductile fracture behavior and suggests that aligning the printed layers parallel to the loading direction enhances interlayer adhesion and load transfer. In contrast, the G0 specimen, where the printed layers are perpendicular to the tensile axis, recorded the lowest maximum force (~780 N) and fractured with minimal elongation, exhibiting a brittle failure mode. The G45 specimen showed intermediate behavior in terms of both strength (~860 N) and ductility. These observations confirm the anisotropic nature of FDM-printed components and underscore the importance of build orientation in optimizing mechanical properties, even when using geometrically continuous infill patterns like Gyroid. Dawood and AlAmeen (2024), in their study on carbon fiber-reinforced PLA parts, similarly reported that the Gyroid infill pattern provided higher tensile strength and fatigue resistance compared to other infill types. They noted that, particularly at high infill densities, the Gyroid structure distributed the load more uniformly and delayed crack propagation, significantly increasing both the strength and fatigue life of the part. A similar orientation-dependent trend was reported by Vanaei et al. (2023), who found that changing the build orientation of FDM-printed PLA from 0° to 90° increased Young's modulus by approximately 40% and ductility by nearly 70%, with numerical simulations (Tsai–Hill, Tsai–Wu criteria) and FE models confirming the experimental results.

Fig. 12 illustrates the tensile force–displacement behavior of PLA specimens fabricated using the Cubic Subdivision infill pattern at three different build orientations: 0°, 45°, and 90°. The results demonstrate a clear orientation-dependent mechanical response, consistent with the anisotropic behavior commonly observed in FDM-printed parts. Among the tested samples, the C90° specimen exhibited the highest tensile strength, reaching approximately 900 N, along with the steepest force increase during loading. However, the displacement at fracture was relatively limited, suggesting a stiffer but more brittle failure mode. This behavior may be attributed to the alignment of the printed layers perpendicular to the tensile axis, where interlayer bonding plays a dominant role in resisting the applied load. In contrast, the C0 specimen demonstrated a lower peak force (~770 N) but sustained deformation over a longer displacement range, indicating a more ductile fracture mode. Since the printed layers were aligned parallel to the tensile direction, the load was distributed more uniformly along the filament paths, which enhanced elongation prior to failure despite a moderate tensile strength. The C45 specimen showed intermediate performance, with a maximum force of approximately 750 N and moderate ductility. This result can be attributed to the oblique alignment of the filament layers, which introduces complex stress paths and partial shear contributions during loading.

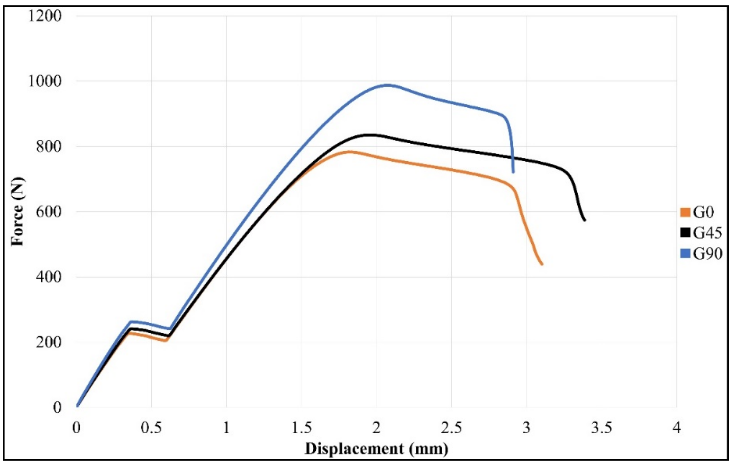

Fig. 11. Effect of Gyroid infill geometry on tensile behavior in 0° - 45° - 90° orientation.

