Available online at
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e-ISSN: 2550-164X

Journal of Mechanical Engineering SI 14 2025, 95 – 109.

Journal of Mechanical Engineering

Investigation of Rheological and Thermal Properties of Recycled PET from Bottles and Preforms for 3D Printing Applications

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ARTICLE INFO

Article history:
Received 25 March 2025
Revised 07 October 2025
Accepted 31 October 2025
Online first
Published 15 November 2025

Keywords:
Recycled PET
3D printing filament
Additive manufacturing
Thermal properties
Rheological properties

DOI:
10.24191/jmeche.v14i1.5783

ABSTRACT

The growing adoption of 3D printing across industries has spurred interest in eco-friendly materials, with recycled polyethylene terephthalate (PET) emerging as a promising candidate. This study investigates the rheological and thermal properties of recycled PET derived from post-consumer bottles and preforms to assess its suitability for 3D printing. Key rheological parameters, including melt viscosity, melt flow rate, and shear-thinning behavior, were characterized using a rheometer, while thermal properties such as glass transition temperature (*Tg*), melting temperature (*Tm*), and crystallization temperature (*Tc*) were analyzed via differential scanning calorimetry (DSC). Results revealed significant shear-thinning behavior, with viscosity decreasing from 40,000 Pa·s (bottles) and 4,000 Pa·s (preforms) to below 500 Pa·s as the shear rate increased from 20 to 1,000 s^{-1}. Thermal analysis indicated a melting point of 255 °C for both materials, with optimal printing temperatures identified at 250 °C for bottles and 253 °C for preforms. These findings highlight the importance of temperature regulation, particularly for PET preforms, which exhibit lower viscosity and are prone to degradation. Based on comprehensive rheological and thermal analyses, optimal processing conditions were established at 250 °C – 260 °C for bottle-derived PET (with 260 °C showing superior flow characteristics) and 253 °C – 256 °C for preform-derived PET (with 253 °C demonstrating optimal filament formation). These findings advance the sustainable implementation of recycled PET in additive manufacturing by providing empirically validated processing parameters that balance material flow properties with thermal stability, enabling reliable printability while minimizing degradation risks.

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https://doi.org/10.24191/jmeche.v14i1.5783

INTRODUCTION

The 3D printing industry has experienced exponential growth, revolutionizing manufacturing processes across diverse sectors such as automotive, aerospace, healthcare, and consumer goods. Central to this innovation is the production of filaments, the essential material used in 3D printers. Traditionally, filaments are predominantly derived from virgin plastics, such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), which contribute to environmental concerns due to resource depletion and plastic waste accumulation (Geyer et al., 2017; Caceres-Mendoza et al., 2023). As the demand for sustainable solutions intensifies, there is a pressing need to transition toward eco-friendly filament production methods. Recycling post-consumer plastic waste, particularly polyethylene terephthalate (PET) from plastic bottles and preforms, emerges as a viable solution, offering a sustainable alternative to conventional materials while addressing environmental challenges (Ragaert et al., 2017; Singh et al., 2017).

PET is one of the most widely used plastics globally, found in everyday products such as beverage bottles, food containers, and polyester fabrics. Its inherent strength, stiffness, and heat resistance make it an ideal candidate for recycling and upcycling into 3D printing filaments (Awaja & Pavel, 2005). However, the extensive usage of PET also contributes to significant volumes of plastic waste, necessitating innovative approaches to mitigate its environmental impact (World Economic Forum et al., 2016). Repurposing PET waste into 3D printing filaments not only reduces plastic pollution but also aligns with the principles of a circular economy by transforming waste into valuable resources (Wohlers Associates, 2022; Mishra et al., 2025).

According to Gibson et al. (2015), the selection and characterization of materials play a crucial role in determining the printability and mechanical performance of 3D-printed components. The effectiveness of recycled PET in 3D printing hinges on its rheological and thermal properties, which are critical for determining printability and performance (Ibrahim et al., 2024). Rheological properties, such as melt viscosity, shear-thinning behavior, and flow characteristics, dictate how the material flows during extrusion, directly impacting print quality and accuracy (Nofar et al., 2019). Marzuki et al. (2022) similarly demonstrated that the rheological flow behaviour of a PLA/HA composite feedstock ($n < 1$, pseudoplastic) directly determined the success of injection-moulded parts and their resulting mechanical and physical properties, highlighting the strong link between flow behaviour and processability. Thermal properties, including glass transition temperature (Tg), melting temperature (Tm), and crystallization temperature (Tc), influence the material's behavior under heat and are essential for optimizing printing parameters and ensuring layer adhesion (Celik et al., 2022). Previous studies have demonstrated that recycled PET exhibits shear-thinning behavior, where viscosity decreases with increasing shear rates, a phenomenon desirable for 3D printing as it facilitates smoother flow and finer detail in printed objects (Cusano et al., 2023; Joseph et al., 2024). However, the variability in recycled PET's properties, influenced by factors such as degradation during recycling, contamination, and molecular weight distribution, poses significant challenges to its consistent performance in additive manufacturing (Cruz Sanchez et al., 2017).

This study prioritizes melt rheology and phase transitions over thermal conductivity/expansion for three key reasons: (1) PET's low thermal conductivity (~0.20 W/m·K) shows minimal recycling-induced variation (Celik et al., 2022); (2) its moderate thermal expansion primarily affects warping, a secondary concern compared to viscosity control; and (3) *Tg*/*Tm*/*Tc* parameters provide the most direct insight into processing challenges like thermal degradation and crystallization kinetics (Joseph et al., 2024). This focused approach aligns with established methodologies for polymer feedstock characterization (Nofar et al., 2019).

