Effect of Recycled Waste Cooking Oil on the Tensile Properties of rPET Filaments for FDM Applications

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Abstract

Recycling polyethylene terephthalate (PET) waste into 3D-printing filament offers a sustainable opportunity to reduce plastic pollution and support circular-economy initiatives. However, recycled PET (rPET) filaments often exhibit brittleness, limited ductility, and poor extrusion behaviour. This study investigates the use of recycled waste cooking oil (rWCO) as a bio-based plasticiser to enhance the mechanical performance and printability of rPET filament for Fused Deposition Modelling (FDM). rPET was blended with 5%, 7.5%, and 10% rWCO by weight and extruded into 1.75 mm filament. Tensile properties were evaluated using ASTM D638 Type IV specimens and compared with a commercial PET-G filament as a control. The results show that the addition of rWCO reduces tensile strength from 14.11 MPa (0% rWCO) to between 10.45 and 11.52 MPa, while improving elongation at break from 21.21% to up to 31.39%. The 7.5% formulation demonstrated the most balanced performance, combining improved ductility with moderate strength retention. These findings demonstrate the feasibility of rWCO as a low-cost, sustainable plasticiser for enhancing rPET filaments, offering promising implications for environmentally conscious additive-manufacturing applications.

Keywords: FDM, Plasticiser, Recycled PET, Recycled Waste Cooking Oil, Tensile Properties

1.0 Introduction

Plastic pollution remains a major global environmental challenge, with single-use polyethylene terephthalate (PET) bottles contributing significantly to land and marine waste. Although recycling initiatives continue to expand, only a limited proportion of collected PET waste is converted into high-value products, with most recycled PET (rPET) being downcycled due to its degraded mechanical performance and reduced molecular weight after repeated processing [1], [2], [3], [4]. These issues often manifest as brittleness, reduced tensile strength, and lower processing stability.

With increasing interest in sustainable manufacturing, rPET has emerged as a promising candidate for additive manufacturing (AM), particularly Fused Deposition Modelling (FDM). FDM provides on-demand production capability, reduced material waste, and lower energy consumption, making it highly compatible with recycled materials [5]. However, despite its advantages, unmodified rPET often exhibits poor ductility and limited printability, performing inferiorly to virgin or commercial filaments such as PET-G [6]. rPET commonly demonstrates lower interfacial adhesion and higher viscosity during extrusion, which can cause surface defects and reduce print quality [7]. Addressing these limitations is therefore crucial for maximising the value of rPET in FDM.

Plasticisers are widely utilised to enhance the flexibility, ductility, and melt flow of polymers. Conventional plasticisers such as dioctyl phthalate (DOP) have been effective but raise environmental and health concerns due to their toxicity and persistence [8]. This has encouraged a shift towards bio-based and biodegradable alternatives. Among these, recycled waste cooking oil (rWCO) has attracted growing attention due to its availability, low cost, and chemical compatibility with polyester-based polymers. The triglyceride structure of waste cooking oil enables favourable interaction with PET ester groups, promoting increased chain mobility and reduced glass transition temperature (Tg), which can enhance melt flow characteristics and flexibility [9], [10], [11], [12].

Despite its potential, few studies have systematically evaluated the effect of rWCO on the mechanical properties and processability of rPET filament for FDM applications. This gap is especially relevant given the increasing interest in upcycling domestic waste streams into value-added engineering materials. This study addresses this research gap by examining the influence of three rWCO concentrations (5%, 7.5%, and 10%) on the tensile properties of rPET filaments. The novelty of this work lies in the utilisation of recycled waste oil as a direct plasticiser for rPET filament production using a low-cost extrusion setup, providing insights into sustainable filament development for prototyping and educational applications.

2.0 Materials and Methods

2.1 Materials

Recycled PET bottles were collected, washed, dried, and mechanically processed into smooth strips as shown in Figure 1. Waste cooking oil was sourced from a common Malaysian vegetable oil brand and filtered at 100 °C using cornstarch flour to remove suspended impurities. rWCO concentrations of 5%, 7.5%, and 10% by weight were prepared for blending with rPET.

