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Fabrication of a fused filament extrusion system for recycled PET and comparative mechanical characterization studies vis-à-vis PLA

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Highlights:

- A filament extruder was fabricated to recycle PET waste for 3D printing.
- Extrusion behavior of recycled PET was compared with PLA under identical parameters.
- Mechanical properties of printed PET and PLA parts were evaluated and compared.

Abstract: Fused Deposition Modelling (FDM) is a popular additive manufacturing (AM) technique that converts three-dimensional computer-aided design (CAD) models into complex-shaped objects using thermoplastic filaments as a raw material. Existing recyclable plastics, such as Acrylonitrile Butadiene Styrene (ABS), Polyetherimide (PEI), Polyether ether ketone (PEEK), Polylactic Acid (PLA), Polyethylene Terephthalate (PET), and Nylon, can be used to fabricate AM components as alternative for commercially available filaments, as they are a significant source of waste and widely available. This study presents a method of converting waste polymers into filaments for 3D printing. A dual-material extrusion system capable of processing both recycled PET and PLA under identical conditions was developed using a band heater, Proportional-Integral-Derivative (PID) temperature controller, motor, extruder screw and hopper, *etc*. The experiments were performed to produce the 3D filaments using recycled plastics (in the form of PET) and PLA pellets, and the results were compared. For recycled PET, waste plastics were collected, shredded, and passed through the hopper. The material was melted in the heating chamber at a temperature range of 150–220 ℃ for PET and 180–210 ℃ for PLA. The auger bit's rotatory action delivered the molten material to the nozzle, where the final filament was extruded. The tensile strength of PLA specimens (44 ± 3.6 MPa) was found ~11% higher than PET (39 ±3.2 MPa). Whereas, the percentage elongation of PET and PLA specimens were found as 4 and 5.2% respectively. This performance affirms that recycled PET, when appropriately processed, can bridge the gap between environmental responsibility and mechanical functionality in 3D

printing applications. This model will likely help industries improve their efficiency and performance by lowering the cost of the new materials and making it more efficient for them. The produced filament can create personalized accessories, household goods, and distinctive, tailored fashion products.

Keywords: 3D printing; fused deposition modelling; filament extrusion; polyethylene terephthalate (PET); polylactic acid (PLA)

1. Introduction

3D printing is one of the AM methods that computer-aided design (CAD) models use to generate 3D solid objects. It is commonly referred to as rapid prototyping [1]. According to ISO/ASTM 52900:2021 [2], AM technologies are classified into seven types; vat photopolymerization (VP), material jetting (MJ), material extrusion (ME), sheet lamination (SL), powder bed fusion (PBF), binder jetting (BJ), and direct energy deposition (DED) [3]. Material extrusion process, also known as fused deposition modelling (FDM) can be further classified according to the mechanism used in extrusion filament, screw and plunger.

The filament-based FDM technology is called fused filament fabrication (FFF), in which thermoplastics are utilized to create 3D models [4]. While printing the thermoplastic filament, construction materials are fed into the top of an extruder, and the material temperature is raised to a predetermined level. The thermoplastic filament is controlled via a heated nozzle. During printing, molten filament extruded through this nozzle is placed on a printing bed in layers. This method allows the use of a range of popular filament materials like polylactic acid (PLA), polyetherimide (PEI), polyether ether ketone (PEEK), acrylonitrile butadiene styrene (ABS), and nylon [5]. ABS creates hazardous monomers upon heat breakdown, making it difficult to use. PLA has excellent thermal stability, but its impact resistance is inadequate compared to its density and hardness, making it unsuitable for several industrial uses [6]. This technique also enables the manufacturing of customized, exact, precise, and complex geometry-shaped products, making it widely employed in aerospace, healthcare, agriculture, and processing [4,7].

Plastic has become a substantial source of garbage, making its management critical [8]. However, plastics are extremely versatile materials with excellent strength and low density-to-weight ratios. They are easy to process, affordable, and widely available. Employing waste plastic materials such as Polyethylene Terephthalate (PET) in 3D printing offers an environmentally responsible approach to address this issue [9]. These recycled waste plastics can be used in place of accessible filament materials (ABS, PLA, *etc.*), significantly reducing waste plastics at the earth's surface and oceans and extending the product's life cycle [10]. This method alters plastic properties by increasing shear stress, temperature, and interference from ambient gases (O_2, N_2, *etc.*) during extrusion [8]. This strategy will benefit the industry by increasing efficiency since, instead of commercially available resources, recycled polymers will be used as 3D printing feedstock [11].

Recent studies have emphasized the growing role of additive manufacturing (AM) in waste reduction and material reuse. For instance, 3D printing has been successfully applied to produce zero-waste protective equipment using recycled materials [12]. Broader reviews have discussed how waste plastics can serve as secondary raw materials for filament production [8]. Further, advances in thermoplastic feedstocks and composite filaments highlight the evolution of high-speed FFE systems and material optimization [13,14].

The growing use of polyethylene terephthalate glycol (PETG) in filament-based additive manufacturing due to its amorphous nature minimizes warpage and improves print reliability. Studies by Trossaert *et al.* [15], Seno Flores *et al.* [16], and Marsavina *et al.* [17] demonstrated that both virgin and recycled PETG exhibit stable extrusion and good mechanical performance. However, recycled PET remains more widely available, and evaluating its direct recyclability offers valuable insight into sustainable material recovery for 3D printing applications.