Recent research has made significant strides in understanding the rheological and thermal properties of recycled PET. For instance, Cusano et al. (2023) investigated the shear-thinning behavior of recycled PET, demonstrating that viscosity decreases exponentially with increasing shear rates, consistent with the power-law model (Oussai et al., 2021). Similarly, Nofar et al. (2019) used differential scanning calorimetry (DSC)

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to characterize the thermal transitions of recycled PET, identifying key parameters such as *Tg*, *Tm*, and *Tc*, which are crucial for optimizing 3D printing conditions. However, these studies often treat recycled PET as a homogeneous material, overlooking the potential variations between different sources, such as bottles and preforms. For example, Joseph et al. (2024) highlighted that PET from bottles and preforms can exhibit different molecular weight distributions and crystallinity levels, leading to variations in rheological and thermal behavior. This underscores the need for a more nuanced understanding of how source-specific properties influence the performance of recycled PET in 3D printing.

Despite these advancements, several gaps remain in the literature. While the shear-thinning behavior of recycled PET has been well-documented (Nisticò, 2020), there is limited research on how processing parameters such as temperature, shear rate, and cooling rate interact to influence viscosity and flow behavior (Cruz Sanchez et al., 2017). In one study using a proprietary additive added to r-PET, the researchers have found that the additive improves the printability of r-PET feedstock (Tabary & Fayazfar, 2025). Additionally, the relationship between thermal properties and printability is underexplored, particularly for different sources of recycled PET. For example, Cruz Sanchez et al. (2017) found that PET preforms exhibit higher viscosity and brittleness compared to PET bottles, suggesting that preforms may require more precise temperature control during printing. Furthermore, the optimal viscosity range for 3D printing (10^2 Pa·s to 10^5 Pa·s) and the influence of molecular weight distribution on melt strength and elasticity require further investigation to ensure consistent printability and material performance (Nofar et al., 2019; Celik et al., 2022).

This study aims to address these gaps by systematically investigating the rheological and thermal properties of recycled PET derived from post-consumer bottles and preforms. Using advanced analytical techniques, including rheometry and DSC, the study examines key parameters such as melt viscosity, shear-thinning behavior, *Tg*, *Tm*, and *Tc*. Additionally, the effects of processing parameters, including temperature, shear rate, and cooling rate, are evaluated to identify optimal printing conditions. By providing critical insights into the material's behavior, this research advances the sustainable utilization of recycled PET in additive manufacturing, offering a pathway for its broader adoption in industrial applications. This study aims to address these gaps by systematically investigating the rheological and thermal properties of recycled PET derived from post-consumer bottles and preforms. Using advanced analytical techniques, including rheometry and DSC, the study examines key parameters such as melt viscosity, shear-thinning behavior, *Tg*, *Tm*, and *Tc*. Additionally, the effects of processing parameters, including temperature, shear rate, and cooling rate, are evaluated to identify optimal printing conditions. By providing critical insights into the material's behavior, this research advances the sustainable utilization of recycled PET in additive manufacturing, offering a pathway for its broader adoption in industrial applications.

METHODOLOGY

This study investigates the potential of two commonly used waste materials, Polyethylene Terephthalate (PET) bottles and PET preforms, for 3D printing applications. Both materials, supplied by Reservoir Industries Sdn. Bhd., a company based in Cheras, Malaysia, were evaluated for their rheological and thermal properties to determine their suitability as feedstock for 3D printing filaments.

Sample preparation for rheological and filament testing

The preparation of PET bottles and preform samples involved a series of steps to ensure consistency and eliminate impurities. For PET bottles, the process began with thorough cleaning to remove contaminants such as labels, adhesives, and residual liquids. The cleaned bottles were then cut into smaller flakes, followed by further size reduction using grinding or milling techniques to achieve uniform particle sizes. The resulting PET bottle flakes, shown in Fig 1, were stored in a dry, clean container to prevent moisture absorption and contamination. Similarly, PET preforms (Fig 2) were carefully inspected to ensure

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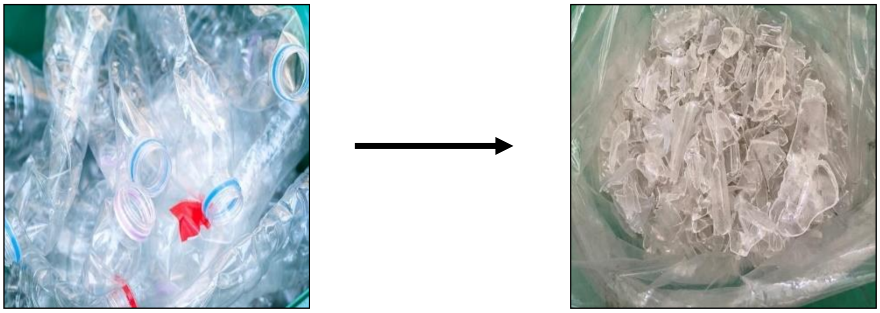
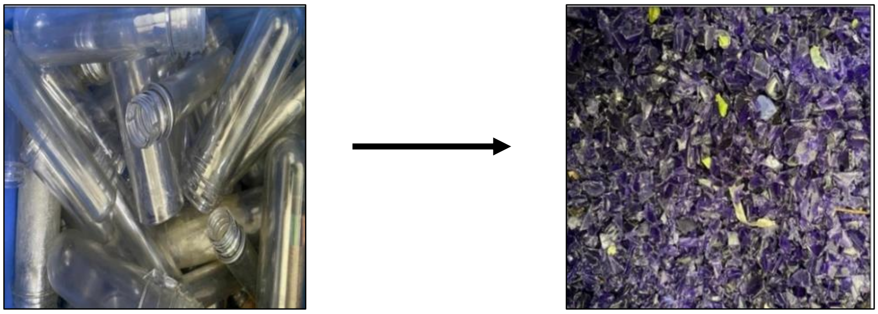
the absence of coatings or labels. The preforms were segmented into smaller pieces to maintain consistency in size and stored under the same conditions as the bottle flakes. This preparation ensured that the samples were free from external impurities, which could otherwise affect the accuracy of rheological and thermal analyses. For pre-filament production, the filaments were produced using a Capillary rheometer machine at temperatures of 250 °C – 260 °C (bottles) and 250 °C – 256 °C (preforms). The filament production process was designed to evaluate the processability of recycled PET under realistic 3D printing conditions and to assess the relationship between bulk material properties and filament performance.