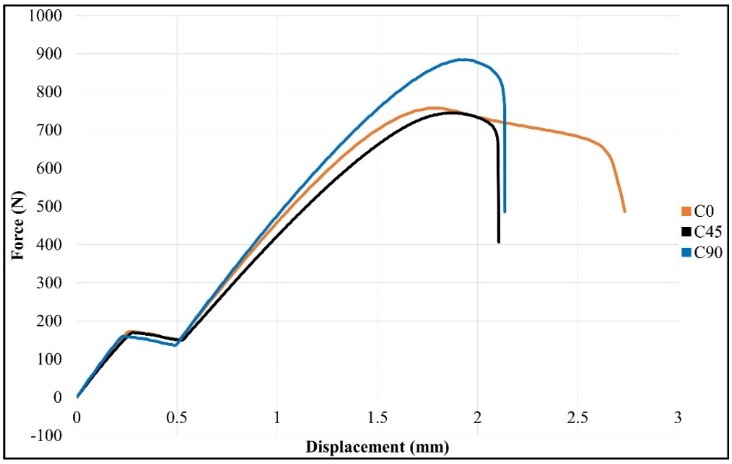

Fig. 12. Effect of Cubic Subdivision infill geometry on tensile behavior in 0° - 45° - 90° orientation.

Fig. 13 illustrates the tensile force–displacement curves for PLA specimens produced using the Tri-Hexagon infill pattern at three build orientations: 0°, 45°, and 90°. The results reveal a clear dependence of mechanical performance on build direction. Among the samples, T90 exhibited the highest tensile strength, reaching approximately 840 N, and also demonstrated the greatest elongation before failure. This indicates enhanced ductility and improved interlayer bonding when the print layers are oriented parallel to the applied load. Conversely, the T0 specimen, with layers-oriented perpendicular to the loading direction, showed a lower peak force (~780 N) and reduced displacement, suggesting a more brittle fracture mechanism. The T45 sample performed intermediately in both strength (~800 N) and ductility. Although the differences among the orientations are less dramatic compared to other infill patterns, the T90 orientation still offers measurable mechanical advantages. These findings confirm the anisotropic behavior of FDM-fabricated parts and highlight the importance of aligning the build orientation with the loading direction to optimize mechanical performance, even in complex infill structures like the Tri-Hexagon pattern.

3.1.3. Analyses of maximum force and maximum displacement

The effects of infill geometry and structure orientation (0°, 45° and 90°) on the maximum force and maximum displacement are presented in Fig. 14. Error bars in Fig. 14 indicate the mean ± standard deviation, providing a visual representation of variability across the two repeated tests for each configuration. When analyzing the maximum force, the highest value was observed for the Gyroid infill with 90° build orientation (G90: 987.3 N). This result suggests that the continuous, wave-like three-dimensional geometry of the Gyroid structure, when aligned perpendicularly to the loading axis, allows for more efficient stress distribution and improved layer adhesion, resulting in enhanced load-bearing capacity. Additionally, G90 outperformed all other combinations, indicating that the synergistic effect of a complex infill geometry and optimized orientation contributes significantly to tensile strength. In comparison, the Tri-Hexagon infill exhibited lower maximum force values across all orientations. The T90 sample recorded a maximum force of 830.1 N, which is approximately 16% lower than G90. Although the Tri-Hexagon pattern offers rigidity due to its hexagonal grid, it may not align as effectively with the tensile load direction, leading to stress concentrations and earlier failure. Nevertheless, an increasing trend was observed with build orientation: T0 (783.5 N), T45 (762.8 N), and T90 (830.1 N), suggesting that higher build angles may contribute positively to interlayer strength and filament alignment. The Cubic Subdivision infill generally showed the lowest tensile strength in 0° and 45° orientations, with values of 757.7 N (C0) and 745.7 N (C45). However, a significant increase was observed at 90° orientation, reaching 884.2 N (C90). This improvement is likely due to the cubic cell structures being better aligned with the tensile axis at 90°, facilitating improved load transfer. Nevertheless, even C90 remained approximately 10% lower in strength than G90, indicating the superior mechanical response of the Gyroid pattern under optimized orientation. Le et al. (2022) demonstrated that specific combinations of infill density, nozzle diameter, and shell count can significantly reduce print time while maintaining over 90% of the original tensile strength, stated the potential for balancing manufacturing efficiency with mechanical performance.

