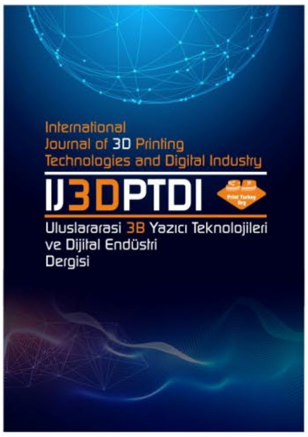

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INVESTIGATING PRINTABILITY AND MECHANICAL PERFORMANCE OF 3D PRINTED RECYCLED PET WITH PLA AND TPU HYBRID ADDITIVES

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ABSTRACT

This paper investigates the printability and mechanical performance of 3D printed recycled PET (rPET) filaments with the incorporation of PLA and TPU blend additives. The study focuses on evaluating the tensile, flexural, and impact properties of the resulting hybrid blends. Tensile testing revealed that the neat rPET specimens exhibited average maximum tensile strength of 51.4 MPa and a tensile elasticity modulus of 3.63 GPa. The addition of PLA and TPU additives slightly reduced the tensile strength and modulus. Regarding flexural properties, the rPET specimens demonstrated an average maximum flexural stress of 43.4 MPa, indicating their ability to withstand bending forces without significant deformation. The addition of the hybrid PLA and TPU additives led to a slight reduction in flexural performance. However, the specimens still exhibited acceptable flexural strength and modulus. Furthermore, the impact test results showed a significant improvement in impact strength for the hybrid blend, with the TPU/PLA (rPET blend) exhibiting a remarkable increase (%187 and 36%) compared to the commercial and neat rPET specimens, respectively. These findings suggest that the hybrid combination of PLA and TPU additives contributes to the microstructural integrity and printability of 3D printed objects made from recycled PET filaments, thereby contributing to the advancement of sustainable manufacturing practices.

Keywords: Additive Manufacturing, Recycled PET, PLA/TPU Blend, FFF, Mechanical Properties.

1. INTRODUCTION

3D printing, also known as additive manufacturing, has revolutionized the manufacturing industry by enabling the production of complex and customized objects with ease. However, the extensive use of conventional plastic materials in 3D printing has raised concerns about environmental sustainability and the accumulation of plastic waste. In response to these concerns, the utilization of recycled PET (polyethylene terephthalate) bottles as a feedstock for 3D printing has emerged as an innovative and eco-friendly solution. Recycled PET (polyethylene terephthalate) bottles are a readily available and abundant source of plastic waste. By collecting and processing these bottles, they can be transformed into high-quality filament, which serves as the raw material for 3D printers. This approach reduces the reliance on virgin plastic materials and helps divert plastic waste from landfills and water bodies, contributing to a more circular and sustainable economy. The utilization of recycled PET bottles in 3D printing offers several advantages. Firstly, it reduces the carbon footprint associated with traditional plastic production by avoiding the energy-intensive process of producing virgin plastic materials [1]. Secondly, it promotes the concept of upcycling, as the discarded PET bottles are transformed into valuable and functional objects through the 3D printing process. This approach aligns with the principles of the circular economy, where resources are kept in use for as long as possible. Furthermore, 3D printing with recycled PET bottles provides designers and manufacturers with a versatile and cost-effective solution for producing a wide range of objects. The utilization of recycled PET filaments derived from plastic bottles in 3D printing represents a significant step in terms of environmental sustainability [2-3]. These filaments contribute to the reuse of plastic waste and offer numerous opportunities in various industries, including prototyping, product design, and manufacturing applications. For instance, investigations demonstrate the feasibility of utilizing 3D printing technology and recycled PET material for the cost-effective fabrication of sensors [4].

Studies have been conducted to evaluate the mechanical properties of 3D-printed parts made from recycled PET bottles. Researchers have examined parameters such as tensile strength, flexural strength, impact resistance, and elongation at break to assess the material's overall mechanical behavior. These investigations have provided valuable insights into the strengths and limitations of recycled PET as a material for 3D printing.