(a) (b)

Fig. 1. (a) Post-consumer PET bottle waste in its original form and (b) after mechanical crushing.



(a) (b)

Fig. 2. (a) Post-consumer PET preform waste in its original form and (b) after mechanical crushing.

Mold and sample preparation for tensile test

To facilitate tensile testing, ASTM D638-compliant molds were prepared using advanced manufacturing processes at Reservoir Industries Sdn. Bhd, as shown in Fig 3. The molds were fabricated using Computer Numerical Control (CNC) machining, a precision technique that ensures dimensional accuracy and consistency. High-quality tooling resin or epoxy composite blocks were used as the base material, and the CNC machine was programmed to carve the mold cavities according to the specified ASTM D638 standard. This process guaranteed precise adherence to the required dimensions, including gauge length and width, ensuring reliable and reproducible tensile test results.

For specimen fabrication, recycled PET flakes from post-consumer bottles and preforms were first dried at 80 °C for 4 hours to eliminate moisture-induced defects. The dried flakes were uniformly loaded into the mold cavities and processed via hot press compression molding. Bottle-derived PET was compressed at 255 °C, while preform-derived PET required a slightly lower temperature of 253 °C, both under 50 MPa pressure. The material was held at these conditions for 5 minutes to achieve complete melting

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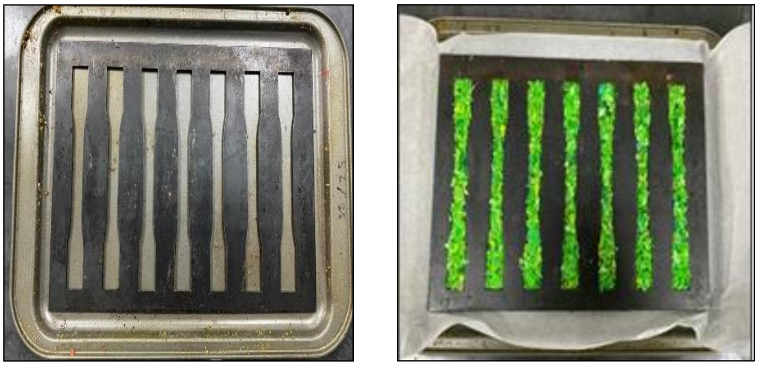
and homogenization, followed by controlled cooling at 20 °C/min to optimize crystallinity and reduce residual stresses. This protocol ensured consistent mechanical properties and reliable tensile test outcomes.



(a) (b)

Fig. 3. (a) Dumbbell-shaped mold for tensile specimens, prepared by Reservoir Industries Sdn. Bhd. and (b) manual lay-up mold filled with recycled PET preform flakes.

Tensile testing

Tensile testing was performed on dumbbell-shaped specimens to establish the baseline mechanical properties of the recycled PET flakes prior to filament extrusion, following standard polymer characterization protocols (Cruz Sanchez et al., 2017). This approach provides three key insights: (i) it reveals the intrinsic strength of the recycled material; (ii) it enables quality comparison between bottle- and preform-derived sources; and (iii) it identifies degradation levels introduced during recycling processes. The data obtained through this method serves as a critical quality control checkpoint before advancing filament fabrication and printing trials.

For sample preparation, the PET bottle and preform wastes were carefully placed into the moulds, with attention to material composition and thickness to ensure representative sampling, as shown in Fig 4. The specimens were measured using calipers to confirm dimensional accuracy, and their surfaces were cleaned with isopropyl alcohol to remove any residual contaminants. The samples were then cured in a vacuum oven to achieve optimal material properties. Five specimens were prepared for each type of PET waste to ensure statistical reliability. Tensile tests were conducted using an Instron 3382 Universal Testing Machine equipped with a 5 kN load cell, following ASTM D638 Type IV specifications. Specimens were tested at a controlled crosshead speed of 5 mm/min (standard rate for brittle polymers) until fracture, with a pre-load of 0.1 N to ensure proper specimen alignment. The system recorded load-displacement data, from which tensile strength (peak stress), elongation at break, and Young's modulus were derived.