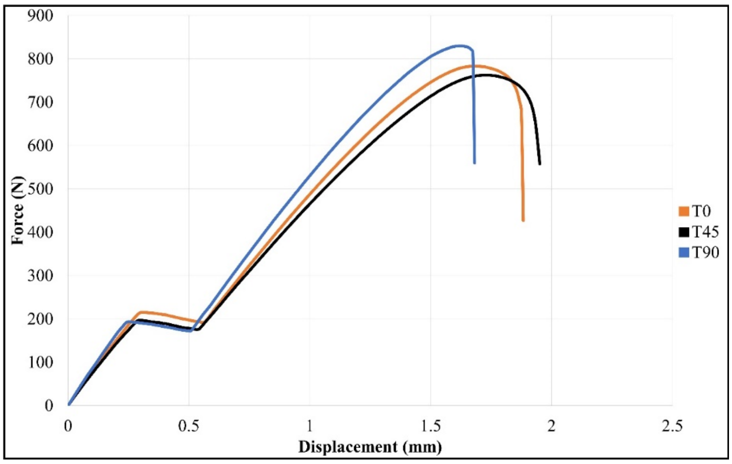

Fig. 13. Effect of Tri – Hexagon infill geometry on tensile behavior in 0° - 45° - 90° orientation.

In terms of maximum displacement, a different trend was observed. The Gyroid infill exhibited the highest deformation capacity, with G45 reaching 3.39 mm, followed by G0 (3.10 mm) and G90 (2.91 mm). This demonstrates the ductile nature of the Gyroid pattern, which can undergo larger elastic deformation due to its isotropic and smoothly interconnected geometry. Such characteristics are beneficial for energy-absorbing or impact-resilient applications. In contrast, the Tri-Hexagon infill resulted in the lowest displacement values among all patterns, with T0 (1.88 mm), T45 (1.95 mm), and T90 (1.68 mm). These findings reflect the more rigid and brittle mechanical response of this infill type, possibly due to its limited ability to distribute stress evenly under tensile loading. This behavior may be suitable for applications requiring dimensional stability but not for that demanding ductility. The Cubic Subdivision infill showed moderate displacement values, with C0 at 2.73 mm, C45 at 2.11 mm, and C90 at 2.14 mm. These results suggest that the Cubic structure offers a balance between rigidity and deformation, behaving less ductile than Gyroid but more flexible than Tri-Hexagon. Overall, the results confirm that the mechanical performance of FDM-printed PLA+ parts is strongly dependent on the interaction between infill geometry and build orientation. The Gyroid infill provided the most favorable performance, offering both high strength and high deformation capacity, particularly in the 90° orientation. The Cubic Subdivision pattern, while less effective than Gyroid, benefitted significantly from increased build orientation, especially in terms of strength. The Tri-Hexagon infill, on the other hand, demonstrated the most rigid and brittle behavior, making it more suitable for applications where dimensional precision and low deflection are prioritized over toughness. These findings emphasize the importance of selecting appropriate infill strategies and orientation settings based on the intended functional requirements of the printed part.

The effects of infill pattern (Gyroid, Tri-Hexagon, Cubic Subdivision) and structure direction (0°, 45°, 90°) on mechanical performance were investigated with Taguchi L9 experimental design. The obtained results are presented in Table 5 and S/N, Means and Std. Dev graph is presented in Fig.15, showing that both factors have different levels of influence on performance.