The mechanical properties of recycled PET filaments can vary depending on factors such as printing parameters, filament chemical composition, the quality of the recycled material, and processing methods [5]. Consequently, the mechanical performance of these filaments may exhibit differences compared to the original PET material.

PLA, a widely recognized biodegradable polymer, can be combined with TPU to create a material that exhibits exceptional shape memory properties (SMP) and improved viscosity characteristics [6]. As such, numerous scientists and scholars are focusing their efforts on the advancement of the PLA/TPU blend, which holds great potential for utilization in the field of 3D printing. As such, numerous scientists and scholars are focusing their efforts on the advancement of the PLA/TPU blend, which holds great potential for utilization in the field of 3D printing [7-8].

Research studies have investigated the impact of TPU and PLA additives on the mechanical properties of 3D-printed parts using the recycled PET filament. The incorporation of TPU improves flexibility, elasticity, and impact resistance, making it suitable for applications that require durability and resilience. On the other hand, PLA additives enhance stiffness, dimensional stability, and heat resistance, expanding the potential uses of 3D-printed parts.

In this paper, we aim to provide a comprehensive overview of the mechanical properties of 3D-printed parts from recycled PET bottles with TPU and PLA additives. It will examine the mechanical properties, printability, and environmental implications of using recycled PET filaments in 3D printing applications. Additionally, we will show potential applications with the goal of advancing sustainable manufacturing practices and expanding the utilization of recycled materials in 3D printing technologies.

2. MATERIAL AND METHOD

2.1. Preparation

Firstly, waste PET bottles were collected for the purpose of recycling. Following the collection of waste PET bottles, a cleaning process was conducted. This process involved removing the PET bottle packaging, adhesive labels, and caps to decontaminate them from foreign substances. Subsequently, the PET bottles were washed with water and acetone to eliminate any remaining label adhesive (Figure 1).

Figure 1. Preparation of waste PET bottles; (a) cleaned PET bottles, (b) collected waste PET bottles and (c) washed bottles.

The cleaned PET bottles were then placed in an oven above the glass transition temperature (approximately 140°C) for 4-5 hours. This allowed the residual water from the washing process to evaporate, additionally increasing the brittleness of the PET and facilitating its shredding. The dried PET bottles were shredded using a blade mill (Figure 2) for the extrusion process. Following this step, the PET surface was dried below the glass transition temperature to remove any remaining moisture. After this process, the PET bottles were prepared to an average particle size of 4 mm for the extrusion process.

Figure 2. Blade mill shredder.

2.2. Twin Screw Extrusion

In the process, waste PET bottle particles were colorized and homogenized using a twin-screw extrusion system with an L/D ratio of 40:1. The extrusion temperature was set at 240 °C for the feed zone and 270 °C for the metering zone. The main motor speed was adjusted to 40 rpm, and under these parameters, a torque value of 28 N/m was observed during production. The polymer output from the twin-screw extruder was passed through a cooling section and directed to a granulator device, resulting in granules with an average size of 2 mm.

Subsequently, the shredded recycled PET (rPET) granules were combined with TPU and PLA polymers at a ratio of 10% each to create a polymer blend (80% rPET, 10% TPU, 10% PLA). The obtained polymer blend was further processed using a twin-screw extruder and shredded to ensure a homogeneous mixture. To minimize the moisture content within the shredded blend, a drying process was carried out in an oven at 100 °C.

2.3. Filament Production Utilizing Single-Screw Extrusion

The prepared granules were transformed into filaments with a diameter of 1.75 mm using a single-screw extrusion device. The rPET filament's interior structure is uniform, and its outward structure lacks any signs of deformation, as shown in the image below (Figure 3). The filament extrusion process, the preheating temperatures of the extruder, and the output nozzle, as well as the extrusion speed, significantly affect the quality and diameter of the filament. In particular, the temperature influences the surface quality, porosity, and structure of the filament [9]. In this context, the preheating and output temperatures of the single-screw extrusion device were optimized to be 255 ºC and 265 ºC, respectively, while the extrusion speed was set between 80-100 rpm, maintaining a head pressure of 2 bar.