Rheological testing

Rheological testing was conducted at three temperatures (250 °C, 255 °C, 260 °C for bottles; 250 °C, 253 °C, 256 °C for preforms) using a Bohlin Instruments RH2000 Capillary Rheometer. These ranges were selected based on the DSC-determined melting point (255 °C) and preliminary tests showing preforms has a greater thermal sensitivity. The temperature variations allow us to: (1) characterize shear-thinning behavior across the actual 3D printing processing window, (2) identify optimal flow conditions while avoiding degradation, and (3) establish temperature-viscosity relationships critical for filament extrusion. The capillary rheometer measurements of viscosity, shear stress and shear rate at these controlled temperatures provide essential data for predicting real-world printability.

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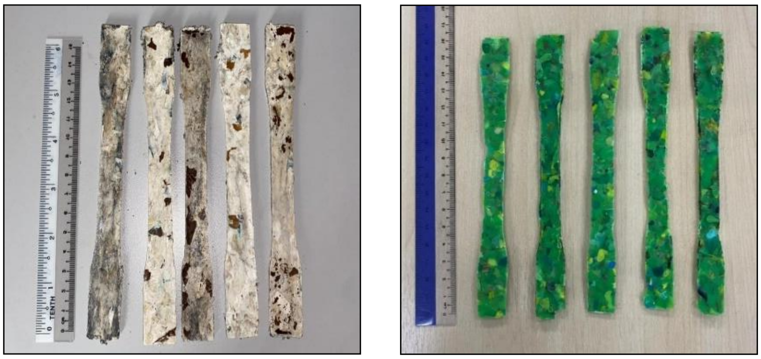

(a) (b)

Fig. 4. (a) Recycled PET bottle specimens and (b) recycled PET preform specimens.

DSC thermal analysis

The thermal properties of the PET samples were analyzed using a Mettler Toledo Differential Scanning Calorimeter (DSC). This instrument measures heat flow into or out of a sample during controlled heating or cooling, enabling the detection of phase transitions such as melting, crystallization, and glass transitions. For this study, approximately 8 mg of each PET specimen was heated from room temperature to 350 °C at a rate of 10 °C/min under a nitrogen gas flow rate of 20 mL/min. The temperature was equilibrated at 30 °C for 1 minute before initiating the heating cycle. The DSC data provided critical thermal parameters, including melting temperature (*Tm*), crystallization temperature (*Tc*), and glass transition temperature (*Tg*), which are essential for optimizing 3D printing conditions and ensuring material stability during processing.

RESULTS AND DISCUSSIONS

Rheological behaviour

The comparative rheological analysis of bottle- and preform-derived PET reveals significant differences in flow behavior that directly reflect their material origins and processing histories. While both materials exhibit characteristic shear-thinning behavior (Fig 5), bottle-derived PET demonstrates substantially higher initial viscosity (40,000 Pa·s at 20 s^{-1} versus 4,000 Pa·s for preforms), attributable to its preserved molecular weight from primary packaging applications where mechanical integrity is paramount (Cusano et al., 2023). The steeper shear-thinning slope observed in preform waste as shown in Fig 5(b) indicates a broader molecular weight distribution, consistent with their production as intermediate products that undergo additional thermal processing during blow molding (Joseph et al., 2024). This molecular heterogeneity explains both the preforms' lower tensile strength (Table 1) and their more pronounced viscosity reduction under shear, as shorter polymer chains in the mixed-weight distribution align more readily during flow (Barnes et al., 1989). Temperature dependence further differentiates the materials: bottle PET maintains stable viscosity across the 250 °C – 260 °C range, while preforms require tighter control (250 °C – 256 °C) due to their greater susceptibility to thermal degradation, which is a consequence of chain scission during initial manufacturing and recycling (Cruz Sanchez et al., 2017).

These rheological differences have direct implications for 3D printing applications. The power-law model ($\eta = K\gamma^{n-1}$) highlights key differences between the materials. Consistent with previous studies (Macosko, 1994; Cusano et al., 2023), bottle-derived PET typically exhibits higher consistency index (K) values and more moderate flow behavior indices (n ≈ 0.4 - 0.6), reflecting its robust molecular network. In contrast, preform PET generally shows stronger pseudoplasticity (n ≈ 0.2 - 0.4), making it more sensitive

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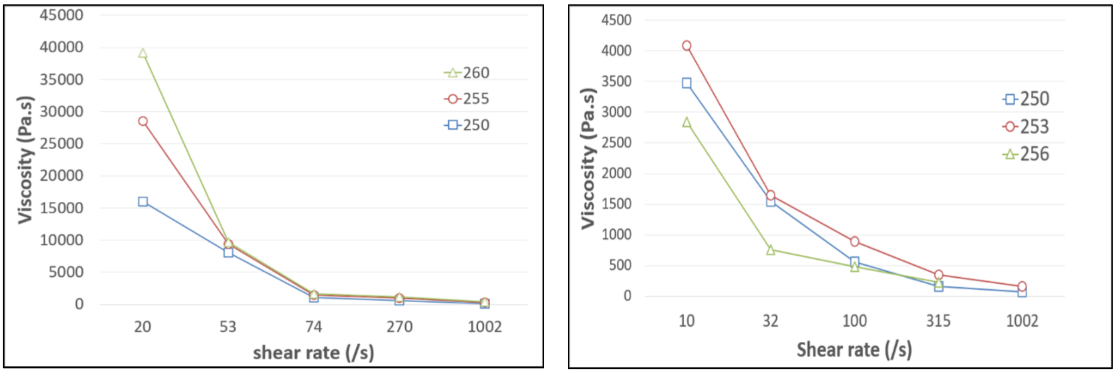
to shear rate changes during extrusion. While this enhanced shear-thinning can improve resolution, it requires tighter temperature control (± 1-2 °C versus ± 5 °C for bottles) to prevent flow instability (Nofar et al., 2019).



