

# Effects of Infill Design and Nozzle Diameter on Tensile Performance of Eco-Friendly PLA

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**Abstract:** This study investigates the combined effect of nozzle diameter (0.2–0.8 mm) and infill pattern (rectilinear vs. concentric) on the tensile performance and production efficiency of eco-friendly PLA components fabricated using Fused Deposition Modeling (FDM). Forty ISO 527-2 Type 1A specimens were printed using a Bambu Lab A1 mini printer and tested for ultimate tensile strength ( $R_m$ ), elongation at break ( $\epsilon_b$ ), and print time. Results indicate that nozzle diameters of 0.4–0.6 mm combined with concentric infill deliver the highest mechanical performance, achieving tensile strengths of 45–55 MPa and elongation superior to rectilinear infill by 10–15%. Increasing nozzle diameter from 0.2 mm to 0.8 mm reduces printing time by up to 80–85%, with only an ~11% decrease in tensile strength, highlighting a favorable strength-to-time trade-off for rapid prototyping and small-series manufacturing. These findings provide practical guidelines for optimizing FDM parameters to enhance sustainability, reduce energy consumption, and support circular economy principles in additive manufacturing.

**Keywords:** FDM, PLA, eco-friendly biopolymer, infill pattern, nozzle diameter, tensile strength, sustainable manufacturing.

## INTRODUCTION

Fused Deposition Modeling (FDM) demonstrates significant potential for sustainable small-series production by enabling complex geometries with minimal waste while supporting the principles of the circular economy. Multiple studies provide strong evidence for these advantages. Additive manufacturing technologies have been shown to reduce material waste and CO<sub>2</sub> emissions while enhancing circular resource strategies (Hegab *et al.*, 2023). N. Quantitative assessments confirm these benefits, indicating a 60.45% reduction in material consumption and an 85.59% reduction in CO<sub>2</sub> emissions compared to conventional manufacturing routes (Top *et al.*, 2023). Additional research highlights that recycled or reused PLA can retain high mechanical performance, achieving material recovery rates up to 92.7% (Subramani *et al.*, 2024). Furthermore, distributed recycling and re-manufacturing approaches offer a viable pathway to extending the life cycle of discarded polymeric components, reinforcing the alignment between FDM and circular economy goals (Al Rashid & Koç, 2023). What is more, FDM enables on-demand creation of customized building components and due to the fact that 3D printers can be installed at any point in the supply chain, it has the potential to reduce the length of the supply chain and facilitate manufacturing decentralization (Abika *et al.*, 2025), (Abid *et al.*, 2025).

For commercial use firms must essentially consider strategic, technological, organizational, operational and

supply chain factors before deciding whether to utilize 3D printing. While some risks related to additive manufacturing can be eliminated, variability in process parameters, materials, and machine configurations continue to affect the consistency of printed components. Therefore, one of the key factors enabling this method to be among the most efficient for single-unit and small-series customised production is the mechanical strength of the finished product (Rouf *et al.*, 2022).

This study systematically investigates the influence of infill strategy (rectilinear vs. concentric) and nozzle diameter (0.2–0.8 mm) on the tensile performance of fully filled PLA components fabricated using FDM technology. Specimens were produced using a Bambu Lab A1 mini printer and tested according to ISO 527-2 to evaluate ultimate tensile strength ( $R_m$ ) and elongation at break ( $\epsilon_b$ ) using an Instron 8872 testing machine, with five replicates per configuration.

The results show that intermediate nozzle diameters (0.4–0.6 mm) combined with concentric infill deliver the highest mechanical performance, yielding up to 15–20% higher  $R_m$  (45–55 MPa) compared to the smallest and largest nozzles. This improvement is attributed to enhanced interlayer adhesion and reduced void formation. Increasing the nozzle diameter reduces porosity by producing thicker layers and wider extrusion paths that enhance inter-layer bonding, but it also leads to more noticeable surface irregularities and larger inter-layer boundaries (Sukindar *et al.*, 2025). However, larger nozzle diameters (0.6–0.8 mm) significantly reduce printing time—by 60–80%—while maintaining acceptable strength, improving the overall

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strength-to-time efficiency of the printing process. A reduction in processing time also leads to a decrease in the total energy required for the process, thereby enhancing both the sustainability and the economic viability of it. For example, printing a part with a 0.2 mm nozzle may take 1 hour, while using a 0.8 mm nozzle could reduce the printing time to just 15 minutes, saving approximately 0.075 kWh of energy per part, which enhances both the sustainability and cost-effectiveness of the process.