Fig. 15a shows that the infill pattern factor (Delta: 4.627) has a significant dominant effect on performance compared to the build orientation (Delta: 1.227). Especially, the Gyroid (G) infill pattern provided the highest performance in terms of both mean values and S/N ratios. The Tri-Hexagon (T) infill pattern had a negative effect on performance, while the Cubic (C) pattern had a moderate effect. In the graphical analysis of the S/N ratios, the delta (difference) value of the infill pattern factor was higher than the build orientation. This reveals that the infill pattern plays a key role in improving the mechanical properties. When the average values are examined (Fig. 15b), the Delta value of the infill pattern (38.8) is lower than the build orientation (62.8). In this case, the effect of the build orientation becomes more prominent compared to the average values. The increased standard deviation observed for specimens printed at 90° orientation suggests a notably higher degree of performance variability compared to the 0° and 45° orientations (Fig. 15c). This variability can affect the reliability and repeatability of FDM-printed parts, especially in critical applications where consistent mechanical behavior is essential. This effect may be due to the increased sensitivity of interlayer bonding when the printed layers are aligned parallel to the loading direction. Minor variations in extrusion temperature, filament feed, or local void distribution could disproportionately affect tensile strength in these orientations. Zhou et al. (2020) Megersa et al. (2024) reported that vertically oriented specimens exhibited a significantly wider distribution in tensile metrics compared to flatly oriented specimens in their study using Taguchi methods. From a practical standpoint, although the 90° orientation yields higher mean tensile strength, ensuring consistent part performance under this orientation necessitates enhanced process control and robust quality assurance protocols—such as tighter thermal regulation, optimized filament flow, and increased replicate testing—to manage variability effectively.