(a) (b)

Fig. 5. (a) The shear viscosity curve for PET plastic wastes bottles and (b) the shear viscosity curve for PET plastic wastes preform.

Thermal analysis

The DSC thermograms in Figs 6 and 7 present the comparative thermal profiles of post-consumer PET bottle waste (Specimen A) and PET preform waste (Specimen B). Both materials exhibit the characteristic thermal transitions of semi-crystalline PET: glass transition temperature (*Tg*), cold crystallization temperature (*Tcc*), and melting temperature (*Tm*). However, the values and magnitudes of these transitions differ in ways that are significant for their potential application as feedstock in the production of 3D printing filaments.

The glass transition temperature for Specimen A was recorded at approximately 38.00 °C, with an enthalpy change (*ΔH*) of 10.330 Jg^{-1}. This relatively high ΔH compared to Specimen B, which exhibited a *Tg* of 34.87 °C and *ΔH* of 3.866 Jg^{-1}, suggests a higher amorphous fraction in the bottle-derived PET prior to crystallization. This difference implies that Specimen A may offer improved melt flow characteristics during filament extrusion, a desirable property for achieving consistent diameter control during production. The slightly higher *Tg* of Specimen A also indicates better dimensional stability of the spooled filament at ambient storage temperatures. These findings are in line with the general behaviour of recycled PET as reported by Celik et al. (2022) and Nofar et al. (2019), who noted that variations in *Tg* and associated enthalpy changes are influenced by processing history and the degree of molecular orientation.

A notable distinction between the two specimens lies in the cold crystallization behaviour. Specimen A exhibits a weak cold crystallization peak at approximately 230.00 °C, with a low enthalpy change of 1.919 Jg^{-1}, while Specimen B shows no distinct *Tcc* peak. The presence of a weak *Tcc* in Specimen A indicates limited chain reordering during heating, a feature typically associated with biaxially stretched and heat-set bottle materials. This can be advantageous in fused filament fabrication (FFF) printing, as it reduces the risk of part warpage caused by rapid crystallization during cooling or secondary reheating. In contrast, the absence of a strong *Tcc* in Specimen B suggests that the preform material is already highly crystalline, which limits further crystallization during reheating. Such behaviour is consistent with prior work by Joseph et al. (2024), who highlighted the influence of thermal history on crystallization kinetics in semi-crystalline polymers.

https://doi.org/10.24191/jmeche.v14i1.5783

Both specimens demonstrated melting temperatures within the expected range for PET processing. Specimen A showed a *Tm* of 251.83 °C with a melting enthalpy of 18.437 Jg^{-1}, while Specimen B exhibited a slightly higher *Tm* of 255.37 °C and *ΔH* of 18.003 Jg^{-1}. These values suggest that both materials possess comparable crystallinity potential after melting, indicating that they could deliver similar stiffness and thermal stability in printed parts if subjected to equivalent processing conditions. This aligns with the conclusions of Nofar et al. (2019), who reported that PET, whether virgin or recycled tends to retain its processing window when the polymer chain integrity is preserved.

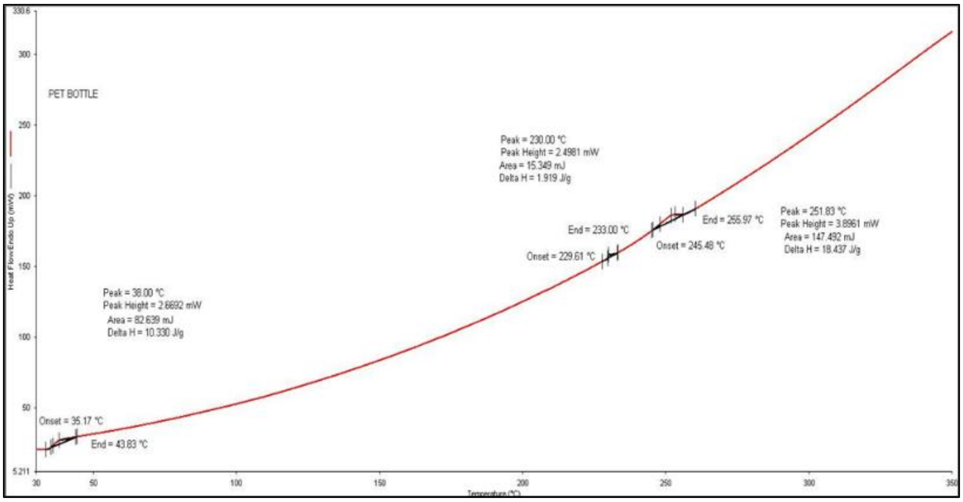


Fig. 6. Specimen A-PET plastic wastes bottles.

