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Pultrusion-Based Recycling of PET Bottle Waste into FDM Filaments: Effects of Feedstock Geometry on Filament Quality

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Abstract

Plastic waste, particularly post-consumer polyethylene terephthalate (PET) bottles, presents a persistent environmental challenge due to its high consumption rate and limited high-value recycling pathways. This study investigates the feasibility and parametric influence analysis of a pultrusion-based process for converting recycled PET (rPET) bottle waste into fused deposition modelling (FDM) filaments. PET bottles were processed into continuous strips and transformed into filaments under controlled thermal conditions. A factorial experimental design was employed to evaluate the effects of nozzle temperature (220–230 °C), strip width (8.0–8.5 mm), and strip thickness (0.14–0.20 mm) on filament diameter stability, cross-sectional morphology, and tensile properties of 3D-printed specimens (n = 5 per condition). The results indicate that all produced filaments fall within commercial tolerance (1.75 ± 0.05 mm), with average diameters ranging from 1.71 to 1.73 mm. Statistical analysis (ANOVA) reveals that strip thickness is the dominant factor influencing tensile strength ($p < 0.05$), while temperature shows no significant effect within the investigated range. Thicker strips (0.20 mm) result in reduced internal voids and improved tensile strength, reaching up to 48.18 MPa. The pultrusion process enables decoupling of melt flow and filament drawing, leading to enhanced geometric stability compared to conventional extrusion. This study demonstrates that pultrusion-based processing provides a viable pathway for producing mechanically reliable rPET filaments and offers strong potential for distributed recycling and sustainable additive manufacturing applications.

Keywords: recycled PET, FDM filament, pultrusion, additive manufacturing, process parameter.

1. Introduction

Plastic waste has become a global environmental challenge due to its persistence, large volume, and limited degradation under natural conditions [1,2]. Among various plastic types, polyethylene terephthalate (PET) is one of the most extensively used thermoplastics, particularly in single-use beverage bottles, resulting in a substantial accumulation of post-consumer waste [3]. Although PET is theoretically recyclable, a significant proportion of PET waste remains underutilized or improperly managed, especially in developing countries, thereby motivating the search for high-value recycling routes that extend beyond conventional downcycling practices.

Several previous researchers have conducted research related to how to reuse plastic waste, especially PET-type waste. Such as the use of PET plastic waste to industry construction [4-6]. Then, the use of PET and PP type plastic waste, processed with the help of a starch adhesive, is used to produce plastic charcoal briquettes, which serve as an alternative fuel and help reduce PET and PP waste [7-9]. The next researcher used PET plastic waste as a substitute for some of the rough aggregate in concrete to determine the effect of PET plastic waste as a substitute for aggregate in non-structural concrete [10-12].

In recent years, additive manufacturing, particularly fused deposition modelling (FDM), has attracted increasing attention as a promising platform for the valorisation of recycled polymers [13—16]. FDM technology offers advantages such as design flexibility, material efficiency, and decentralized manufacturing, making it suitable for integrating recycled materials into production chains [17]. Several studies have demonstrated the feasibility of using recycled PET as feedstock for FDM filaments, reporting acceptable printability and mechanical performance under certain processing conditions [18-22]. However, despite these encouraging findings, recycled PET filaments often suffer from limitations related to inconsistent filament diameter, unstable feeding behaviour, and variability in mechanical properties, which hinder their broader adoption in FDM applications [18].

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These limitations are largely associated with the filament fabrication process. Most existing studies rely on conventional extrusion, where melt flow and filament drawing are strongly coupled. This coupling makes the process sensitive to fluctuations in material properties and operating conditions, particularly when recycled feedstocks with inherent variability are used [23,24]. As a result, achieving consistent filament geometry remains a significant challenge.

The quality of FDM-printed components is highly sensitive to filament characteristics, particularly dimensional stability and mechanical integrity. Filament diameter fluctuations can lead to inconsistent material flow [25], and defects during printing [26,27], while insufficient tensile strength may compromise filament handling and printed part performance [28]. Both the process time and the degree of surface roughness of the print product are influenced by the height of the layer [29,30]. The print product's mechanical strength is influenced by the infill density [31-34]. The effect of print speed and extrusion temperature on the dimensional quality [35]. The rate at which the filaments melt to form a homogenous product depends on the nozzle's temperature [36]. The percentage of infill that influences the 3DP product's strength is related to the infill pattern [37,38].

Pultrusion-based filament fabrication offers a potential alternative by decoupling melt flow from filament drawing. This approach enables more stable thermal and mechanical control during filament formation, potentially improving dimensional consistency [39,40,41]. While pultrusion has been widely applied in composite manufacturing [42–46], its application to thermoplastic filament production using recycled PET remains largely unexplored. In particular, the influence of feedstock geometry, such as strip width and thickness, on filament morphology and mechanical performance has not been systematically investigated.

Despite extensive studies on recycled PET filaments, most existing works rely on conventional extrusion-based processes, where melt flow and filament drawing are intrinsically coupled. This coupling often leads to diameter instability and sensitivity to feedstock variability, particularly when recycled materials are used. Moreover, previous studies predominantly focus on feasibility rather than systematically quantifying the influence of feedstock geometry and processing parameters using statistical approaches. As a result, the relationship between strip geometry, internal filament structure, and mechanical performance remains insufficiently understood. Therefore, there is a clear need for an alternative fabrication approach that enables improved geometric control and a more robust process–structure–property understanding.

Therefore, this study aims to evaluate the feasibility of producing FDM filaments from recycled PET bottle waste using a pultrusion-based process and to quantify the influence of key processing parameters on filament quality and mechanical performance. A structured experimental design and statistical analysis are employed to establish a process, structure, property relationship, providing insights for improving filament reliability in sustainable additive manufacturing systems.