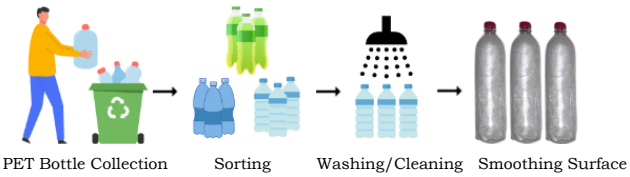

Figure 1: Preparation of the rPET bottle before extrusion

2.2 Filament Extrusion

rPET strips and rWCO were manually mixed at the specified weight ratios before extrusion. The mixture was fed into a portable single-screw filament extruder equipped with temperature-controlled heating zones (Figure 2). An extrusion temperature range of 240–260 °C was selected based on the melting behaviour of PET, which typically melts between 245–260 °C, ensuring adequate polymer flow while preventing thermal degradation. Filament diameter was maintained at approximately 1.75 mm using manual measurement with a vernier calliper (Figure 3).

Figure 2: The extrusion machine

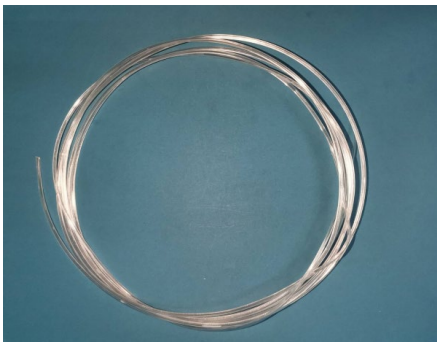

Figure 3: Filament produced from the extrusion process

2.3 3D Printing of Specimens

Filaments were used to print tensile specimens following ASTM D638 Type IV using a Creality K1C FDM printer (Figure 4). Printing parameters included 0.2 mm layer height, 100% infill, and 250 °C nozzle temperature. A total of 12 specimens were produced across four material groups to ensure reproducibility:

- rPET (0% rWCO)
- rPET + 5% rWCO
- rPET + 7.5% rWCO
- rPET + 10% rWCO

Each group was printed in triplicate (n = 3).

Figure 4: Printer Creality K1

Figure 5: Dog-bones printed using rPET

2.4 Tensile Testing

Tensile tests were performed using a Shimadzu Universal Testing Machine at a crosshead speed of 5 mm/min, as shown in Figure 6. The recorded mechanical properties included tensile strength, Young's modulus, and elongation at break.

Figure 6: Tensile strength testing

3.0 Results and Discussion

3.1 Tensile Behaviour of rPET and rPET–rWCO Filaments

0% rWCO (Pure rPET)

Figure 7 shows tensile-tested specimens made from 0% rWCO (pure rPET) filament. Visual inspection indicates clear signs of brittle fracture, as evidenced by the sharp, clean break lines and minimal elongation before failure. The fractured edges lack significant necking or plastic deformation, suggesting limited ductility, a known characteristic of recycled PET without additives.

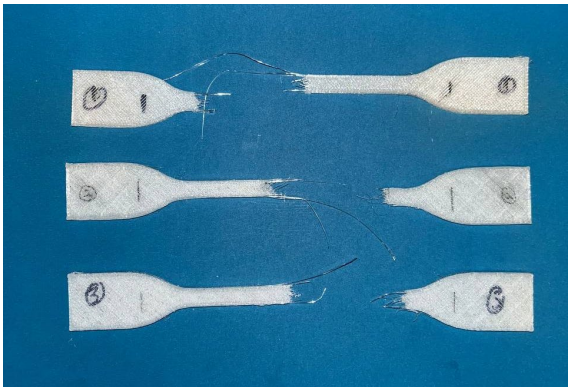

Figure 7: Tensile strength testing of 0% rWCO

5% rWCO

Figure 8 shows the tensile test results for specimens containing 5% rWCO. Compared to the 0% rWCO samples, these specimens display more stretching and fibre pull-out before breaking, indicating improved ductility and better energy absorption. Although specific studies on 5 % rWCO in rPET are lacking, research on 5 % epoxidised waste cooking oil (EWCO) in PLA shows significant increases in flexural extension and impact energy [13]. Moreover, reviews of bio-sourced plasticisers (e.g., epoxidised castor oil) report marked boosts in elongation at break, often beyond 300 % [13]. By analogy, incorporating 5 % rWCO into rPET is expected to enhance ductility and toughness through similar plasticisation mechanisms.