These findings provide practical guidelines for designing high-strength, resource-efficient PLA structures used in mechatronic, prototyping, and environmentally conscious applications. By optimizing FDM parameters, the study aligns with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production), contributing to the development of sustainable smart materials and manufacturing strategies.

## MATERIALS AND METHODS

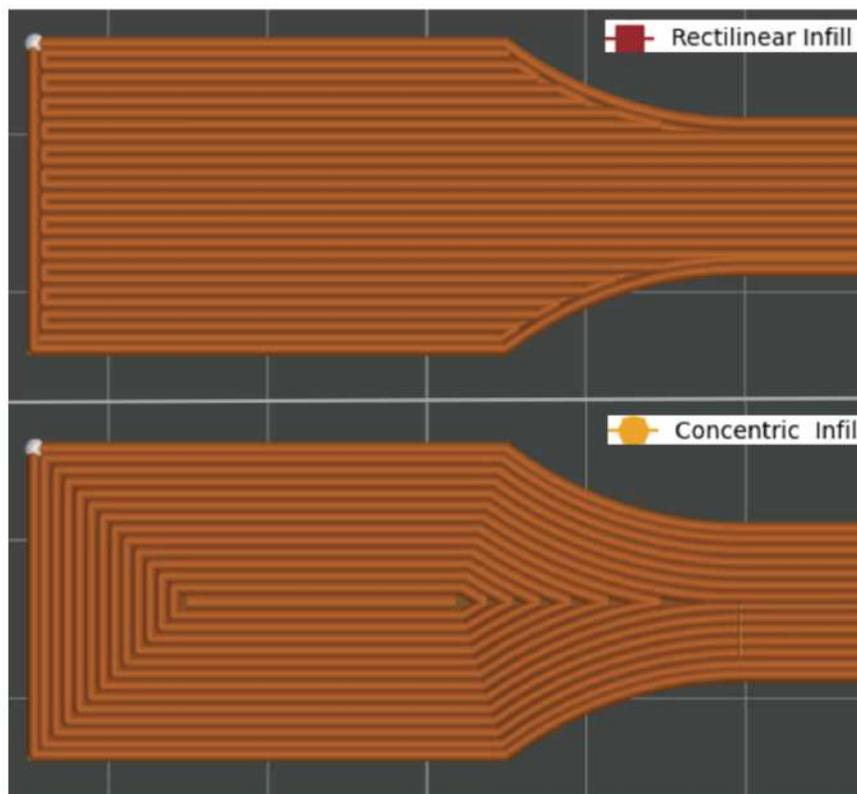
Polylactic acid (PLA) is an eco-friendly, bio-based polymer derived from corn starch, offering substantial environmental benefits over fossil-based thermoplastics. It exhibits a density of 1.24 g/cm<sup>3</sup>,

tensile strength of 50–70 MPa, and a melting temperature of ~180°C, making it well-suited for FDM processing (Tümer & Erbil, 2021). Its biodegradability under industrial composting conditions further enhances its sustainability profile (Bardot & Schulz, 2020). Studies also highlight its favorable mechanical performance, ease of processing, and compatibility with reinforcement strategies, reinforcing its relevance in modern material engineering (Tahir & Seyam, 2025).

Infill geometry and nozzle diameter are known to significantly influence the mechanical response of FDM-printed structures. Previous studies reported increases in tensile strength with nozzle diameter up to 0.6 mm before a decline (Sudin *et al.*, 2023). Concentric infill has been shown to enhance tensile strength by up to 123% compared to linear patterns (Agrawal *et al.*, 2023). More complex infill geometries such as grid and gyroid can provide superior strength, although at the cost of longer printing times (EisaZadeh & Torabi, 2024).