Previous studies have primarily focused on commercial filament production or single-material extrusion systems. In contrast, the objective of this research is to design and develop a dual-material functional filament extrusion system capable of processing both recycled PET waste and commercial PLA under identical operating conditions. The study focuses on evaluating the extrusion characteristics, filament discharge behavior, and mechanical properties of 3D-printed specimens fabricated from these filaments. Through a comparative analysis, the performance of recycled PET is assessed against PLA to determine its suitability for additive manufacturing applications. The comparative mechanical and extrusion behavior of the two materials provides direct evidence of the potential of recycled PET as a sustainable alternative in AM.

2. Materials and methods

To develop a working model for 3D printing PET filament was fabricated using recycled PET. The recycled PET used in this study was obtained from local transparent post-consumer beverage bottles. All bottles were hand sorted prior to processing to remove caps, labels, colored containers and other visible contaminants to minimize variability in the material. The selected PET bottles were washed thoroughly with water, dried and shredded into flakes before oven drying and extrusion. Although no detailed compositional or purity analyses were performed, the use of a single waste stream and careful manual sorting led to reasonably consistent feedstock quality throughout the experimental work. The same model was also used to convert commercial PLA pellets into filaments. Figure 1 shows the components and working model of the filament extruder. A hollow section was designed on the barrel to fit the plastic hopper and contain the necessary amount of raw material for feeding to the extruder screw. The screw diameter with 20 mm and effective length of approximately 29 cm, having a L/D ratio of ≈ 14.5 was used. The pitch of the screw was nearly similar to that of diameter, *i.e.*, 20 mm with the compression ratio of 2.5:1. The core diameter of the screw was taken as 13 mm, nearly 65% of the screw diameter. The flight depth was kept as 3.6 mm in the feed zone, which gradually decreases with the compression zone for smooth melting and pressure build-up.

A round-shaped steel barrel serves as a chamber for the extruder screw, which transfers raw material. The inner and exterior diameter of the barrel were kept as 20 and 30 mm, respectively. The length of the barrel was kept at 31 cm. The extruder screw (Figure 1c) was used to transfer the feed material into the heating chamber (barrel) via rotatory action. A flange was utilized in the extruder; first, it was screwed to the support plate, and then welded to provide robust joints.

A 12V wiper motor (Figure 1f) was connected to an extruder screw shaft, providing sufficient power to the extruder to move the material with its motion [18]. A 12V, 10A motor speed controller with regulator was utilized to control the motor’s speed, resulting in control over the rotating speed of the extruder screw [18]. The motor speed of 50 rpm was determined through preliminary experimental trials conducted different ranges (includes higher and lower than the optimized value of 50). Below 50 rpm, the extrusion rates were found low, inconsistent with poor surface finish. However, above this, an increased strain fluctuation, surface irregularities and filament diameter variations were observed due to an insufficient cooling time. The present optimized value of 50 rpm provided an optimal balance between material throughput, melt stability, and cooling efficiency, resulting in consistent filament formation with a minimum diameter variation.

A 120V, 200-watt band heater (Figure 1b) was installed on top of the barrel as the heating element to supply the heat energy required to melt raw material [19]. The mica sheet was wrapped around the barrel before attaching the band heater to act as an insulator between it and the barrel interface. To keep the extrusion process running smoothly, a PT-100 A thermocouple with a Platinum resistance temperature detector (RTD) (Figure 1a) was attached to the band heater. It is an electrical device that uses the thermoelectric effect to measure temperatures between −50 ℃ and 500 ℃ [20]. Filament extrusion necessitates a heating control system to monitor the temperature required to melt the raw material; a UTC 421P Multispan PID temperature controller (Figure 1d) was utilized to ensure a precise, consistent temperature [20]. A solid-state relay (SSR) (Figure 1e) was utilized as an electrical switching device to control the temperature of a heating element by turning it on or off in response to a small external voltage applied to its control terminals. When the temperature is insufficient, the SSR sends power to the heater; when the temperature rises over the specified level, the SSR turns off the current [20]. It was compatible with a PID temperature controller.

The nozzle was attached to the barrel to extract the filament. It preserves the final dimension of the extrudate based on the appropriate form and size. It has a cylindrical shape with a small hole in the center of the bottom surface [21]. The size of the nozzle was kept smaller than the required diameter of the filament, since it allows controlled expansion while extrusion and exit from the nozzle. Therefore, the diameter of the nozzle was selected as 1.5 mm to achieve the stable melt flow of constant filament diameter (nearly 1.75 mm), which is generally used in conventional 3D FDM printers. Also, a number of trails were conducted using variation in size of the nozzle before finalizing the 1.5 mm diameter. Smaller nozzle diameter resulted in unstable discharge and clogging in some cases of PET. However, larger diameter increased the deviation in accuracy of filament size. The 1.5 mm nozzle showed a balanced output (in the range of 1.65–1.75 mm, with the swell ratio of 1.16) with having flow stability and minimum variation in filament diameter. The nozzle’s pressure was increased to the point where material began to extrude.