2. Materials and methods

2.1. Feedstock Preparation

Post-consumer PET bottles (600 mL and 1500 mL) were collected from a local waste bank. The bottle surfaces were flattened using a combination of mechanical pressing and controlled thermal treatment with a heat gun. The bottle bottoms were removed to facilitate cutting, and continuous PET strips were produced using a manual bottle-cutting tool. The resulting strips had average thicknesses of 0.14 mm (600 mL bottles) and 0.20 mm (1500 mL bottles), with widths of 8.0 mm and 8.5 mm.

2.2. Pultrusion-Based Filament Fabrication

Filaments were produced using a custom pultrusion setup, as shown in Figure 1. The PET strip was fed into a heated nozzle connected to a heat block, where melting and reshaping occurred before continuous pulling and winding. The investigated nozzle temperatures were 220, 225, and 230 °C. The nozzle diameter was fixed at 1.9 mm, and the pulling speed was maintained constant at 0.19 rpm throughout all experiments. Each strip had a length of approximately 2.5 m. Filaments were cooled naturally without forced cooling.

2.3. Experimental Design

The experimental design was structured as a full factorial design involving three factors: nozzle temperature (220, 225, and 230 °C), strip width (8.0 and 8.5 mm), and strip thickness (0.14 and 0.20 mm). This resulted in a total of 12 experimental conditions. For each condition, five tensile specimens were produced, yielding a total of 60 mechanical test samples. Control variables included nozzle diameter, pulling speed, strip length, and cooling conditions. Filament quality was evaluated based on diameter stability, cross-sectional morphology, and tensile performance of FDM-printed specimens.

2.4. Filament Characterization

Strip width and thickness were measured using a digital calliper (±0.01 mm). Filament diameter was measured every 10 cm along the filament length in two orthogonal directions using a digital calliper (±0.01 mm). Cross-sectional morphology was examined using a digital microscope, and cross-sectional areas were quantified using ImageJ software.

2.5. 3D Printing and Tensile Testing

Tensile specimens (ASTM D638-14 Type IV) were printed using a Creality Ender 3 V3 SE. Printing parameters were fixed for all variations: nozzle temperature 260 °C, bed temperature 85 °C, print speed 35 mm/s, flow rate 130%, nozzle diameter 0.4 mm, and layer height 0.2 mm. Five specimens were printed for each filament variation. Tensile testing was conducted to determine ultimate tensile strength, strain at break, and elastic modulus.

3. Results and discussion

3.1. Filament Production Characteristics

The recycled PET (rb-PET) filaments were produced via a pultrusion-based process and subsequently used to fabricate tensile test specimens in accordance with ASTM D638-14 Type IV using an FDM 3D printer (Creality Ender 3 V3 SE). **Table 1** summarizes the processing parameters and resulting filament characteristics for all experimental variations. Two types of post-consumer PET bottles were employed, namely 1500 mL bottles with an average strip thickness of 0.20 mm and 600 mL bottles with an average strip thickness of 0.14 mm. For each bottle type, strip widths of 8.0 mm and 8.5 mm were investigated at nozzle temperatures of 220 °C, 225 °C, and 230 °C.

3.2. Influence of Processing Parameters on Filament Diameter

The pultrusion approach applies direct heat to the strip by connecting the nozzle to the pultrusion device's heat block. Thus, it is possible to say that the heat block temperature and the nozzle temperature are the same. After being sliced into long sheets, the material enters a heat block that has been preheated before emerging out of the nozzle as a hollow circular that resembles a filament. A thermocouple, whose sensor is directly attached to the heater, has been used to control the heat block's temperature for the temperature calibration.

Next, using a digital calliper with an accuracy of ± 0.01 mm on the measurement device, the outer diameter of the filament is measured in two directions. Every 10 cm throughout the entire length of the filament produced in each variation, the outside diameter of the filament is measured. The average filament diameters obtained for different strip widths, strip thicknesses, and nozzle temperatures are presented in **Table 1**.

As shown in **Table 1**, filaments produced from 1500 mL PET bottles with an strip width of 8.0 mm exhibited average diameters of 1.72, 1.73, and 1.73 mm at nozzle temperatures of 220, 225, and 230 °C, respectively. For a strip width of 8.5 mm, the corresponding average diameters ranged from 1.71 to 1.72 mm. Similarly, it shows that filaments fabricated from 600 mL bottles exhibited average diameters between 1.72 and 1.73 mm across all temperature and width variations.

These results indicate that nozzle temperature influences filament diameter; however, within the temperature range investigated, its effect was relatively limited. Increasing temperature slightly improved melt flow and dimensional stability, but the resulting diameter variations were small. Overall, all filaments produced in this study fell within the commonly accepted tolerance for commercial FDM filaments (1.75 ± 0.05 mm), indicating that the pultrusion process can produce dimensionally consistent filaments from recycled PET [40].

Table 1 further illustrates the combined effect of strip width and strip thickness on filament diameter. For a strip width of 8.0 mm, filament diameter remained relatively stable across both thicknesses and temperature conditions. Minor deviations were observed for filaments produced from thinner strips (0.14 mm), which can be attributed to slight non-circular filament geometry and measurement sensitivity. These deviations are likely associated with manual pulling during fabrication and local thickness variations caused by non-uniform heating during strip preparation.

For a strip width of 8.5 mm, thicker strips (0.20 mm) generally resulted in slightly smaller filament diameters. The smallest average diameter (1.71 mm) was obtained at 220 °C with a thickness of 0.20 mm, suggesting that thicker feedstock strips may promote improved structural stability during pultrusion and reduce outward expansion of the molten material.