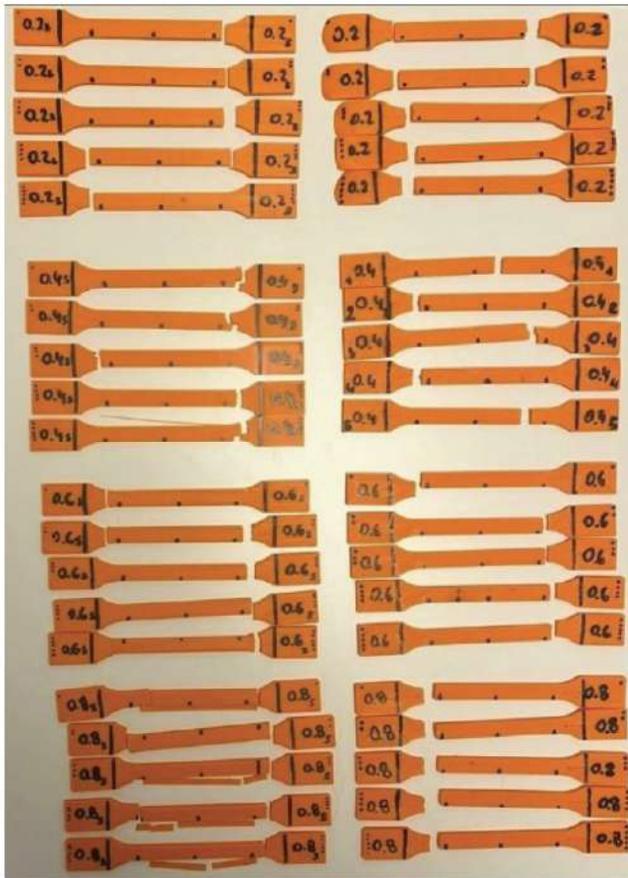
## Printing Procedure

Printing was performed on a Bambu Lab A1 mini desktop FDM printer equipped with interchangeable nozzles (0.2, 0.4, 0.6, 0.8 mm diameters), selected for



**Figure 1:** Structural differences between concentric and rectilinear infill patterns used in PLA FDM printing.

precision and efficiency in small-series production. Specimens were designed in Autodesk Inventor 2024 and sliced in Bambu Studio software. Key parameters: nozzle temperature 210–220°C (optimized per nozzle size), bed temperature 60°C, print speed 50–100 mm/s, layer height 0.1–0.4 mm (matched to nozzle), 100% infill density with two strategies—rectilinear (linear paths) and concentric (circular rings)—to evaluate anisotropy effects. Five replicates per configuration (nozzle × infill) minimized variability. A total of 40 tensile specimens were produced. Tensile specimens followed ISO 527-2 Type 1A (gauge length 50 mm, width 10 mm, thickness ~4 mm).



**Figure 2:** A summary of all samples printed and tested.

### Mechanical Testing

Tensile tests were performed using an Instron 8872 servohydraulic machine (25 kN capacity, ISO 7500-1 calibrated) at 5 mm/min crosshead speed (23°C, 50% RH per ISO 291), recording force-displacement for ultimate tensile strength ( $R_m$ ), elongation at break ( $\epsilon_b$ ), and Young's modulus ( $E$ ). Print time per specimen batch was logged to assess sustainability metrics (energy/time efficiency). The tensile test configuration is presented in Figure 3.



**Figure 3:** Instron 8872 with sample mounted.

### RESULTS AND DISCUSSION

The experimental results indicate a clear dependence of tensile properties on both nozzle diameter and infill pattern. Specimens printed with concentric infill consistently exhibited higher ultimate tensile strength ( $R_m$ ) and elongation at break ( $\epsilon_b$ ) compared to rectilinear infill, highlighting the positive effect of radial stress distribution and improved interlayer adhesion. Table 1 presents the experimental plan for evaluating the influence of nozzle diameter and infill type on the tensile performance of PLA specimens. Eight combinations were tested, covering four nozzle diameters (0.2, 0.4, 0.6, and 0.8 mm) and two infill strategies (rectilinear and concentric), with five replicates per configuration. All specimens were subjected to tensile testing according to ISO 527-2, and print time for each batch was recorded to assess production efficiency.