The solidification and uniformity are primarily governed by the constant cooling rate provided near the nozzle outlet. Therefore, a forced convection cooling environment using a 12V DC fan with an air flow rate of ~10 L/min was employed to cool and solidify the molten extrudate at the nozzle outlet, resulting in high-quality, smooth filaments [22]. The stand-off distance was kept as 50 mm from the nozzle outline. This arrangement was made to avoid very slow cooling or rapid quenching, which can lead to high residual stresses and dimensional inaccuracy.

2.1. Construction of the extruder

A 5 mm thick medium-density fiberboard (MDF) sheet was used to make an electronics box, and a mounting platform of dimension 19 × 55 × 15 cm^3. Multiple sheets were cut into pieces with a plywood cutter, and the pieces were put together with a drill and screws to form the finished box. Different machining procedures were employed to manufacture the mechanical components of the extruder, such as the barrel and shaping die. The front side of the control panel was cut from an MDF sheet. A trim router was used to make holes for mounting the switches and controller. The motor mount was manufactured from a 12 mm-thick MDF board. Two boards were combined to form a mounting bracket. Thereafter, the filament extruder machine was built with various assembly tools and equipment, such as nuts, bolts, and washers. The final assembly of the filament extruder machine is shown in Figure 1g.

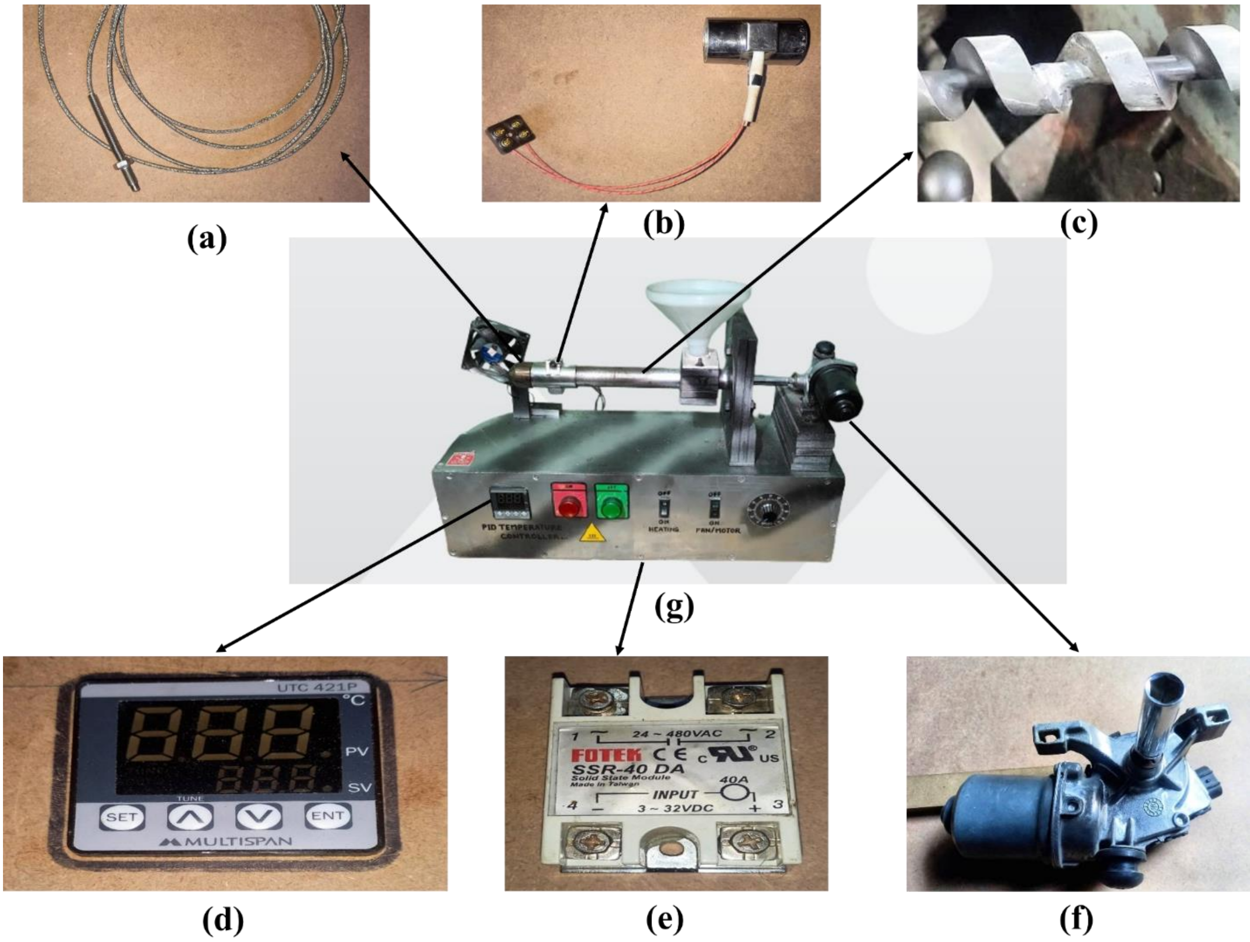

Figure 1. In clockwise. **(a)** Thermocouple; **(b)** Band Heater; **(c)** Extruder Screw; **(d)** PID Controller; **(e)** SSR; **(f)** Motor and **(g)** Extruder Machine.