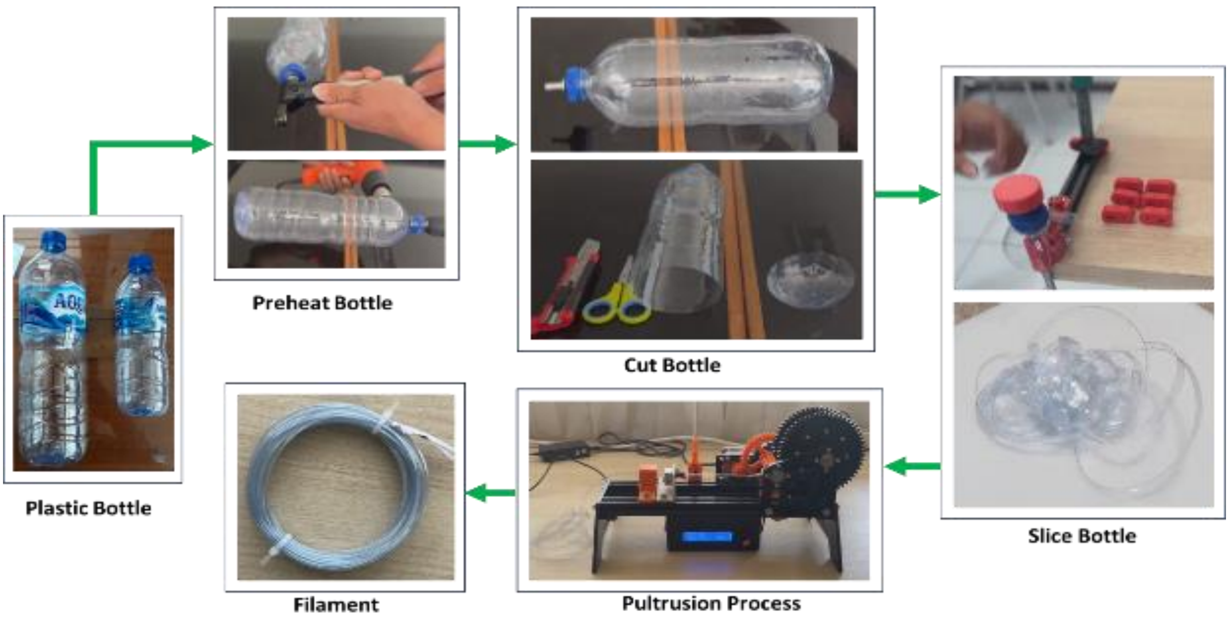


Figure 1. RB-PET Filament Manufacturing Process Scheme

As shown in **Table 1**, the average filament diameters obtained under different processing conditions exhibited only minor variations across the investigated temperature range. The measured diameter values consistently remained within a narrow range of approximately 1.71–1.73 mm. This limited variation suggests that, within the experimental conditions examined, nozzle temperature exerts a secondary influence on filament diameter compared to geometric parameters such as strip width and thickness.

Although slight increases in diameter were observed with increasing nozzle temperature, particularly for thicker strips, the magnitude of these changes was relatively small and did not indicate a strong temperature dependence. Considering the measurement resolution (0.01 mm) and the inherent variability associated with recycled feedstock and manual pulling, the observed differences in filament diameter are best interpreted as weak trends rather than statistically significant changes.

For filaments produced from thinner strips (0.14 mm), slightly higher variability in diameter was observed. This increased scatter can be attributed to local non-circular filament geometry and minor fluctuations during filament drawing, which introduce measurement sensitivity when diameters are recorded in orthogonal directions. Nevertheless, even under these conditions, the filament diameters remained within the acceptable tolerance range for commercial FDM filaments (1.75 ± 0.05 mm).

3.3. Cross-sectional area of RB-PET filament

The cross-sectional morphology of the produced filaments was examined using a digital microscope in combination with ImageJ software. Cross-sectional images were taken at three locations along each filament (beginning, middle, and end), and representative micrographs are presented in **Figures 2** and **3.**

All filaments exhibited a hollow cross-sectional structure, which is characteristic of pultrusion-based filament fabrication using PET strips. Filaments produced from 1500 mL bottles displayed a relatively uniform and symmetrical hollow cross-section, whereas filaments produced from 600 mL bottles exhibited folded or partially collapsed inner walls. This difference can be attributed to the lower thickness of the 600 mL bottle strips, which provides reduced structural rigidity when the strip walls meet inside the nozzle during the pultrusion process.

Table 1. Filament data of the pultrusion process

Variation	Bottle Type (ml)	Strip Width (mm)	Strip Thickness (mm)	Temperature (°C)	Filament Diameter (mm)
1	Aqua 1500	8	0.2	220	1.72 ± 0.01
2				225	1.73 ± 0.01
3				230	1.73 ± 0.01
4		8.5		220	1.71 ± 0.01
5				225	1.72 ± 0.01
6				230	1.72 ± 0.01
7	Aqua 600	8	0.14	220	1.72 ± 0.02
8				225	1.72 ± 0.01
9				230	1.73 ± 0.03
10		8.5		220	1.72 ± 0.01
11				225	1.73 ± 0.01
12				230	1.73 ± 0.01