The table presents the total printing time required to produce five samples using different nozzle diameters (0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm) and two types of infill patterns: concentric and linear. For concentric infill, the printing time decreases significantly as the nozzle diameter increases, ranging from 8 hours 29 minutes with a 0.2 mm nozzle to 1 hour 6 minutes with

**Table 1: Summary of Experimental Plan**

Nozzle Diameter (mm)	Infill Type	Tensile Tests (ISO 527, n=5)	Print Time Recorded
0.2	Rectilinear	✓	✓
0.2	Concentric	✓	✓
0.4	Rectilinear	✓	✓
0.4	Concentric	✓	✓
0.6	Rectilinear	✓	✓
0.6	Concentric	✓	✓
0.8	Rectilinear	✓	✓
0.8	Concentric	✓	✓

**Table 2: Printing Time of 5 Samples Depending on Nozzle Diameter and Infill Pattern**

Nozzle [mm]	0.2	0.4	0.6	0.8
Concentric infill	8h 29m	2h 13m	1h 22m	1h 6m
Linear infill	8h 17m	2h 21m	1h 22m	1h 5m

a 0.8 mm nozzle. A similar trend is observed for linear infill, where the printing time ranges from 8 hours 17 minutes (0.2 mm nozzle) to 1 hour 5 minutes (0.8 mm nozzle). The results indicate that larger nozzle diameters greatly reduce printing time, while the choice of infill pattern has only a minor impact on the total duration.

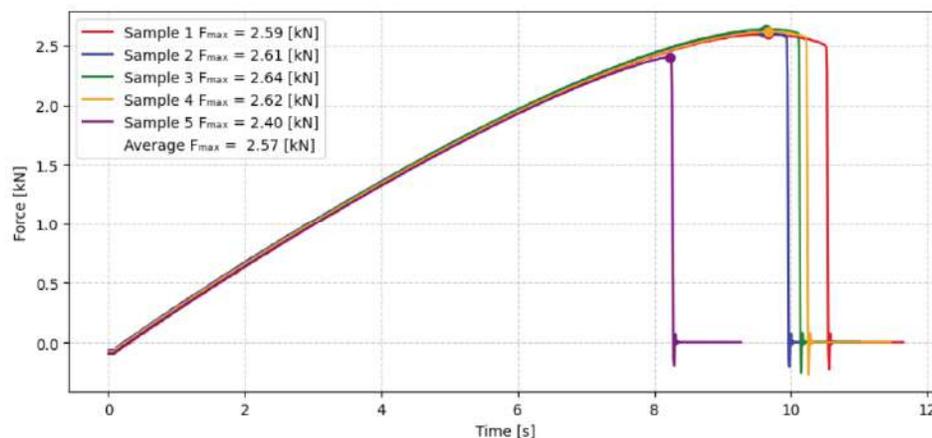
### Tensile Properties

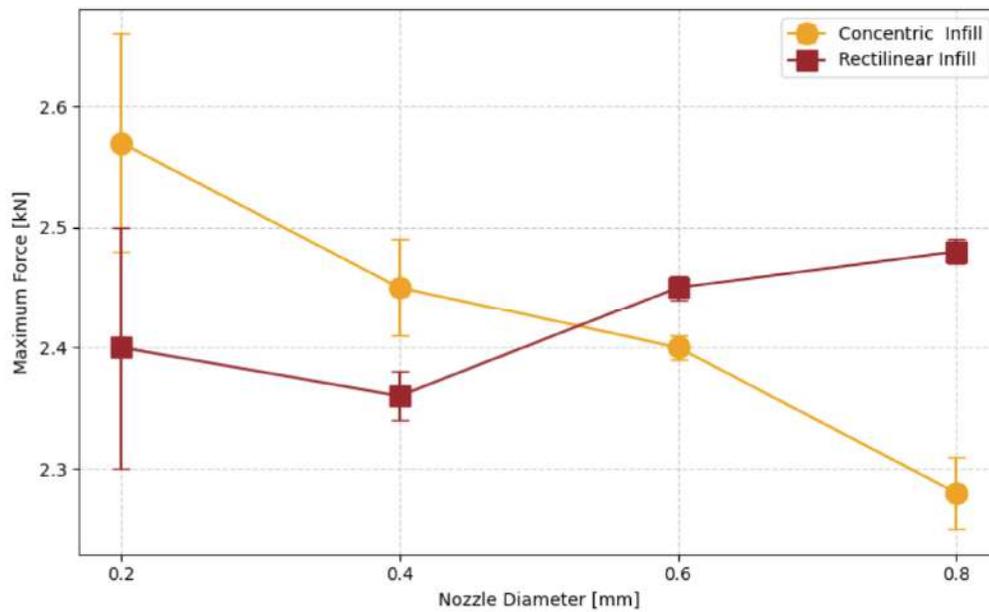
Ultimate tensile strength ranged from 38–55 MPa across all configurations, with the highest values achieved using 0.4–0.6 mm nozzles combined with concentric infill. These configurations outperformed rectilinear patterns by 10–15% due to improved interlayer fusion and radial stress distribution. The