2.2. Process of filament extrusion from filament extruding machine

PET flakes with particle size distribution range of 1–4 mm was used for the filament extrusion process. The particle size was measured using standard sieve analyzer. The recycled PET flakes were first washed with distilled water and dried in air to remove surface contaminants. Since material was manually segregated to remove unwanted non-PET materials particles like labels and caps and followed by washing and drying, therefore achieves purity of approximately 90%–95%, sufficient for extrusion related applications. The flakes were then oven-dried at 80 ℃ for 6 hours in a hot-air circulating oven to minimize moisture content and prevent hydrolytic degradation during extrusion. The chosen temperature was below the onset of PET thermal degradation but sufficient for effective drying. The PLA

pellets were dried at 45 ℃ for 4 hours under the same conditions to eliminate residual surface moisture. After drying, both materials were stored in airtight containers containing silica gel until extrusion.
The materials were first shredded to prepare for filament extrusion. The material was fed into the hopper, and the auger bit's rotatory motion pushed the shredded waste plastic (PET)/PLA into the barrel/heating chamber. A geared motor was used to rotate the auger bit/extruder screw and control the speed. A band heater heats the barrel to melt the inserted raw material, and a PID temperature controller maintains the temperature of the heating chamber based on the material utilized. After melting, the material was extruded out of the heating chamber through the nozzle. The fan was employed to lower the temperature and harden the filament. Figure 2 depicts an overview of filament extrusion.

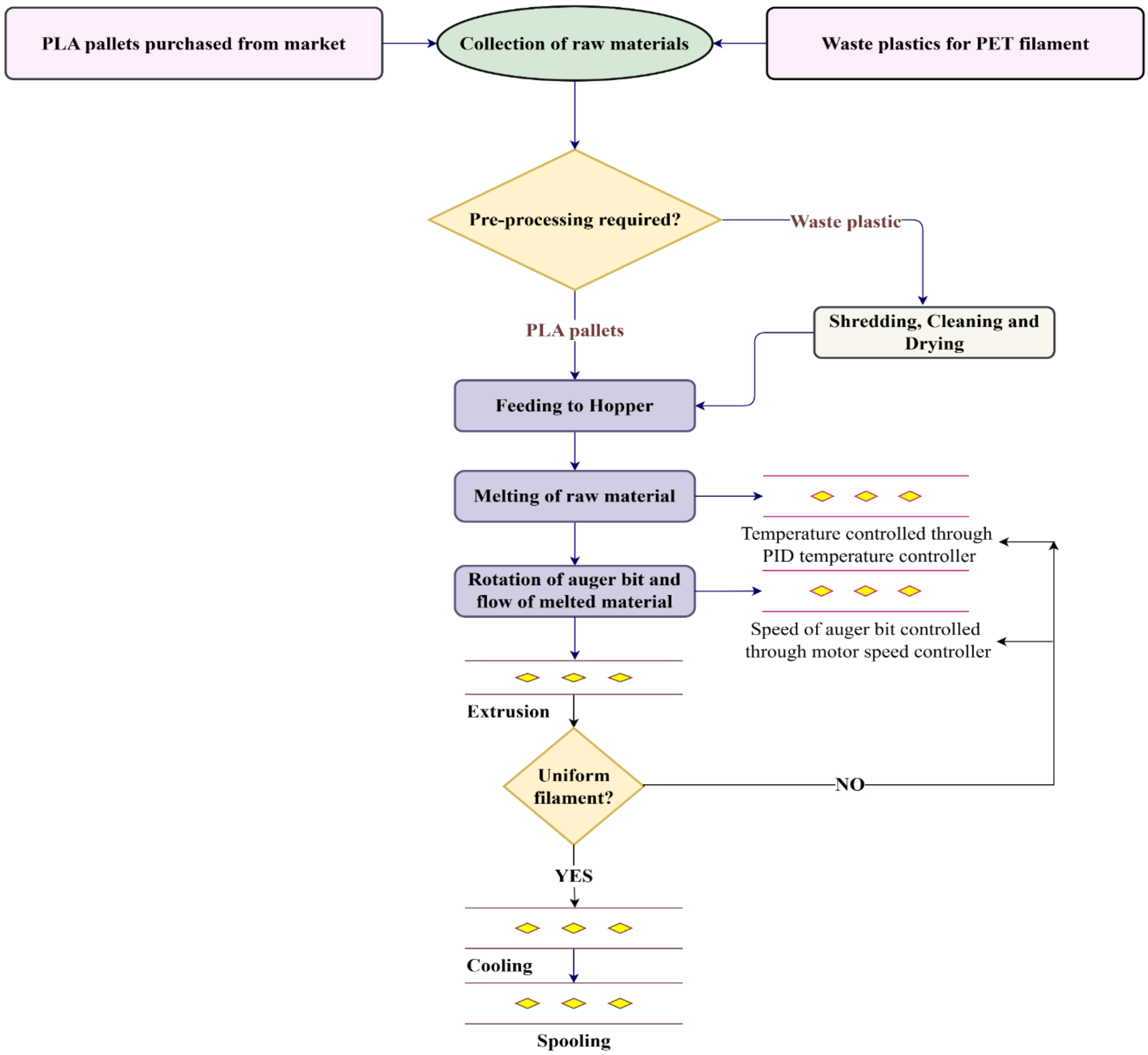

Figure 2. Overview of filament extrusion process.