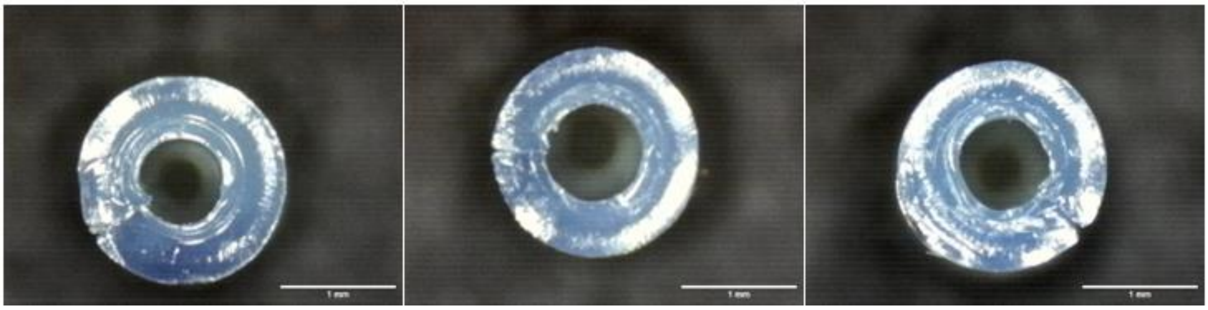


Figure 2. Micrographs of the cross-sectional area of 1500 ml RB-PET filaments.

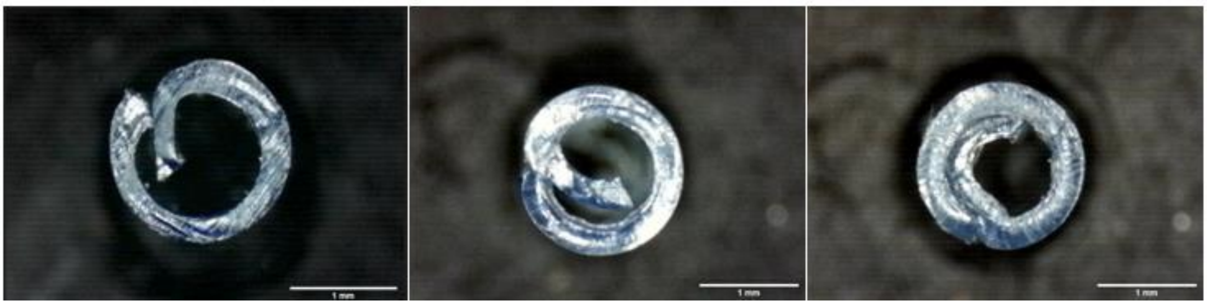


Figure 3. Micrographs of the cross-sectional area of 600 ml RB-PET filaments.

Quantitative analysis of the filament cross-sectional area was conducted using ImageJ, and the results are summarized in **Table 2**. The data show a general trend of increasing cross-sectional area with increasing strip width, indicating a reduction in internal void volume as wider strips are used. This observation is consistent with previous findings, which reported that larger strip widths reduce the size of hollow voids in recycled PET filaments [42].

The cross-sectional area measurements showed consistent trends across repeated observations, with average values providing a representative description of filament morphology for each parameter set. While localized deviations were present due to internal folding or partial collapse of the hollow structure, particularly for thinner strips, the overall variation within each group did not obscure the observed influence of strip width and thickness on cross-sectional area.

The increase in average cross-sectional area with increasing strip width indicates a systematic reduction in internal void volume. Similarly, filaments fabricated from thicker strips exhibited consistently larger cross-sectional areas than those produced from thinner strips. These trends suggest that geometric feedstock parameters exert a dominant influence on filament internal structure, even when variability associated with recycled material and manual processing is considered.

In addition, the present study reveals that strip thickness also plays a significant role in determining cross-sectional characteristics. Filaments produced from thicker strips (0.20 mm) exhibited larger average cross-sectional areas compared to those produced from thinner strips (0.14 mm). This suggests that thicker PET strips are more effective in maintaining structural integrity during pultrusion, thereby reducing internal deformation and void collapse.

Table 2. Cross-sectional area of RB-PET filaments

Variation	Area Average (mm^2)
1	1.99 ± 0.11
2	1.95 ± 0.01
3	2.09 ± 0.07
4	2.26 ± 0.09
5	2.03 ± 0.18
6	2.16 ± 0.16
7	1.44 ± 0.05
8	1.53 ± 0.04
9	1.43 ± 0.18
10	1.71 ± 0.01
11	1.6 ± 0.05
12	1.5 ± 0.06

3.4. Tensile Properties of 3D-Printed Specimens

To evaluate the printability and mechanical performance of the produced filaments, all filament variations were used to fabricate tensile test specimens via FDM printing. Five specimens were printed for each variation using identical printing parameters to minimize the influence of printing conditions on mechanical performance. **Figure 4** illustrates the specimen printing and tensile testing processes. For the parameters used for the entire variation to be set equally, this aims to equalize the settings on the 3D print tool with each resulting filament variation. For one variation with 5 samples of 3d prints, a filament with a total length of 13.24 m, a weight of 39.5 grams, and a total print time of 4 hours and 49 minutes is needed. A 1500 ml bottle of aqua produces a strip length of ± 6 m, so printing specimens in each variation for a 1500 ml bottle requires 3 bottles of aqua. Meanwhile, a 600 ml aqua bottle produces a strip length of ± 3 meters, so printing specimens in each variation for a 600 ml aqua bottle requires 6 aqua bottles.

The tensile strength values obtained in this study, as shown in **Table 3**, are comparable to previously reported values for recycled PET filaments used in FDM applications, which typically range around 40–45 MPa [35]. This comparison suggests that the pultrusion-fabricated rb-PET filaments investigated here exhibit mechanical performance suitable for functional FDM printing under the tested conditions. Isolated low tensile strength values were observed for certain specimens, such as variation 10 sample 4, which exhibited a tensile strength of 24.13 MPa.