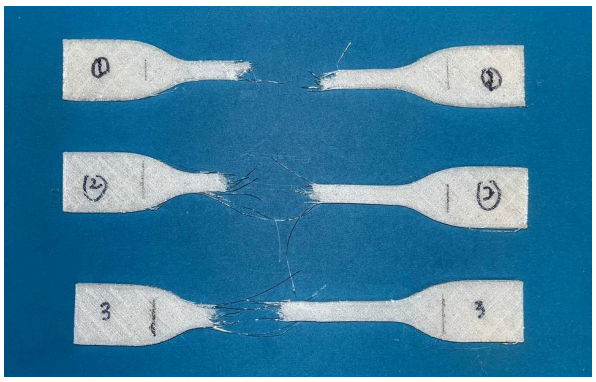

Figure 8: Tensile strength testing of 5% rWCO

7.5% rWCO

Figure 9 shows the tensile test results for specimens with 7.5% rWCO. The samples exhibit noticeable elongation and more ductile fracture characteristics compared to lower rWCO concentrations. This suggests that 7.5% rWCO effectively improves the flexibility and toughness of rPET, leading to better load distribution and energy absorption before failure [14].

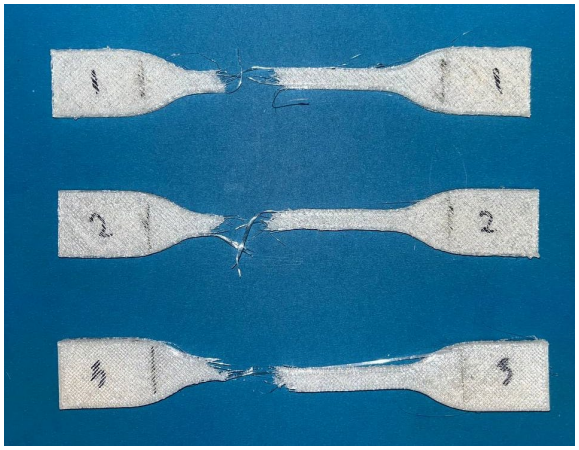

Figure 9: Tensile strength testing of 7.5% rWCO

10% rWCO

Figure 10 displays three samples after a tensile strength test. It is observed that all three samples appear to have failed in the middle, which is the expected gauge section for a standard tensile test. The failure shows fibre pull-out and breakage, indicating that 10% rWCO underwent ductile failure to some extent, or a combination of fibre pull-out and matrix failure. The observed fibre pull-out instead of a clean break implies that the fibre matrix interface is a critical determinant of composite behaviour. Literature shows that fibres tend to debond and pull out in systems with moderate interfacial shear strength, a mechanism that governs load transfer, crack bridging, and energy dissipation during fracture [15]. In finite element models, interfacial shear strength directly determines peak load and displacement in pull-out tests.

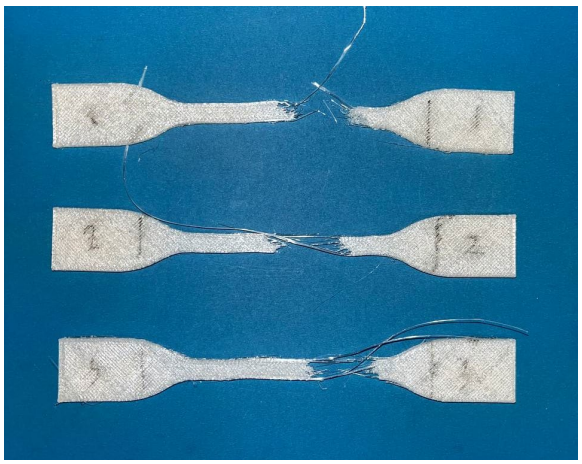

Figure 10: Tensile strength testing of 10% rWCO

3.2 Quantitative Properties Summary

The quantitative properties of the modified rPET samples are summarised in Figure 11. The figure displays the tensile properties of recycled polyethylene terephthalate (rPET) modified with varying concentrations of rWCO, tested using ASTM 638 Type IV specimens. It presents both Ultimate Tensile Strength (UTS) in MPa and strain at break, offering a comparative view of how rWCO affects mechanical behaviour.