For PLA, an extrusion grade Commercial IngeoTM 4043D, popularly used for the purpose of filament production was used with the melt flow index (MFI) of 6 g/10 min, as measured using ASTM D1238 at 210 ℃/2.16 kg, relative viscosity = ~4.0, number average molecular weight (Mn) of 80,000–100,000 g/mol. In the case of PET, the system began to produce fumes at temperatures above 250 ℃, and the extruded part seemed virtually burned and black, indicating that it had been overheated. At 230 ℃, a filament formed with dotted lines, lengthy bubbles, and pits. A temperature of 210 ℃ produced a filament flow but with inconsistent diameter and poor surface quality. Therefore, this was chosen as the experiment's upper range. Each experiment ran for a total of 15 minutes.

In case of PLA, below 170 ℃, the raw material clogged the nozzle, preventing filament extrusion. The continuous filament extrusion process started at temperatures above 170 ℃. It was also found that beyond 220 ℃, the filament completely melted. As a result, the temperature range for the experiment was set between 180 ℃ and 210 ℃ to account for precautionary measures, with a 5 ℃ increase for each new trial. A minimum of three experiments were performed for each condition.

The processing temperature profiles for PLA and PET were selected based on their distinct thermal properties. PLA exhibits a relatively narrow melting range (~155–170 ℃) and is more sensitive to the thermal degradation. However, PET has a broader melting range (~250–260 ℃). Accordingly, a smaller temperature gradient (5 ℃) was sufficient for PLA, while a larger gradient (10 ℃) was necessary for PET to ensure complete melting and stable flow. The chosen temperature ranges were aligned with values reported in polymer processing literature and were further refined through controlled extrusion trials [23,24].

Fabricated filament was inserted into 3D printing machine (Model: Stemrobo arctic 3D printer, a single nozzle size of 0.4 mm with FDM technique). A layer thickness of 100 μm, printing speed of 60 mm/s, infill density of 100% and raster orientation of 45°/−45°, was used to fabricate tensile testing specimen as shown in Figure 3. The nozzle temperatures of 250 ℃ and 200 ℃ with bed temperatures were taken as 70 ℃ and 60 °C for PET and PLA, respectively. These settings were selected to achieve complete infill and strong inter-layer bonding, thereby minimizing porosity in the printed specimens. Nearly identical process parameters were maintained for both materials to ensure a valid comparison of mechanical properties. Tensile testing was performed as per ASTM D638 standards. A minimum of three tests were conducted for both the recycled PET and PLA samples to ensure reproducibility [25].

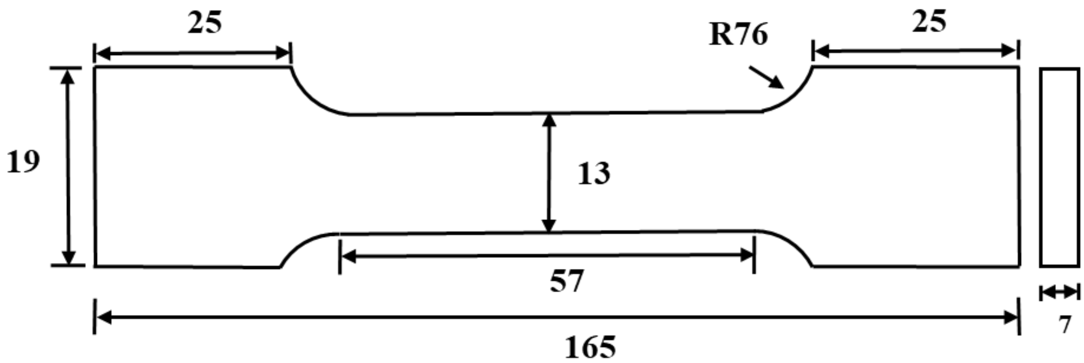

Figure 3. Dimensions of tensile testing specimen (in mm).

The quality of the filament was assessed on the basis of three distinct parameters: solidification, continuity and straightness. Solidification was considered after occurrence of completion of complete melting and re-solidification. In this condition, no unmelted particles or internal voids were observed and material fusion was found to be above 95%. Continuity was defined on the basis of extrusion without any breakage up to a minimum length of 1 meter. Straightness of the filament was measured using the condition that the linearity deviation limit of not more than 0.5 mm over a minimum 10 cm length.

3. Results and discussions

3.1. Extrusion of PET filaments

Extrusion of shredded polymers (PET) was carried out at various temperatures ranging from 150 ℃ to 220 ℃, with each successive trial increasing the temperature by 10 ℃. Table 1 presents the data from each trial. Below 160 ℃, the shredded plastics did not melt adequately due to insufficient temperature to completely melt the plastic, resulting in an uneven and rough filament surface. In both cases, the nozzle was repeatedly clogged. At 220 ℃, the plastic melted fast, leaving the extruded filament in liquid form. This happened because the temperature was too high for the PET. As a result, no values were measured in such circumstances, and the tests were rejected. The extruded filament was smooth and consistent at 170 ℃, with varied diameters due to contaminants in the barrel and hand pulling. To avoid non-uniformity and roughness in the results, the temperature ranges for the experiments were set between 170 and 210 ℃.