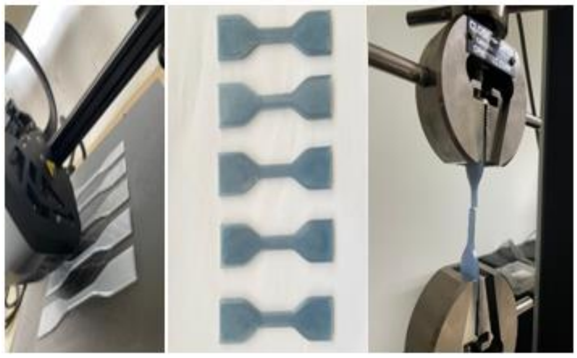


Figure 4. 3D prints tensile test specimen

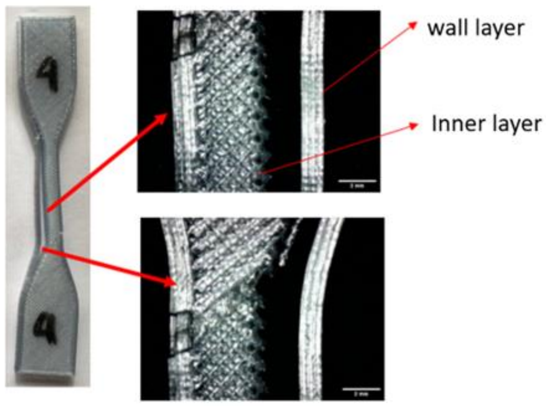
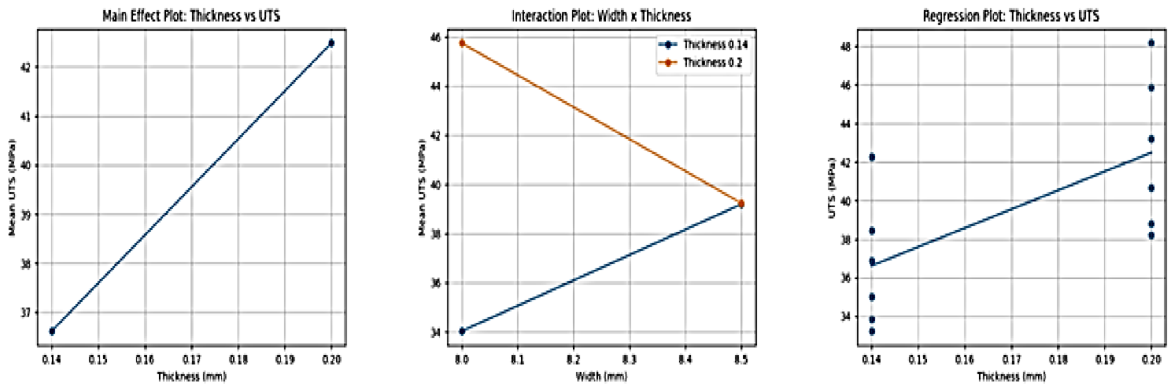


Figure 5. Defects observed in 3D-printed specimens

As shown in **Figure 5**, this behavior can be attributed to printing-induced defects, including insufficient bonding between wall layers and internal infill, as well as the presence of voids. These results highlight that, in addition to filament quality, printing parameters and internal structure significantly influence the mechanical performance of FDM-printed parts.

Table 3. Ultimate Tensile Strength, strain, and modulus of elasticity testing results of 3d printed.

Variation	Ultimate Tensile Stress (MPa)		Strain		Modulus of Elasticity (GPa)	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
1	48.18	1.526	0.100536	0.009	0.6952	0.013
2	43.1926	5.853	0.080895	0.014	0.6676	0.015
3	45.8744	2.182	0.092391	0.009	0.6624	0.011
4	38.788	2.298	0.073868	0.004	0.6504	0.020
5	40.6716	1.595	0.085363	0.009	0.643	0.022
6	38.238	4.286	0.078657	0.006	0.6808	0.074
7	33.224	5.994	0.070357	0.009	0.5632	0.071
8	33.836	4.770	0.071794	0.012	0.6066	0.039
9	35.038	3.272	0.073549	0.006	0.582	0.042
10	36.874	8.049	0.077539	0.006	0.5962	0.091
11	42.292	1.723	0.084883	0.007	0.642	0.016
12	38.44	2.463	0.076262	0.005	0.6626	0.021



(a) (b) (c)

Figure 6. (a) Main effect Plot (Strip thickness vs UTS). (b) Interaction plot (Strip width and thickness). (c) Regression Plot (Strip thickness vs UTS)

Table 4. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	11	1201.16	109.197	6.22	0.000
Linear	4	530.33	132.582	7.55	0.000
Temperature	2	6.09	3.043	0.17	0.841
Width	1	6.80	6.801	0.39	0.537
Thickness	1	517.44	517.441	29.46	0.000
2-Way Interactions	5	667.38	133.476	7.60	0.000
Temperature*Width	2	100.87	50.433	2.87	0.066
Temperature*Thickness	2	54.47	27.233	1.55	0.223
Width*Thickness	1	512.05	512.051	29.16	0.000
3-Way Interactions	2	3.45	1.727	0.10	0.907
Temperature*Width*Thickness	2	3.45	1.727	0.10	0.907
Error	48	843.02	17.563		
Total	59	2044.19			

The main effect plot (**Figure 6.a**) clearly indicates that strip thickness has the most significant influence on tensile strength, with thicker strips (0.20 mm) consistently producing higher UTS values. The interaction plot (**Figure 6.b**) reveals a strong interaction between strip width and thickness, confirming the ANOVA results and indicating that the effect of thickness is dependent on strip width. The regression analysis (**Figure 6.c**) further confirms a positive correlation between strip thickness and tensile strength, supporting the hypothesis that increased material volume improves structural integrity.