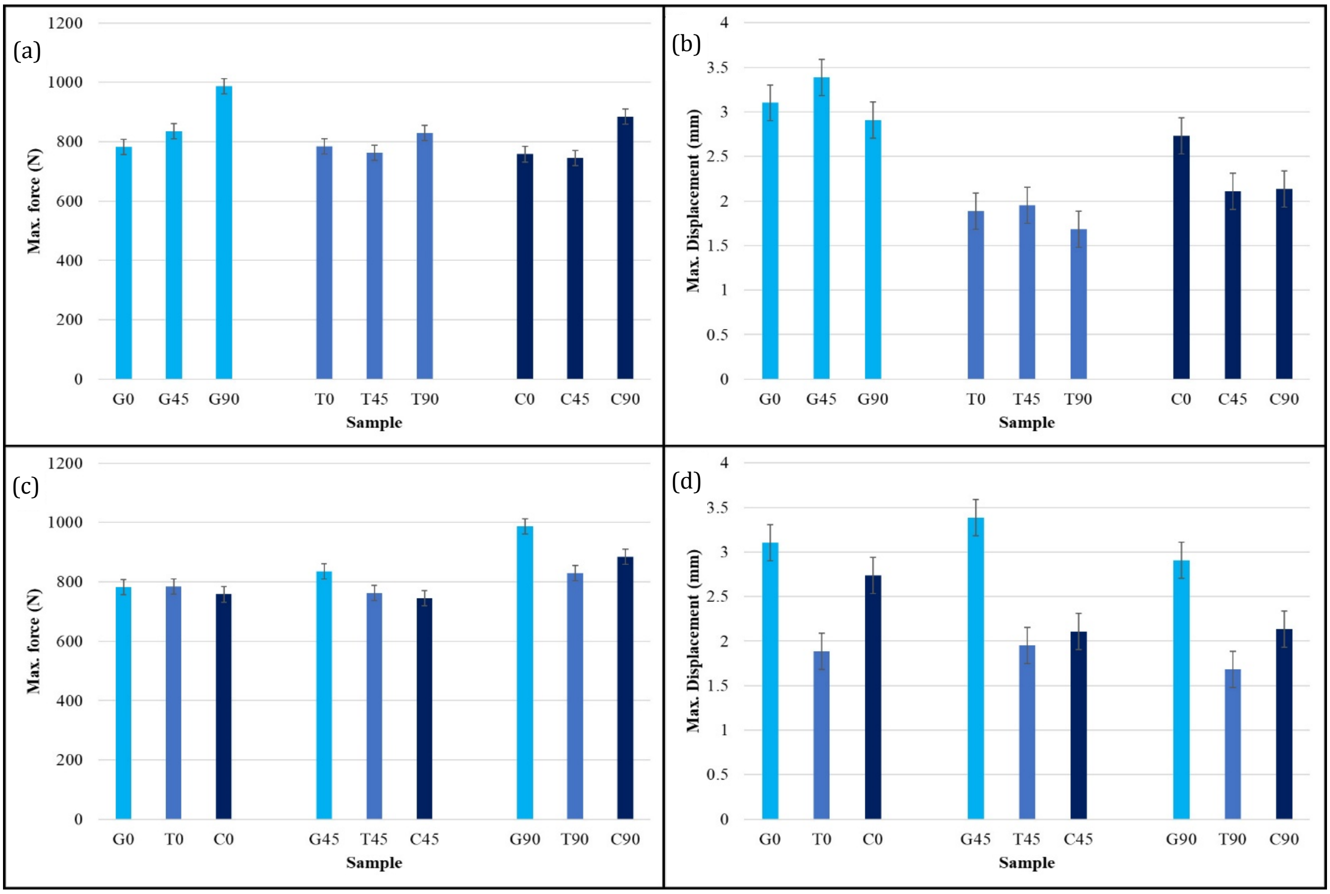

Fig. 14. Effects of infill geometry and build orientation on:
(a, c) Maximum tensile force; (b, d) Maximum displacement.

Table 5. Response table for S/N, means and std. deviations (larger is better).

Level	S/N		Means		Standard deviations	
	Infill pattern	Build orientation	Infill pattern	Build orientation	Infill pattern	Build orientation
1	12.910	11.031	435.8	388.6	611.9	546.0
2	8.283	10.632	397.0	391.9	558.8	550.7
3	10.275	9.805	399.1	451.4	561.1	635.2
Delta	4.627	1.227	38.8	62.8	53.0	89.2
Rank	1	2	2	1	2	1

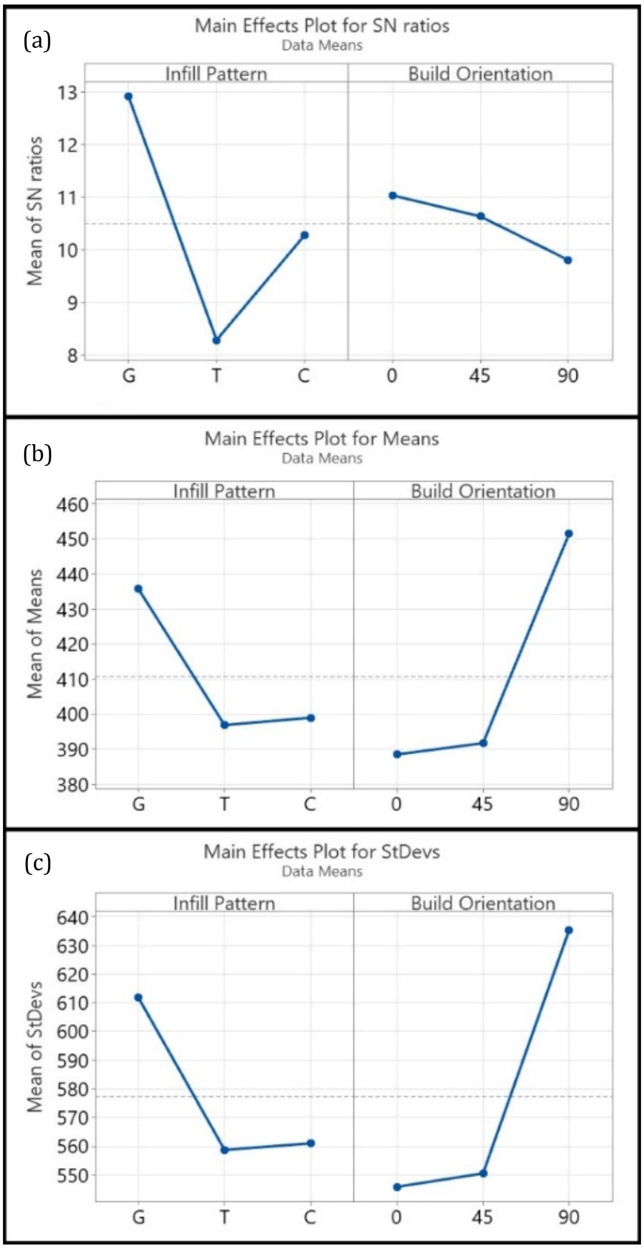

Fig. 15. Main effect plot for:
(a) S/N; (b) Means; (c) Standard deviation.