The filament at 180 ℃ produced better results than 170 ℃ due to PET's higher melting temperature. Setting the temperature to 190 °C resulted in a higher quality filament with a diameter of 1.64 mm and minimized surface defects. This was due to the filament melting perfectly in the barrel and consistent hand pulling to maintain the diameter. Under these conditions, all three trials resulted in a smooth surface finish. The extruded filament could not be found straight due to the high barrel temperature of 200 and 210 ℃. The discharge could not be measured at temperatures above 220 ℃ because the PET filament had melted entirely due to the high temperature. Thus, diameters were not measured, and the tests were discarded. Table 1 shows that at temperatures of 170, 180, 190, 200, and 210 ℃, the discharges were 1.44, 1.72, 3.01, 2.76, and 1.81 cm^3/minute. Figure 4 shows the variation in discharge rate with respect to temperature. The discharge rate was found to be increased until 190 ℃, after which it declined. The highest discharge was observed at 190 ℃ with homogeneous and smooth filament quality. This is because the melting rate of PET volume at 190 ℃ was the slowest, resulting in a higher surface finish with the optimal discharge value. The reduction in discharge rate after 190 ℃ is attributed to the thermal degradation such as chain scission and decrease in the stability of melt viscosity. Screw-barrel interface might have faced a possible melt backflow in this case.

Table 1. Extrusion result data of PET.

No.	Temperature (℃)	Filament initiation time (min, sec)	Molten Result			Total time (min)	Mass (g)	Discharge (cm^3/min)	Standard Deviation
			Solid (Yes/No)	Continuity (Yes/No)	Straightness (Straight/ Non-straight)				
1	150	NO	NO	NO	NO	NA	NA	NA	NA
2	160	NO	NO	NO	NO	NA	NA	NA	NA
3	170	1,30	Yes	Yes	Straight	15	32.0	1.44	0.16
4	180	1,21	Yes	Yes	Straight	15	38.1	1.72	0.16
5	190	1,12	Yes	Yes	Straight	15	66.0	3.01	0.23
6	200	1,05	Yes	Yes	Non-Straight	15	60.2	2.76	0.25
7	210	0,57	Yes	Yes	Non-Straight	15	39.2	1.81	0.15
8	220	0,51	No	No	Non-Straight				

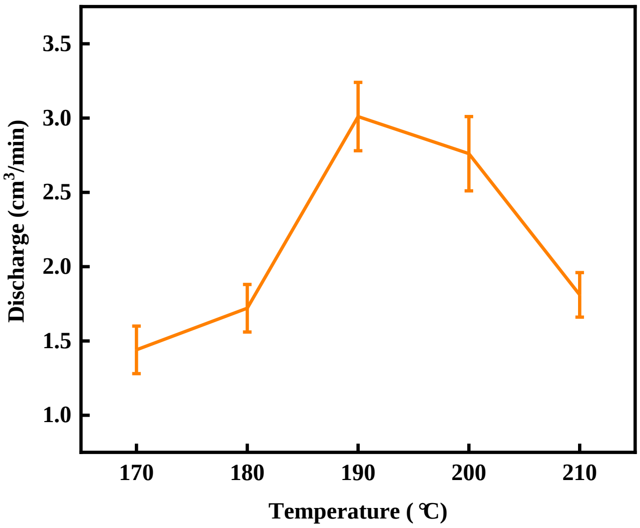

Figure 4. Discharge *vs*. temperature profile of filament extruded from PET.

3.2. Extrusion of PLA filaments

A 15-minute timeframe was selected for PLA filament extrusion. Table 2 shows the filaments' discharge with respect to temperature, and Figure 5 shows the trend. At higher temperatures of 205 ℃ and above, filament straightness was still not maintained, and contaminants within the barrel caused a variation in filament diameter. At 200 ℃, a straight and smooth filament was extruded. At 180 ℃, the extruded filament had a smooth surface, round shape, consistent extrusion, and superior filament quality compared to higher temperatures.

Table 2 shows the time taken for the extruder to release filament via the nozzle, and it can be observed that the time required to release the filament decreases with increase in temperature. This is because PLA melts more quickly at higher temperatures. The discharge rates at 180, 185, 190, 195, 200, 205, and 210 ℃ were found to be 0.45, 0.893, 1.681, 1.56, 1.34, 0.979, and 0.594 cm^3/minute respectively. The trend suggests that the rate of discharge increases from 180 ℃ to 190 ℃, then drops from 190 ℃ to 210 ℃. The best grade PLA filament was extruded at 195 ℃, since although the discharge was lower at that temperature, the surface smoothness was better than at 190 ℃. Unlike PET, in this case, the decrease in discharge rate can be attributed to the thermal softening and accumulation of the localized melt near the nozzle area, leads to disruption of the steady flow. Also, such long exposure at elevated temperatures can lead to oxidative or thermal degradation and flow efficiency.

Table 2. Extrusion result data of PLA pellets.