Across all variations, the strain at break remained within a relatively narrow range (approximately 0.07–0.10), indicating comparable deformation behavior among the printed specimens. Similarly, elastic modulus values showed moderate variation, with higher average moduli associated with filaments fabricated from thicker strips. These observations suggest that strip thickness has a more pronounced influence on tensile performance than nozzle temperature within the investigated range.

It should be noted that isolated low tensile strength values were observed for certain specimens, reflecting specimen-specific defects rather than systematic process effects. As illustrated in **Figure 5**, inadequate bonding between wall layers and internal infill, as well as the presence of printing-induced voids, contributed to premature failure. Such variability is commonly reported in FDM-printed components and highlights the combined influence of filament quality and printing parameters on mechanical performance.

It should be noted that this study focuses on short-term mechanical performance under controlled laboratory conditions. Long-term durability, thermal aging, and fatigue behavior of the produced filaments were not evaluated and remain important areas for future investigation.

3.5. Analysis of Variance

The Minitab software statistical analysis shown in **Table 4** confirmed the significant effects of temperature, width, and thickness on tensile strengths. The ANOVA results indicate that thickness has a statistically significant effect on UTS ($p < 0.05$). In addition, the interaction between width and thickness is also significant, suggesting that the influence of thickness on tensile strength depends on strip width. Temperature does not show a significant main effect within the investigated range.

4. Conclusions

This study demonstrates that pultrusion-based processing is a feasible and robust method for converting recycled PET bottle waste into FDM filaments with stable geometry and competitive mechanical properties. The produced filaments consistently met commercial FDM filament standards in terms of average diameter (1.71–1.73 mm) across the tested strip widths, thicknesses, and temperatures. Cross-sectional analysis revealed that strip width and thickness systematically influenced filament internal structure, with thicker and wider strips producing larger cross-sectional areas and reduced internal voids. Tensile testing of 3D-printed specimens indicated that filament strip thickness was the dominant factor affecting mechanical performance. Filaments produced from thicker strips (0.20 mm) exhibited higher average tensile strength (up to 48.18 MPa) and modulus of elasticity (0.6952 GPa) compared to filaments from thinner strips (0.14 mm), while strain at break remained relatively consistent across all variations (0.07–0.10). Observed variations among individual specimens were attributed to localized defects and printing-induced voids rather than systematic process effects, suggesting that the overall trends provide a robust indication of filament performance. Overall, these findings indicate that PET bottle waste can be effectively recycled into functional 3D printing filaments, with filament geometry and processing parameters influencing mechanical and morphological characteristics in predictable ways. Future studies may incorporate statistical analysis with larger sample sizes to further quantify the significance of the observed trends and optimize process parameters for high-performance FDM filament production. The findings establish a clear process, structure, and property relationship, highlighting strip thickness as the dominant factor influencing filament performance. These insights provide a foundation for future optimization and scaling of pultrusion-based filament production systems.

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References

[1] Yun Arifatul Fatimah, Kannan Govindan, Rochiyati Murniningsih, Agus Setiawan, “Industry 4.0-based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia”, Journal of Cleaner Production, Vol. 269, 2020, pp.122263. https://doi.org/10.1016/j.jclepro.2020.122263

[2] Plohl, O., Zemljič, F., Erjavec, A., Sep, N., Čolnik, M., Fan, Y., Škerget, M., Vujanović, A., Čuček, L., & Valh, V., “Decomposition and fragmentation of conventional and biobased plastic wastes in simulated and real aquatic systems”, Clean Technologies and Environmental Policy, Vol. 27, No. 12, 2024, pp. 8569–8584. https://doi.org/10.1007/s10098-024-02972-2.

[3] P Benyathiar, P Kumar, G Carpenter, J Brace, and D Mishra, “Polyethylene Terephthalate (PET) Bottle-to-Bottle Recycling for the Beverage Industry: A Review”, Polymers, Vol. 14, No. 12, 2022, pp.2366. https://doi.org/10.3390/polym14122366.

[4] Sakr, N., & AbouZeid, M., “Recycling of Plastic Waste in the Construction Industry”, Polymers, Vol. 17, No. 9, 2025, pp.1282. https://doi.org/10.3390/polym17091282.

[5] Leng, Z., Padhan, R., & Sreeram, A., “Production of a sustainable paving material through chemical recycling of waste PET into crumb rubber modified asphalt”, Journal of Cleaner Production, Vol. 180, 2018, pp.682-688. https://doi.org/10.1016/j.jclepro.2018.01.171.

[6] Askar, M., Al-Kamaki, Y., & Hassan, A., “Utilizing Polyethylene Terephthalate PET in Concrete: A Review”, Polymers, Vol. 15, No. 15, 2023, pp.3320. https://doi.org/10.3390/polym15153320.

[7] Guo, S., Liu, L., Zhao, D., Zhao, C., Li, X., & Li, G., “Optimization of Briquette Fuels by Co-Torrefaction of Residual Biomass and Plastic Waste Using Response Surface Methodology”, Molecules, Vol. 28, No. 6, 2023, pp.2568. https://doi.org/10.3390/molecules28062568.

[8] Song, B., Cooke-Willis, M., Theobald, B., & Hall, P., “Producing a high heating value and weather resistant solid fuel via briquetting of blended wood residues and thermoplastics”, Fuel, Vol. 283, 2021, pp.119263. https://doi.org/10.1016/j.fuel.2020.119263.

[9] Akhator, P., Bazuaye, L., Ewere, A., & Oshiokhai, O., “Production and characterisation of solid waste-derived fuel briquettes from mixed wood wastes and waste PET bottles”, Heliyon, Vol. 9, No. 11, 2023, pp.e21432. https://doi.org/10.1016/j.heliyon.2023.e21432.