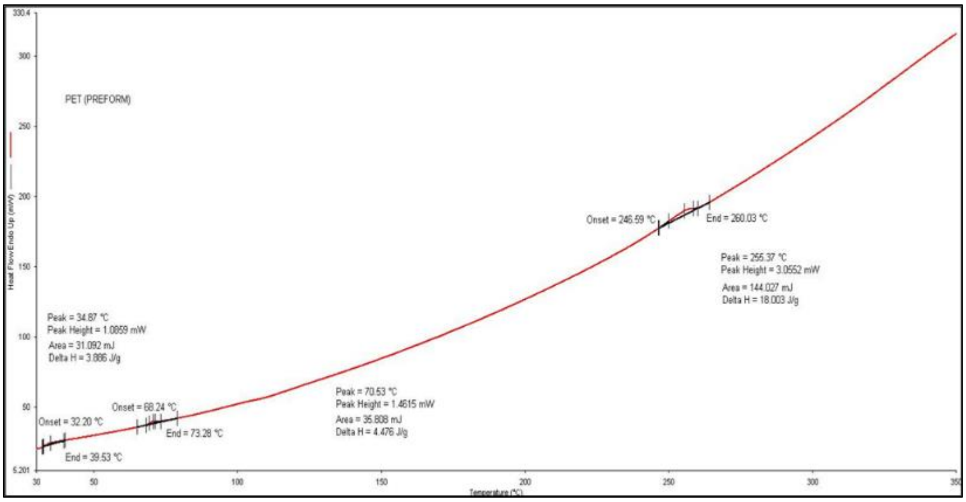


Fig. 7. Specimen B-PET plastic wastes preform.

From a 3D printing perspective, both feedstocks fall within the PET processing range and could be extruded into filament at temperatures between 255 °C and 260 °C. The higher amorphous fraction of Specimen A supports easier melt flow, which facilitates extrusion consistency but may require precise

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cooling management to prevent sagging during overhang printing. Conversely, the higher initial crystallinity of Specimen B can provide excellent dimensional stability and sharper feature definition in printed parts, though it may necessitate higher extrusion torque and careful control of cooling rates to avoid brittleness. A blend of the two feedstocks could potentially harness the advantages of both, combining the processability of bottle-derived PET with the dimensional stability of preform PET, while advancing the broader objectives of polymer recycling and circular economy strategies.

The detailed DSC parameters for both specimens are summarised in Table 1, providing a concise comparison of their thermal transitions and corresponding implications for processing. The practical significance of these findings lies in their direct application to filament production and fused filament fabrication, where control over thermal properties directly influences extrusion behaviour, print quality, and the mechanical performance of final parts. This is particularly relevant in the context of recycled PET, where variability in feedstock properties can challenge process consistency but also offer opportunities for property tailoring through blending and controlled thermal conditioning.

Table 1. DSC thermal properties of PET waste specimens

Parameter	Specimen A (Bottle)	Specimen B (Preform)	Processing implication
Tg (°C)	38.00	34.87	Higher Tg in A suggests improved spool stability at ambient.
ΔH (Tg) (Jg^{-1})	10.330	3.866	Higher amorphous fraction in A favours melt flow; requires cooling control.
Tcc (°C)	230.00	-	Weak Tcc in A reduces warpage risk during printing.
ΔH (Tcc) (Jg^{-1})	1.919	-	Limited chain reordering in A ensures predictable extrusion.
Tm (°C)	251.83	255.37	Both within PET filament printing range.
ΔH (Tm) (Jg^{-1})	18.437	18.003	Similar crystallinity potential after melting.

Tensile properties

Fig 8 and Fig 9 reveal significant differences in the mechanical performance of recycled PET specimens sourced from bottles and preforms, underscoring the impact of waste origin on material properties. In Table 2, the recycled PET bottle exhibited a substantially higher ultimate tensile strength (UTS: 8.996 MPa) compared to the preform (UTS: 0.829 MPa), indicating that bottle-derived PET retains greater structural integrity, likely due to its initial manufacturing for higher stress applications (Joseph et al., 2024). Conversely, the preform's lower UTS and Young's modulus (1.45 GPa vs. 3.58 GPa for bottles) suggest molecular degradation or contamination during recycling, as observed in reprocessed PET with reduced chain lengths (Nisticò, 2020). Despite these differences, both materials exhibited similar yield strain values (~3%), implying comparable initial deformation behavior, a phenomenon attributed to PET's amorphous regions exhibiting uniform chain mobility thresholds under stress (Awaja & Pavel, 2005).

The fracture patterns observed in both materials exhibit limited plastic deformation, though they display subtle differences in brittleness. Bottle PET shows marginally greater elongation before failure, a trait inherited from its original molecular orientation during blow molding. Preform specimens fracture more abruptly, with crack propagation likely initiated by localized stress concentrations from crystalline heterogeneities (Celik et al., 2022). While recycled PET generally behaves as a brittle material compared to ductile polymers like polyethylene, its failure mechanism is more accurately described as semi-brittle, exhibiting minimal but measurable strain before fracture (Nikam et al., 2024). This distinction is critical for 3D printing applications, where bottle-derived PET's retained toughness better accommodates layer adhesion stresses, while preform material requires blending or additives to mitigate its extreme brittleness (Atakok et al., 2022).

These findings underscore the importance of waste segregation in recycling. The consistent mechanical properties of bottle PET, confirmed through reproducible testing, make it a more reliable feedstock for

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structural prints. Preform material, while mechanically inferior, may still serve in non-load-bearing applications if processed with tighter thermal controls to minimize further degradation (Cruz Sanchez et al., 2017). The results highlight how a material's initial manufacturing purpose continues to influence its performance through multiple lifecycles, a crucial consideration for circular economy strategies in additive manufacturing.