No.	Temperature (℃)	Filament initiation time (min, sec)	Molten Result			Total time (min)	Mass (g)	Discharge (cm^3/min)	Standard Deviation
			Solid (Yes/No)	Continuity (Yes/No)	Straightness (Straight/ Non-straight)				
1	180	1,20	Yes	Yes	Straight	15	10.4	0.45	0.05
2	185	1,17	Yes	Yes	Straight	15	20.8	0.89	0.09
3	190	1,13	Yes	Yes	Straight	15	39.0	1.68	0.12
4	195	1,08	Yes	Yes	Straight	15	36.0	1.56	0.1
5	200	1,04	Yes	Yes	Straight	15	31.0	1.34	0.11
6	205	1,00	Yes	Yes	Non-Straight	15	22.4	0.98	0.1
7	210	0,56	Yes	Yes	Non-Straight	15	13.6	0.59	0.06

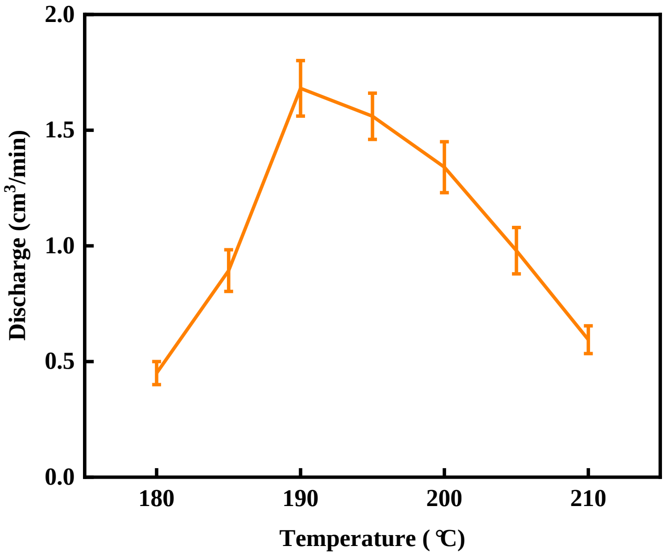

Figure 5. Discharge *vs.* temperature profile of filament extruded from PLA pellets.

3.3. Comparison of mechanical properties

A comparative analysis of the tensile properties of 3D-printed specimens fabricated from recycled PET and commercially available PLA is shown in Figure 6 and their extrapolated values are presented in Table 3. The recycled PET, sourced from post-consumer plastic waste and reprocessed into filament, demonstrated a tensile strength of 39 ±3.2 MPa. Notably, this value falls within the lower range of PLA, which showed an ~11% higher strength than PET in this study. However, considering the origin of the PET material recovered from waste streams, the mechanical performance is both encouraging and industrially significant. It highlights the capability of recycled PET to retain structural integrity suitable for functional applications, especially when processed under optimized conditions. The lower value of strength can also be attribute to its thermal and processing effects. Such prolong exposures in PET can degrade the molecular structure and lead to reduced chain length and microstructural defect formations. The defect like voids and weak interlayer bonding can affect the overall strength of the printed specimens using PET filament.

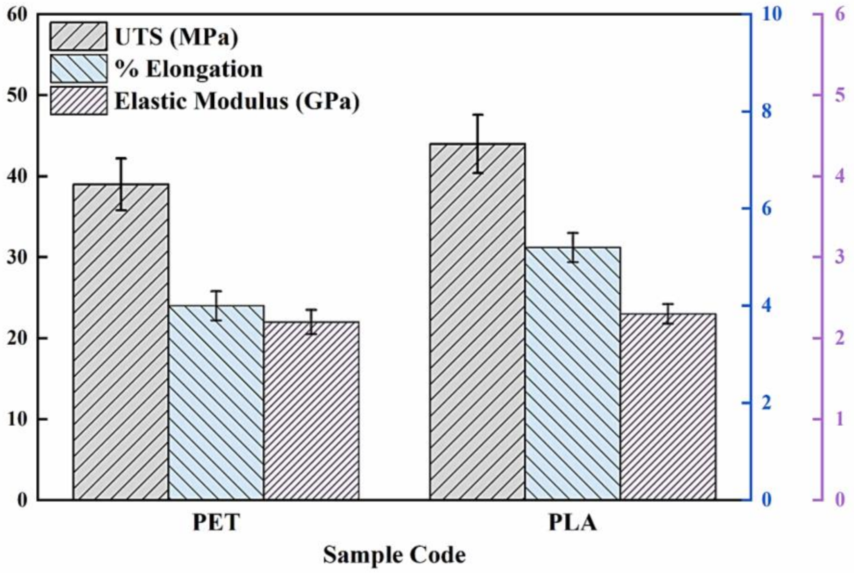

Figure 6. Comparison of UTS, % elongation and elastic modulus of PET and PLA samples.

Table 3. Tensile properties of 3D-printed specimens.

Condition	UTS (MPa)	Young's modulus (GPa)	Elongation at break (%)
PET	39 ±3.2	2.2 ±0.15	4 ±0.3
PLA	44 ±3.6	2.3 ±0.12	5.2 ±0.3

In terms of ductility, PLA exhibited a slightly higher elongation at break (5.2 ±0.3%) compared to PET (4 ± 0.3%). While PLA's flexibility is marginally superior, the recycled PET still demonstrated adequate elongation for applications where moderate strain accommodation is acceptable. The mechanical behavior of both materials is in close agreement with reported values in the literature [26–29], further validating the experimental methodology and processing conditions. Importantly, the findings underscore the potential of recycled PET as a viable and sustainable alternative to virgin polymer feedstock in AM. The ability of PET to deliver comparable tensile performance to standard PLA highlights its promise of reducing plastic waste and supporting circular economy models.