[10] Sau, D., Shiuly, A., & Hazra, T., “Utilization of plastic waste as replacement of natural aggregates in sustainable concrete: effects on mechanical and durability properties”, Int. J. Environ. Sci. Technol. Vol. 21, No. 2, 2024, pp.2085–2120. https://doi.org/10.1007/s13762-023-04946-1

[11] Ahmad, S., Amin, N., Ali, N., Adnan, N., Hisham, N., Mahmud, N., & Mulyadi, L., “The Effects of Domestic Plastic Waste on Concrete Properties: Sustainable Replacement of Aggregates”, Journal of Advanced Research in Applied Mechanics, Vol. 6, No. 1, 2025, pp.203-210. https://doi.org/10.37934/aram.132.1.185194.

[12] Dawood, A., Al-Khazraji, H., & Falih, R., “Physical and mechanical properties of concrete containing PET wastes as a partial replacement for fine aggregates”, Case Studies in Construction Materials, Vol. 14, 2021, pp.e00482. https://doi.org/10.1016/j.cscm.2020.e00482.

[13] Mishra, V., Negi, S. & Kar, S., “FDM-based additive manufacturing of recycled thermoplastics and associated composites”, J Mater Cycles Waste Manag Vol. 25, No. 2, 2023, pp.758–784. https://doi.org/10.1007/s10163-022-01588-2

[14] Madhu, N.R., Erfani, H., Jadoun, S. et al., “Fused deposition modelling approach using 3D printing and recycled industrial

materials for a sustainable environment: a review", Int J Adv Manuf Technol, Vol. 122, No. 5, 2022, pp.2125–2138. https://doi.org/10.1007/s00170-022-10048-y

[15] Shanmugam, V., Das, O., Neisiany, R.E. et al., "Polymer Recycling in Additive Manufacturing: an Opportunity for the Circular Economy", Mater Circ Econ, Vol. 2, No. 1, 2020, pp.11. https://doi.org/10.1007/s42824-020-00012-0

[16] Sola, Antonella, and Adrian Trinchi, "Recycling as a key enabler for sustainable additive manufacturing of polymer composites: a critical perspective on fused filament fabrication", Polymers, Vol. 15, No. 21, 2023,pp.4219. https://doi.org/10.3390/polym15214219

[17] Kassab, Ali, et al., "Advancing plastic recycling: Challenges and opportunities in the integration of 3D printing and distributed recycling for a circular economy", Polymers, Vol. 15, No.19, 2023,pp.3881. https://doi.org/10.3390/polym15193881

[18] Ibrahim I, Ashour AG, Zeiada W, Salem N, Abdallah M., "A Systematic Review on the Technical Performance and Sustainability of 3D Printing Filaments Using Recycled Plastic", Sustainability, Vol. 16, No. 18, 2024,pp.8247. https://doi.org/10.3390/su16188247

[19] Schneevogt, Helge, et al., "Sustainability in additive manufacturing: Exploring the mechanical potential of recycled PET filaments", Composites and Advanced Materials, Vol. 30, 2021, pp.1-8.https://doi.org/10.1177/26349833211000063

[20] Ogunsakin, Adesanmi, and Modupe Onitiri, "Recycling PET bottles for additive manufacturing: a method for 3D printer filament production", Nigerian Journal of Technology, Vol. 43, No.4, 2024:pp.676-684. https://doi.org/10.4314/njt.v43i4.8

[21] Bremer, M., Janoschek, L., Kaschta, D. et al., "Influence of plastic recycling—a feasibility study for additive manufacturing using glycol modified polyethylene terephthalate (PETG)", SN Appl. Sci,Vol. 4, No. 5, 2022, pp. 156. https://doi.org/10.1007/s42452-022-05039-3

[22] Karohika, I. M. G., Andhika, R., Widiyarta, I. M., Lokantara, I. P., Negara, D. N. K. P., &Budiarsa, I. N., "Tensile strength analysis of single filament 3D printing from single-use plastic bottle waste", In Journal of Physics: Conference Series, Vol. 3186, No. 1, 2026, pp. 012086. https://doi.org/10.1088/1742-6596/3186/1/012086

[23] Nikam, M., Pawar, P., Patil, A., Patil, A., Mokal, K., & Jadhav, S., "Sustainable fabrication of 3D printing filament from recycled PET plastic", Materials Today: Proceedings, Vol. 103, 2024, pp.115-125.https://doi.org/10.1016/j.matpr.2023.08.205.

[24] Bustos Seibert, Maximilian, et al.,"Manufacturing of a PET filament from recycled material for material extrusion (MEX)", Recycling, Vol. 7, No.5, 2022, pp.69. https://doi.org/10.3390/recycling7050069

[25] Ponsar, Hanna, Raphael Wiedey, and Julian Quodbach, "Hot-melt extrusion process fluctuations and their impact on critical quality attributes of filaments and 3D-printed dosage forms", Pharmaceutics,Vol. 12, No.6, 2020,pp.511. https://doi.org/10.3390/pharmaceutics12060511

[26] Yu, Kaicheng, et al., "A process parameter design method for improving the filament diameter accuracy of extrusion 3D printing", Materials, Vol. 15, No.7, 2022,pp.2454. https://doi.org/10.3390/ma15072454

[27] Yadav, A., Rohru, P., Babbar, A. et al., "Fused filament fabrication: A state-of-the-art review of the technology, materials, properties and defects", Int J Interact Des Manuf, Vol. 17, No. 6, 2023, pp.2867–2889. https://doi.org/10.1007/s12008-022-01026-5