Table 2. Tensile test for both recycled PET plastic

Type of specimen	Ultimate tensile strength (MPa)	Yield strength (MPa)	Young modulus (GPa)	Yield strain (%)
Recycled PET (bottle)	8.996	1.164	3.5829	3.49
Recycled PET (preform)	0.829	1.4468	1.4468	3.167

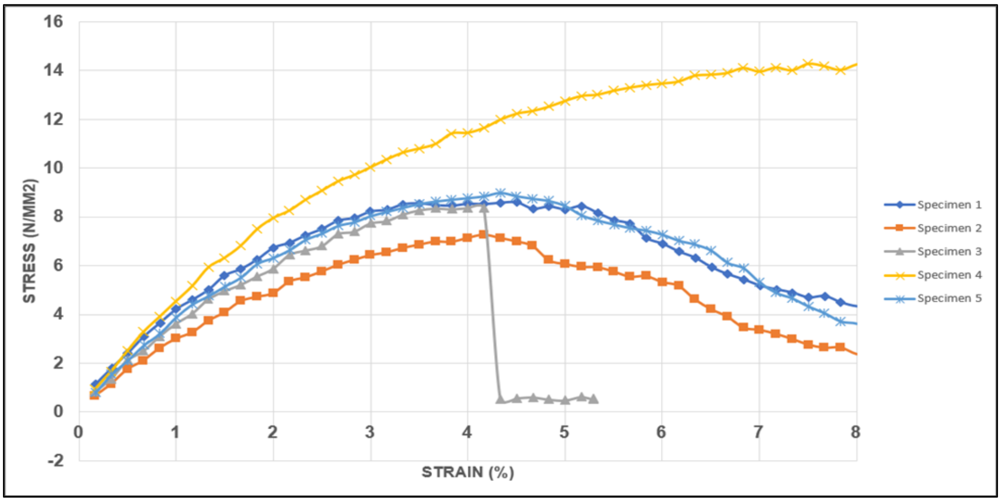

Fig. 8. Stress strain curve PET wastes bottles.

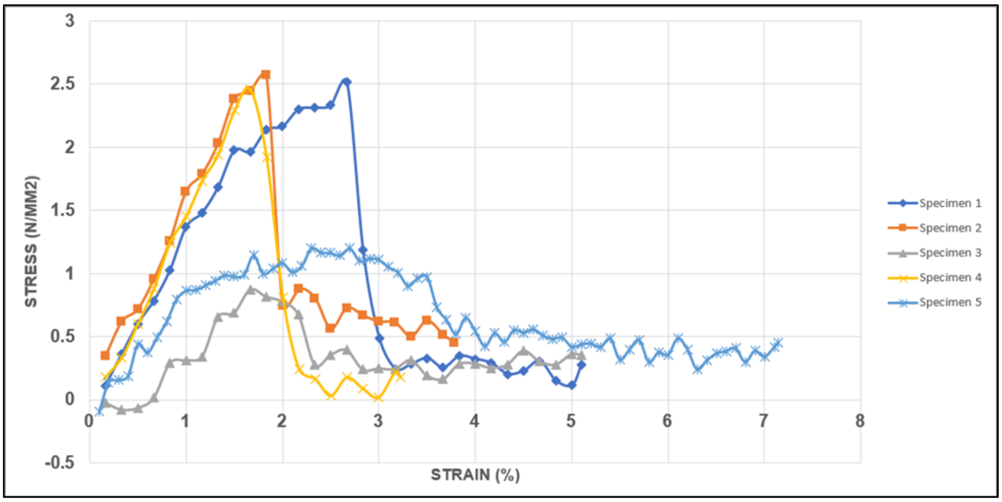

Fig. 9. Stress strain curve PET wastes preform.

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Pre-filament production

The pre-filament production process for recycled PET waste, derived from plastic bottles and preforms, reveals critical insights into the influence of temperature on material behavior and filament quality, which can be directly linked to the rheological, thermal, and tensile properties discussed earlier. For PET bottle waste, Fig 10, the pre-filaments produced at 260 °C exhibited the longest length, while those at 250 °C were the shortest, consistent with the shear-thinning behavior observed in rheological tests, where higher temperatures reduced viscosity and improved flowability (Cusano et al., 2023). This aligns with the DSC results, which showed a melting temperature (Tm) of around 255 °C, indicating that temperatures near or above this point enhance chain mobility and facilitate smoother extrusion (Celik et al., 2022). Conversely, for PET preform waste, shown in Fig 11, the longest pre-filaments were achieved at 253 °C, with shorter lengths observed at 256 °C, suggesting that preform waste requires more precise temperature control due to its higher viscosity and brittleness, as evidenced by its lower ultimate tensile strength (UTS) and Young's Modulus in tensile tests (Cruz Sanchez et al., 2017). These observations highlight the interconnectedness of rheological, thermal, and mechanical properties in determining filament quality.

The significant findings from this study emphasize the role of temperature in determining filament quality and mechanical properties, which are influenced by the material's inherent characteristics, as shown in Table 3. Higher temperatures generally reduce viscosity, facilitating smoother extrusion, but excessive heat can lead to material degradation, particularly in PET preform waste, which exhibited lower thermal stability and higher brittleness in tensile tests (Joseph et al., 2024). This behavior is consistent with the DSC results, which showed that preform waste has a slightly different thermal profile compared to bottle waste, likely due to variations in molecular weight distribution or crystallinity (Nofar et al., 2019). The brittle nature of the filaments, consistent across all tested temperatures, further supports the tensile test results, where both materials exhibited low strain percentages and abrupt fracture behavior (Cruz Sanchez et al.,). These findings align with theoretical knowledge of polymer processing, where temperature, viscosity, and mechanical properties are interdependent (Macosko, 1994). When compared to the literature, these results are consistent with studies such as those by Cusano et al. (2023) and Nofar et al. (2019), which reported similar temperature-dependent behavior in recycled PET. However, the observed brittleness and variations in filament length suggest that further research is needed to improve the ductility and consistency of recycled PET filaments, potentially through blending with other polymers or incorporating plasticizers (Joseph et al., 2024). These insights provide valuable guidance for optimizing filament production parameters, enabling the sustainable use of recycled PET in 3D printing and advancing eco-friendly manufacturing practices.