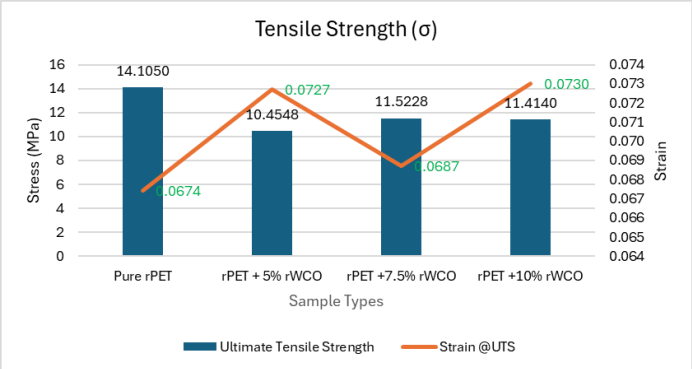

Figure 11: Tensile strength and strain at ultimate tensile strength (σ) graph

Pure rPET exhibited the highest tensile strength at 14.1050 MPa but demonstrated a relatively low strain of 0.0674, indicating a brittle behaviour. When 5% rWCO was incorporated, the tensile strength decreased to 10.4548 MPa, likely due to disrupted polymer chain interactions, while the strain increased to 0.0727, reflecting enhanced ductility. At 7.5% rWCO, the tensile strength slightly increased to 11.5228 MPa, accompanied by a reduction in strain to 0.0687. This trend suggests an improved balance between strength and flexibility as the plasticiser disperses more uniformly.

The 10% rWCO sample shows a tensile strength of 11.4140 MPa and the highest strain of 0.0730, indicating enhanced flexibility but continued strength reduction. The observed behaviour aligns with well-established plasticiser effects, which penetrate polymer chains, increasing free volume and segmental mobility while disrupting intermolecular attractions. This leads to greater elongation and flexibility but typically lowers tensile strength patterns consistently described by mechanisms such as lubricity, gel theory, and free volume theory [16].

Figure 12 illustrates the Young's Modulus (E), which reveals the stiffness of the material samples under tensile loading. Young's modulus, expressed in megapascals (MPa), quantifies the material's resistance to elastic deformation. The pure rPET sample exhibited the highest Young's modulus at 278.28 MPa, indicating superior stiffness and rigidity compared to the modified blends. Upon the addition of 5% rWCO, the modulus significantly decreased to 221.80 MPa, suggesting that the plasticising effect of rWCO reduced the intermolecular forces within the polymer matrix, thereby lowering its stiffness.

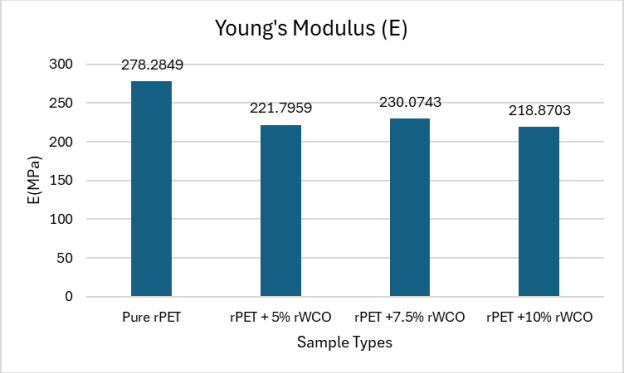

Figure 12: Young's Modulus graph

Interestingly, the sample with 7.5% rWCO showed a slight recovery in modulus to 230.07 MPa, which may be attributed to a more favourable dispersion or interaction of rWCO within the rPET matrix at this concentration. However, further increasing the rWCO content to 10% resulted in a further decline in modulus to 218.87 MPa, reinforcing the trend that excessive plasticiser content compromises the structural integrity of the composite.

Overall, the use of ASTM D638 Type IV specimens ensures that these mechanical property evaluations are reliable and standardised. The observed trend highlights the trade-off between flexibility and stiffness in rPET composites modified with rWCO, which is critical for tailoring materials for specific engineering applications.