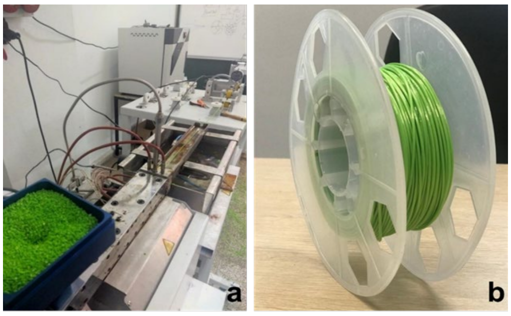

Figure 3. Filament production process; (a) single-screw extrusion, and (b) the resulting filament.

2.4. Mechanical Tests

In this study, tensile, flexural, and impact tests were conducted to determine the mechanical properties of filaments produced from the neat rPET and a blend of 10% TPU, 10% PLA, and 80% recycled PET (rPET blend). The tensile, flexural, and impact specimens were designed using the CAD program SolidWorks, according to the ISO 527 1A, ISO 178, and ISO 179 standards, respectively. Subsequently, the designs were converted to the STL (Standard Triangle Language) format for transfer to the slicer program. Printing parameters, such as printing temperature, bed temperature, printing speed, etc., were adjusted using the slicer program Cura (Table 1). The infill direction parameter in 3D printing has been chosen as 0° according to the printer bed in order to be parallel to the tensile direction during the tensile testing. The filaments were then printed using a Creality brand CR6SE model FFF-type printer. Three prints were on each specimen type for tensile, bending, and impact tests (Figure 4).

Table 1. Printing parameters of filaments

Parameter	Unit	Value
Nozzle Temperature	°C	255
Bed Temperature	°C	80
Layer Thickness	mm	0.1

Printing Speed	mm/s	30
Infill Ratio	%	100
Infill Pattern	-	Lines [0°]

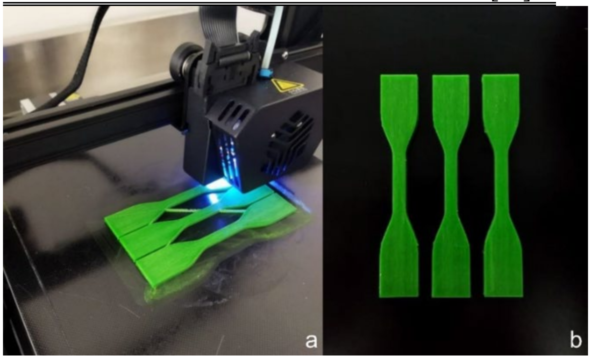

Figure 4. Preparation of tensile test specimens; (a) during printing, and (b) printed specimens.

Tensile tests, in accordance with ISO 527 standards, were performed on the MTS Model 45 Universal Testing Machine at a speed of 5 mm/min for the tensile specimens. Flexural specimens were tested on the same device at a crosshead speed of 10 mm/min, following the ISO 179 standard for flexural properties. The impact strength of the specimens was evaluated using an Instron Charpy impact testing machine with a 50 J capacity (Figure 5c).

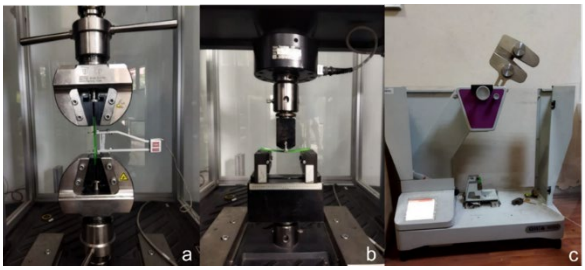

Figure 5. Mechanical tests; (a) tensile test, (b) 3-point bending, and (c) impact test.

3. RESULTS

3.1. Tensile Test

The stress-strain curves obtained from the tensile tests are illustrated in Figure 6.