Table 3. Temperature setup for rheology test

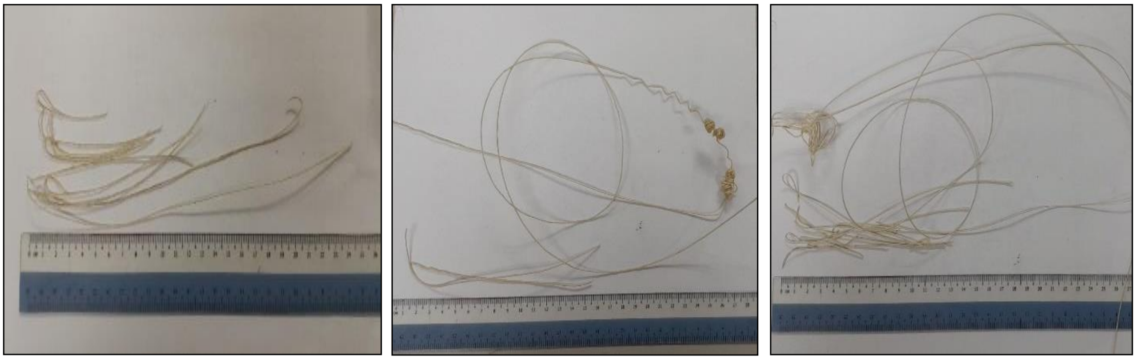
Type of materials	Temperature set (°C)		
PET bottle wastes	250	255	260
PET preform wastes	250	253	256

CONCLUSION

This study investigated the potential of recycled PET derived from post-consumer bottles and preforms as a sustainable feedstock for 3D printing filaments. This work demonstrates that recycled PET from bottles and preforms can be processed into 3D printing filaments when temperature, viscosity, and crystallinity are precisely controlled. Rheological testing revealed pronounced shear-thinning behavior in both PET bottle and preform wastes, with viscosity decreasing from 40,000 Pa·s (bottles) and 4,000 Pa·s (preforms) to below 500 Pa·s as shear rates increased from 20 s^{-1} to 1,000 s^{-1}, aligning with the power-law model. Differential scanning calorimetry (DSC) analysis identified key thermal transitions critical for process

https://doi.org/10.24191/jmeche.v14i1.5783

optimization: a glass transition temperature (*Tg*) at 75 °C, crystallization (*Tc*) at 130 °C, and melting (*Tm*) at 255 °C for both material types. These consistent thermal profiles, particularly the narrow *Tc* –*Tm* window (130 °C – 255 °C), highlight the need for precise temperature control during printing to ensure proper crystallization and layer adhesion.



(a) (b) (c)

Fig. 10. PET bottle wastes (a) 250 °C, (b) 255 °C, and (c) 260 °C.

(a) (b) (c)

Fig. 11. PET preform wastes (a) 250 °C, (b) 253 °C, and (c) 256 °C.

Tensile testing underscored the brittle nature of recycled PET, with PET bottle waste exhibiting higher ultimate tensile strength (8.996 MPa) and Young's modulus (3.583 GPa) compared to preform waste (0.829 MPa and 1.447 GPa, respectively), revealing source-dependent performance variations. Pre-filament production experiments demonstrated optimal processing temperatures at 260 °C for bottle-derived PET and 253 °C for preform-derived PET, balancing flowability with thermal stability. These findings collectively emphasize the importance of tailoring processing conditions to the specific characteristics of recycled PET, ensuring consistent printability and material performance.

While this study provides valuable insights, limitations include potential variability in recycled PET properties due to contamination or degradation during recycling, which may affect material consistency. Future research should investigate polymer blending to improve ductility and conduct long-term stability testing for 3D-printed parts. Nevertheless, this work advances the sustainable use of recycled PET in additive manufacturing, offering practical guidance for industries adopting eco-friendly 3D printing materials.

https://doi.org/10.24191/jmeche.v14i1.5783

ACKNOWLEDGEMENTS/ FUNDING

The authors would like to express their sincere appreciation to Reservoir Industries Sdn. Bhd. for supplying the raw materials (waste PET) and fabricating the moulds used for specimen preparation. Special thanks are also extended to the Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), for funding the publication of this article and the continuous support provided throughout this project. The authors also acknowledge the contributions of the academic and technical staff who were directly or indirectly involved in this work.

CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts.

AUTHORS' CONTRIBUTIONS

Putri Nuha Roslan and Bibi Intan Suraya Murat conceptualized the study, designed the experimental framework, and prepared the draft of the manuscript. Farrahshaida Mohd Salleh and Afeeqa Puteri Marzuki were responsible for data validation, statistical analysis, and critical interpretation of the findings. Izdihar Tharazi contributed to laboratory experimentation, including material preparation and characterization processes. Lau Shing Pui, representing the industry partner, facilitated access to raw materials, technical resources, and specialized equipment necessary for the research. All authors contributed to manuscript revisions, provided critical feedback, and approved the final version for submission.

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