The experimental results demonstrate that the fabricated system can support localized filament production using recycled PET without compromising process stability. The measured discharge-temperature relationships and corresponding mechanical outcomes offer guidance for optimizing extrusion throughput and melt consistency when using secondary polymers. These findings contribute to current efforts in distributed, resource-efficient manufacturing, where small-scale equipment complements industrial production by closing material loops and reducing logistic demands.

3.4. Sustainability, environmental Impact, and economic viability

Utilizing recycled PET feedstock markedly reduces environmental impact by cutting energy consumption and diverting plastic waste from landfills. This presents a compelling case for decentralized manufacturing in educational or community settings. The adoption of recycled PET filament for 3D printing offers compelling environmental advantages, especially when assessed within a lifecycle framework. A recent life-cycle assessment study comparing distributed recycled filament production to virgin PLA supply chains found that the distributed recycling approach achieved at least a 97% reduction in environmental impacts related to climate change, eutrophication, and resource depletion. The exception was ionizing radiation impact, which increased due to France's energy mix dominated by nuclear power [30]. The recycled PET manufactured for filament extrusion consumes substantially less energy and produces less CO_2 than traditional virgin PET methods. Although exact figures vary by context and equipment, these results support the clear environmental benefits of localized recycling [18,31]. The environmental and economic benefits discussed here are based on published life cycle assessment and distributed recycling studies which consistently indicate that localized production of recycled polymer filament can significantly reduce both environmental burdens and material costs relative to conventional virgin filament supply chains.

Regarding material performance in long-term use, studies show that recycled PET filaments retain mechanical properties comparable to virgin formulations. Ibrahim *et al.* [32] highlighted that recycled PET filaments exhibited only minor reductions in tensile strength but maintained similar stiffness (Young's modulus) to virgin PET glycol. Further improvement in mechanical performance was demonstrated by hybrid blends, such as recycled PET reinforced with PLA and TPU, showing enhanced impact strength and satisfactory tensile and flexural behavior in 3D-printed specimens [33]. From an economic standpoint, distributed filament production dramatically lowers material costs. The cost reduction may be transformative, particularly for educational institutions, makerspaces, and low-resource environments.

4. Conclusion

The present work describes the design of a dual-material functioning filament extruder for converting waste PET and virgin PLA into 3D-printing filament, thereby contributing to the growth of the circular economy. Waste plastic and PLA were successfully converted into filament using the built equipment. The results reveal that the PET and PLA filaments are well compatible with the established literature. The optimum values of filament discharge were obtained at 190 ℃ for both PET and PLA. Mechanical testing confirmed that recycled PET filaments achieved tensile properties (39 ± 3.2 MPa) close to those of PLA (44 ± 3.6 MPa), validating their suitability for structural applications under moderate loading conditions. The observed tensile strength and elongation values are consistent with prior studies, indicating that recycled feedstock, when properly processed, can yield mechanical performance comparable to virgin materials.

These findings support the feasibility of incorporating recycled polymers into AM workflows, contributing to material sustainability without significant compromise in mechanical integrity. Combining recycled plastic and PLA reduces raw material utilization in industries while reducing the environmental impact of waste plastics by giving them a new form. A key challenge was the presence of bubbles in PET filament, traced to inadequate pre-drying which can develop residual moisture and hydrolytic degradation during melting. In future, this could be mitigated by integrating an improved drying stage to approximately 90–100 ℃ for extended duration of 6–8 hours. In-line vacuum degassing at reduced pressure values in the range of −0.06 to 0.08 MPa may also prove helpful in eliminating the entrapped volatiles during extrusion process. Additionally, while this study focuses on mechanical testing, supplementary FTIR (Fourier-transform infrared spectroscopy) and thermal analyses using DSC may be studied for studying the melting and degradation phenomenon over a higher temperature up to 300 ℃ at a specific heating rate of 10 ℃/min under a nitrogen (inert) atmosphere. Also, rheological characterization at higher temperatures with a specific shear rate (e.g., up to 220 ℃, 1–100 s^{-1}) would deepen understanding of melt viscosity and flow behavior of PET and enable precision tuning of extrusion parameters. Future studies may also include microscopic characterization to study the filament morphology, crystallinity, thermal transitions, and possible molecular changes after extrusion. The present approach provides a scalable and adaptable solution for producing recycled waste and PLA filaments in AM applications. The developed system's adaptability allows further exploration of a larger spectrum of materials.

Data availability statement

No supplementary or additional data were generated in this study.

Declaration of generative AI and AI-assisted technologies

The authors did not use generative AI or AI-assisted technologies in the writing of this manuscript. The author takes full responsibility for the content of the manuscript.

Authors' contribution

Writing—original draft, review and editing, supervision, resources, project administration, investigation, conceptualization, A.K.S.C.; data curation, writing—original draft, investigation, methodology, visualization, U.M. and A.V.S.; writing—review and editing, M.S. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Mukul Shukla holds the position of associate editor for *Advanced Manufacturing* and has not peer reviewed or made any editorial decisions for this paper.

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