[28] Akhoundi, Behnam, and Faramarz Hajami, "Extruded polymer instability study of the polylactic acid in fused filament fabrication process: printing speed effects on tensile strength", Polymer Engineering & Science, Vol. 62, No.12, 2022, pp.4145-4155. https://doi.org/10.1002/pen.26174

[29] Vyavahare S, Kumar S, Panghal D., "Experimental study of surface roughness, dimensional accuracy and time of fabrication of parts produced by fused deposition modelling", Rapid Prototyping Journal, Vol. 26, No. 9, 2020 pp.1535–1554. https://doi.org/10.1108/RPJ-12-2019-0315

[30] Shirmohammadi, M., Goushchi, S.J. & Keshtiban, P.M., "Optimization of 3D printing process parameters to minimize surface roughness with hybrid artificial neural network model and particle swarm algorithm", Prog Addit Manuf, Vol. 6, No. 2, 2021, pp.199–215. https://doi.org/10.1007/s40964-021-00166-6.

[31] Tanveer, Md Qamar, et al., "Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts-a current review", Materials Today: Proceedings, Vol. 62, No. 1, 2022, pp.100-108. https://doi.org/10.1016/j.matpr.2022.02.310

[32] Suteja, T. J., and Arum Soesanti, "Mechanical properties of 3D printed polylactic acid product for various infill design parameters: a review", Journal of Physics: Conference Series, Vol. 1569, No. 4, 2020, pp.042010.https://doi.org/10.1088/1742-6596/1569/4/042010

[33] Lalegani Dezaki, Mohammadreza, et al.,"Influence of infill patterns generated by CAD and FDM 3D printer on surface roughness and tensile strength properties", Applied Sciences, Vol. 11, No.16, 2021, pp.7272. https://doi.org/10.3390/app11167272

[34] Agrawal, Anant Prakash, et al.,"An investigation of combined effect of infill pattern, density, and layer thickness on mechanical properties of 3D printed ABS by fused filament fabrication", Heliyon, Vol. 9, No.6, 2023, pp.e16531. https://doi.org/10.1016/j.heliyon.2023.e16531

[35] Ansari, Anis A., and M. Kamil,"Effect of print speed and extrusion temperature on properties of 3D printed PLA using fused deposition modeling process", Materials Today: Proceedings, Vol. 45, No. 6, 2021, pp.5462-5468. https://doi.org/10.1016/j.matpr.2021.02.137

[36] Zhang, Jie, Fankai Meng, and Eleonora Ferraris,"Temperature gradient at the nozzle outlet in material extrusion additive manufacturing with thermoplastic filament", Additive Manufacturing, Vol. 73, 2023,pp.103660. https://doi.org/10.1016/j.addma.2023.103660

[37] Mishra, Pradeep Kumar, et al.,"An investigation to study the combined effect of different infill pattern and infill density on the impact strength of 3D printed polylactic acid parts", Composites Communications, Vol. 24, 2021,pp.100605. https://doi.org/10.1016/j.coco.2020.100605

[38] Pernet, Benoît, Jacquelyn Kay Nagel, and Hao Zhang,"Compressive strength assessment of 3D printing infill patterns", Procedia CiRP, Vol. 105, 2022, pp.682-687. https://doi.org/10.1016/j.procir.2022.02.114

[39] Sanassee, L., & Henrage, K., "The production of 3D printed filaments from plastic bottle waste using low-income setting extruders as an opportunity to reduce plastic pollution in the developing small islands", Journal of Material Cycle and Waste Management, Vol. 26, No. 5, 2024, pp.2841–2852. https://doi.org/10.1007/s10163-024-02005-6.

[40] Méndez, MG, Pérez, CDA, & Velázquez, "CDF Prototype of Pultrusion of Recycled Polyethylene Terephthalate Plastic Bottles into Filaments for 3D Eco-Printing: Education for Sustainable Development Projects". Journal of Sustainability, Vol. 16, No. 19, 2024, pp.1–17. https://doi.org/10.3390/su16198347

[41] Budiono, S. H., & Purnomo, J. S., "Effect of Extrusion Temperature Variations for Manufacturing 3D Printer Filament Based on Used Bottle Waste on Impact Strength", Jurnal E-Komtek (Elektro-Komputer-Teknik), Vol. 8, No. 1, 2024, pp.168–176. https://doi.org/10.37339/e-komtek.v8i1.1725

[42] Oussai, A., Bártfai, Z., & Kátai, L., "Development of 3D printing raw materials from plastic waste. Case study on

recycled polyethylene terephthalate". Journal of Applied Sciences (Switzerland), Vol. 11, No. 16, 2021, pp.1–10. https://doi.org/10.3390/app11167338

[43] Vedernikov, Alexander, et al.,"Pultruded materials and structures: A review", Journal of Composite Materials, Vol. 54, No.26, 2020, pp.4081-4117. https://doi.org/10.1177/0021998320922894

[44] Correia, João Ramôa. Pultrusion of advanced composites,In: Jiping Bai, editor. Advanced fiber-reinforced polymer (FRP) composites for structural applications, Woodhead Publishing, 2023, pp.137-177. https://doi.org/10.1016/B978-0-12-820346-0.00007-1

[45] Minchenkov, Kirill, et al.,"Thermoplastic pultrusion: a review", Polymers, Vol. 13, No.2, 2021, pp.180. https://doi.org/10.3390/polym13020180

[46] Ferreira, Filipe, et al.,"Development of a pultrusion die for the production of thermoplastic composite filaments to be used in additive manufacture", Journal of Composites Science, Vol. 5, No.5, 2021, pp.120. https://doi.org/10.3390/jcs5050120