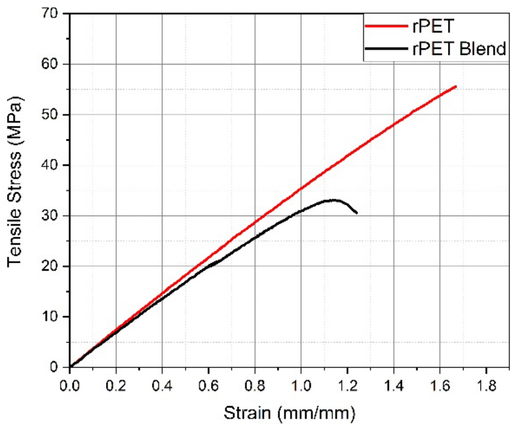

Figure 6. The representative stress-strain curves of tension test.

Upon examination of the results, it was observed that the addition of TPU and PLA additives to the neat recycled PET filament resulted in a reduction in both the tensile strength and elastic modulus of the material.

The rPET specimens exhibited an average maximum tensile strength of 51.4±3.6 MPa, indicating that the recycled PET filaments possess good tensile strength. This suggests their potential suitability for applications requiring structural integrity, where the material needs to withstand significant tensile forces.
In terms of the tensile elasticity modulus, the rPET specimens displayed a value of 3.63±0.85 GPa. This modulus value suggests that the recycled PET filaments possess a reasonable level of stiffness and are capable of resisting deformation under applied tensile stress. This characteristic is crucial for maintaining the shape and structural integrity of printed objects when subjected to tensile loads.

When comparing these results with prior studies, Helen et al. [10] utilized recycled PET bottles to produce tensile specimens using a 3D printer and reported an average maximum tensile stress of 20.35 MPa for their specimens. Van de et al. [5] investigated the mechanical properties of recycled PET filaments at different crystallinity levels and various production parameters. They achieved the highest tensile stress of 46.43 MPa among the specimens printed using different production parameters. In another study by Saidi et al. [11], the effect of adding polybutylene terephthalate (PBT) to recycled PET at different ratios on its mechanical properties was examined. The maximum tensile stress for neat rPET was determined as 60.6 MPa, with a modulus of elasticity of 1.09 GPa. It was noted that the addition of PBT resulted in lower tensile strength compared to neat PET.

3.2. Flexural Testing

The stress-strain curves obtained from the three-point flexural tests are summarized in Figure 7. It is evident that the addition of TPU and PLA additives led to a decrease in the maximum flexural strength and flexural modulus.

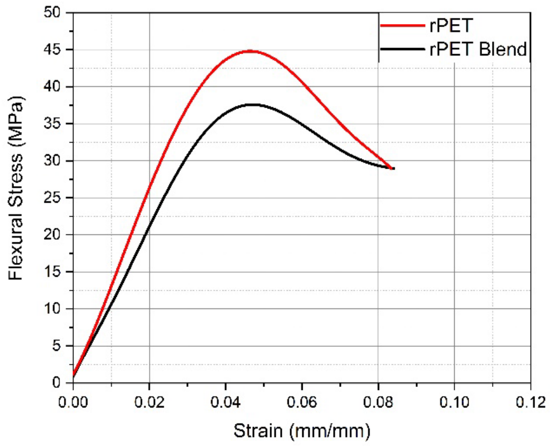

Figure 7. Representative flexural stress strain curves of three-point bending test

The rPET specimens demonstrated an average maximum flexural stress of 43.36±0.65 MPa, indicating their ability to withstand bending forces without significant deformation. The flexural elasticity modulus of the rPET specimens was measured at 1.22±0.12 GPa, reflecting their resistance to bending and ability to maintain shape under applied flexural loads.

Comparing these results with the available literature, specific values for the flexural properties of recycled PET filaments with TPU and PLA additives are not directly provided in the mentioned studies. However, it is worth noting that the flexural properties of polymer composites can vary based on several factors, including the composition of the material, processing parameters, and specimen geometry.

In the context of the present study, the addition of TPU and PLA additives in the rPET blend specimens resulted in a slightly lower average maximum flexural stress of 35.42±0.89 MPa, indicating a reduction in flexural strength compared to the neat rPET specimens. Similarly, the flexural elasticity modulus of the rPET blend specimens was measured at 1.01±0.07 GPa, reflecting a slight decrease compared to the rPET specimens.

Table 2. Summarized mechanical properties obtained from tensile and flexural tests.