smallest nozzle (0.2 mm) exhibited reduced strength (38–42 MPa) due to increased void formation, whereas the largest nozzle (0.8 mm) maintained moderate strength (45–48 MPa) but offered significant gains in production efficiency.

Elongation at break followed comparable trends, reaching 4–6% for the optimal configurations.

As shown in Figure 4, an exemplary tensile test result is presented to illustrate the force–displacement behavior and the onset of failure for the concentric infill configuration printed with a 0.2 mm nozzle. Most specimens exhibit fracture initiation at approximately 2.6 kN, with one specimen failing earlier at 2.4 kN, likely due to a localized printing defect.

**Figure 4:** Force-time tensile diagram for 5 samples (nozzle: 0.2 [mm], filling: concentric).



**Figure 5:** Tensile strength vs. nozzle diameter / infill type.

### Relationship between Printing Time and Tensile Performance

The results also reveal a clear relationship between printing time and the mechanical performance of PLA specimens. Printing time decreases dramatically with increasing nozzle diameter: from approximately 8.5 hours for a batch printed with a 0.2 mm nozzle to just 1.1 hours for a 0.8 mm nozzle in both infill strategies. This reduction reflects the substantially higher extrusion rate achievable with larger nozzles.

Interestingly, this decrease in time is not linearly correlated with a proportional drop in tensile strength. For concentric infill, maximum tensile force decreases from 2.57 kN (0.2 mm) to 2.28 kN (0.8 mm), corresponding to only an 11% reduction despite a ~85% decrease in print time. In rectilinear infill, the tensile force even slightly increases with larger nozzle sizes, ranging from 2.40 kN at 0.2 mm to 2.48 kN at 0.8 mm.

This finding indicates that larger nozzle diameters provide a highly favorable strength-to-time balance, particularly important for small-series manufacturing and rapid prototyping. The results demonstrate that tensile strength becomes less sensitive to nozzle diameter beyond 0.4–0.6 mm, whereas printing time continues to decrease sharply. As shown in Figure 5, concentric infill maintains consistently high performance across all nozzle diameters, while rectilinear infill exhibits greater variation but comparable ultimate strength at larger extrusion widths.

Overall, optimizing nozzle diameter allows manufacturers to significantly reduce production time—up to 80–85%—with only minimal reduction in mechanical performance. This efficiency directly supports sustainable manufacturing objectives by lowering energy consumption per part while preserving functional integrity, aligning with SDG 12 on responsible production.

### CONCLUSIONS

This study demonstrates that both nozzle diameter and infill pattern significantly influence the tensile performance and production efficiency of PLA components manufactured using FDM technology. The results indicate that nozzles in the 0.4–0.6 mm range combined with a concentric infill pattern provide the most favorable mechanical performance, achieving ultimate tensile strengths of 45–55 MPa and elongations at break superior to rectilinear infill by approximately 10–15%. These improvements can be attributed to enhanced interlayer adhesion and the reduction of internal voids. Furthermore, concentric infill consistently yields better stress distribution and bonding between successive layers, which translates into higher overall structural integrity.

From a production standpoint, increasing the nozzle diameter from 0.2 mm to 0.8 mm enables a substantial reduction in printing time—up to 80–85%—while only slightly decreasing tensile strength (by around 11%). This trade-off highlights the potential of larger nozzles for efficient small-batch manufacturing and rapid

prototyping. Importantly, the optimization of FDM parameters not only improves process efficiency but also contributes to sustainability by reducing energy consumption and fabrication time.

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