According to the results of the ANOVA presented in Table 6, the infill pattern explained 86.52% of the total variance (p=0.006) and confirmed its statistical significance; while the contribution of the build orientation remained limited to 6.29% (p=0.285). Standard deviation analyses and related graphs show that the variation increased depending on the build orientation and the standard deviation value increased especially in the 90° orientation. This finding suggests that orientation changes may lead to greater performance differences between parts.

The regression model results are presented in Table 7 and show that there is a high agreement between the experimental data and the obtained values (R^2=92.81%). In the model, it is confirmed that the Gyroid infill pattern has a positive effect on the mechanical performance, while the Tri-Hexagon pattern has a negative effect. As a result, the findings show that the infill pattern has a decisive effect on the mechanical properties, while the build orientation affects the performance variation more. Graphical analysis also shows that the Gyroid infill pattern stands out and the 90° build orientation creates a significant difference in terms of both mean and variation.

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4. Conclusions

In this study, the effects of different infill patterns (Gyroid, Tri-Hexagon, Cubic Subdivision) and build orientations (0°, 45°, 90°) on the mechanical performance of parts manufactured with PLA material using the FDM method were systematically investigated using the Taguchi L9 experimental design. The findings show that both factors affect the mechanical performance to different extents, and the detailed results are presented below:

Table 6. Analysis of variance.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Infill pattern	2	32.320	86.52%	32.320	16.1600	24.07	0.006
Build orientation	2	2.349	6.29%	2.349	1.1743	1.75	0.285
Error	4	2.685	7.19%	2.685	0.6713	–	–
Total	8	37.354	100.00%	–	–	–	–

Table 7. Model summary

S	R-sq	R-sq (adj)	PRESS	R-sq (pred)	AICc	BIC
0.819330	92.81%	85.62%	13.5939	63.61%	68.66	27.84

- The Gyroid infill pattern exhibited superior mechanical properties, achieving the highest tensile strength (987.3 N) at 90° build orientation, while the 45° orientation provided the highest ductility (3.39 mm). This reflects the anisotropic behavior of FDM-printed parts and highlights a trade-off between strength and deformation capacity.
- The Tri-Hexagon pattern showed the lowest performance, with brittle fracture behavior, while the Cubic Subdivision pattern demonstrated intermediate results.
- A 90° build orientation consistently enhanced tensile strength across all infill patterns, particularly for Gyroid, due to improved interlayer adhesion and alignment with the load direction.
- Specimens printed at 0° and 45° displayed lower strength and varied fracture modes, highlighting the anisotropic nature of FDM-printed parts.
- ANOVA revealed that the infill pattern accounted for 86.52% of the variance in mechanical performance, confirming its dominant role.
- Build orientation contributed only 6.29%, though its interaction with infill geometry influenced ductility and failure modes.
- The Gyroid infill pattern at 90° orientation demonstrated the highest tensile strength together with notable ductility, making it a promising choice for lightweight structural components in aerospace applications and for automotive parts, including interior trim components.
- The superior energy absorption capacity of the Gyroid structure also indicates its potential use in biomedical implants, medical splints, and protective devices where controlled deformation is advantageous.

This study is limited to a single polymer material (PLA+) and a specific set of infill patterns. Future research should investigate other materials, including biocompatible and high-performance polymers, explore a broader range of infill strategies and densities, and evaluate performance under varied environmental conditions (e.g., temperature, humidity) and loading scenarios (e.g., fatigue, impact). Such studies would help establish a more comprehensive understanding of the applicability of these findings in diverse engineering contexts.

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Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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