Further, Figure 13 shows that the pure rPET sample exhibited an elongation at break of 21.21%, indicating a moderate level of ductility typical of recycled thermoplastics. Upon the incorporation of 5% rWCO, the elongation significantly increased to 30.01%, suggesting that the rWCO acted as a plasticiser, enhancing the polymer chain mobility and thereby improving the material's ability to deform before fracture.

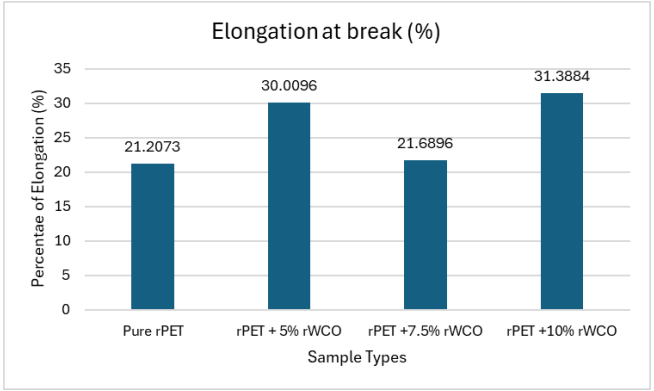

Figure 13: Elongation at break

Interestingly, the sample with 7.5% rWCO showed a reduction in elongation to 21.69%, nearly reverting to the level of pure rPET. This suggests that at this concentration, the plasticising effect may have been offset by phase

separation or incompatibility between rPET and rWCO, leading to reduced ductility. This phenomenon is also noted in other bio-based plasticiser systems where poor miscibility at mid-range concentrations leads to morphological defects [17]. However, at 10% rWCO, the elongation at break increased again to 31.39%, the highest among all samples. This indicates that at higher concentrations, rWCO may have reestablished its plasticising influence, possibly due to better dispersion or saturation of the polymer matrix [18].

The use of ASTM D638 Type IV specimens ensures that these results are obtained under standardised conditions, allowing for accurate comparisons and reproducibility [19]. The remarked trends highlight the complex interplay between rPET and rWCO, where the concentration of the additive critically influences the mechanical performance. The findings from this study are essential for optimising the formulation of rPET-based composites for applications requiring specific ductility and flexibility characteristics.

4.0 Conclusion and Recommendations

This study successfully demonstrated that recycled waste cooking oil (rWCO) can serve as an effective bio-based plasticiser for improving the mechanical performance of recycled PET (rPET) filament for FDM applications. Incorporating rWCO reduced the brittleness of pure rPET and increased elongation at break, confirming enhanced ductility [20]. Among the formulations, the 7.5% rWCO blend exhibited the most balanced properties, offering improved flexibility while retaining moderate tensile strength. The study achieves its stated objectives by establishing the feasibility of rWCO-modified rPET as a sustainable material for 3D-printing applications. Its novelty lies in the direct utilisation of domestic waste streams, PET bottles and used cooking oil into functional engineering filaments. Future work should include optimising the plasticiser concentration through thermal (DSC), rheological (MFI), and microstructural analyses. The incorporation of compatibilisers may also improve interfacial bonding at higher rWCO contents. Long-term performance evaluation under environmental ageing is recommended to determine commercial potential. Overall, rWCO-modified rPET filaments offer a promising pathway for greener and cost-effective FDM materials.

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Author Contributions

Amirul Anniq Mohd Yusof: Conceptualisation, Methodology, Investigation, Formal Analysis, Data Curation; Writing – Original Craft, Writing – Review and Editing; **Rahimah Abdul Hamid**: Conceptualisation, Supervision, Funding Acquisition, Resources, Writing – Review and Editing; **Muhammad Aiqal Syuffri Azman**: Methodology, Investigation, Writing – Review and Editing; **Noraiham Mohamad**: Methodology, Writing – Review and Editing; **Jeefferie Abd Razak**: Formal Analysis, Writing – Review and Editing; **Sayed Kushairi Sayed Nordin** and **Khairul Fadzli Samat**: Validation, Writing – Review and Editing; **Teruaki Ito**: Resources, Writing – Review and Editing.

Conflicts of Interest

The authors declare no conflict of interest.

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