	Max. Tensile Strength (MPa)	Elasticity Modulus (GPa)	Max. Flexural Strength (MPa)	Flexural Modulus (GPa)
Commercial rPET[12]	57	2.3	-	-
rPET	54±4	3.6±0.9	43±1	1.2±0.1
rPET Blend	31±2	3.1±0.3	35±1	1.0±0.1

The results obtained from the tensile and flexural tests provide insights into the mechanical properties of the specimens. Comparatively, the rPET blend specimens, which contained 80% recycled PET and 10% each of TPU and PLA additives, exhibited a lower average maximum tensile strength of 30.8±2.23 MPa. This reduction in tensile strength might be attributed to the incorporation of additives, which could affect the overall structural integrity of the material.

However, it is noteworthy that the rPET blend specimens still exhibited reasonable tensile strength values, albeit lower than the rPET specimens but with higher elasticity values than commercial rPET (OnePET, Filamentium). This suggests that the hybrid combination of recycled PET with TPU and PLA additives can still provide a level of strength suitable for certain applications.

Overall, the results indicate that while the incorporation of TPU and PLA additives slightly affected the tensile and flexural properties of the recycled PET filaments, the hybrid combination, which still demonstrated acceptable mechanical performance. These findings suggest the potential of using recycled PET filaments with TPU and PLA additives in 3D printing applications where lower strength requirements are needed.

3.3. Impact Test

The impact test results according to ISO 179 standards are presented in Table 3, showcasing the impact strength of the specimens. A notable observation from the table is the significant increase in impact strength exhibited by the TPU/PLA mixture samples (rPET blend) compared to both the commercial rPET and the neat rPET specimens.

Table 3. Charpy impact test results

Specimens	Re (kJ/m^2)	Standard Deviation
Commerical rPET	3.9	-
rPET	8.2	1.6
rPET Blend	11.2	1.1

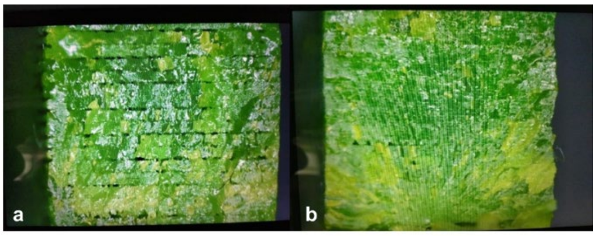

Figure 8. Fracture surfaces of (a) neat rPET and (b) rPET blend impact test specimens

The rPET blend specimens demonstrated an impact strength of 11.2 kJ/m^2, which is significantly higher than that of the commercial rPET (3.9 kJ/m^2) and the neat rPET (8.2 kJ/m^2). This result indicates a remarkable increase of 187% and 36% in impact strength for the PLA/TPU mixture samples compared to the commercial rPET and neat rPET specimens, respectively. Moreover, the optical images provided in Figure 8 illustrate the fracture surfaces of the impact specimens. These images likely depict the microstructural integrity of the materials and can potentially offer visual evidence supporting the higher impact results achieved by the rPET blend specimens (Figure 8).

4. CONCLUSION

In conclusion, this study investigated the printability and mechanical performance of 3D-printed recycled PET filaments with PLA and TPU hybrid additives. The findings indicate that the addition of PLA and TPU additives influenced the mechanical properties of the resulting hybrid materials. While there was a slight reduction in tensile and flexural properties compared to the neat rPET specimens, the rPET specimens still exhibited good mechanical performance, suggesting their potential suitability for applications requiring structural integrity. The incorporation of PLA and TPU additives contributed to the microstructural integrity of the specimens, resulting in improved impact resistance with a significant 36% increase in impact strength compared to the neat rPET specimens. These results highlight the potential of utilizing a PLA and TPU hybrid combination to enhance the mechanical properties of 3D printed objects made from recycled PET filaments. By leveraging these hybrid additives, it is possible to improve the overall performance of recycled PET filaments while promoting sustainability in manufacturing processes. Future research could explore further optimization of the hybrid composition and investigate the influence of printing parameters on the printability and mechanical properties of the hybrid materials.

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