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Development and Preliminary Analysis of 3D Printing Filament from Post-consumer Polypropylene

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ABSTRACT

In the past few years, many researchers have focused on using recycled or post-consumer materials in three-dimensional (3D) printing, which leads to better plastic waste management and sustainable practices. This study focuses on the fabrication of post-consumer polypropylene (rPP) filaments for use in the most common 3D printing method, fused filament fabrication (FFF). The rPP filaments were prepared by blending injection-grade rPP (i-rPP) and extrusion-grade rPP (e-rPP) at various ratios. The effect of different rPP grade ratios on filament diameter consistency, filament ovality, and melt flow index (MFI) was measured. The various ratios of i-rPP to e-rPP, such as 100:0, 40:60, 50:50, 60:40, and 0:100, were prepared. The 50:50 ratio was found as the starting point for achieving a consistent filament diameter. The MFI results showed that the MFI decreases when more e-rPP is incorporated in the blend. The tensile properties of 3D printed 50:50 rPP blend are also measured and compared with commercial PP. Overall, this research exhibits the potential of upcycling PP waste materials into functional filaments for sustainable 3D printing applications.

Keywords: *Post-consumer PP, Fused Filament Fabrication, 3D Filament, Melt Flow Index, Tensile Properties*

1. INTRODUCTION

Recently, fused filament fabrication (FFF) has become one of the most common methods in three-dimensional (3D) printing technology among hobbyists, educators, and researchers. It has also gained significant attention due to its advantages in being user-friendly, compatible with a wide range of thermoplastic materials, consistent, precise, and cost-efficient [1]. Moreover, this method is simpler compared to formative manufacturing (such as injection moulding) and subtractive manufacturing methods (such as computer numerical control (CNC) machining and milling), as FFF products can be designed in complex shapes using 3D computer-aided design (CAD) software and then directly printed [2]. Besides, complex scientific data can be represented clearly through 3D printing, making it easier to understand and visualize [3].

Today, plastic products are widely used in many applications, especially plastic packaging; however, not everyone participates in recycling practices. According to Alsabri et al. (2021), approximately 16% of plastic products are made from polypropylene (PP), a common thermoplastic material used in consumer goods such as packaging [4]. Therefore, the demand for PP is increasing annually, resulting in plastic waste, which has raised serious environmental concerns. However, as reported by the Gulf Petrochemicals and Chemicals Association (GPCA), the global recycling rate for PP is about 1%. As a result, a large amount of PP waste ends up in landfills and further contributes to plastic pollution [4]. Although recycling plastics is not a perfect solution, the challenge of managing plastic waste has led to increasing efforts in this area.

The low recycling rate of post-consumer PP (rPP) is mainly due to its material properties (such as complex molecular structure, inconsistent melt flow, and contamination issues), limited recycling infrastructure, and lack of public awareness and participation in recycling programs [4]. However, 3D printing offers a promising solution by upcycling rPP into higher-value products and encouraging more recycling efforts. Upcycling through 3D printing also reduces the need for virgin plastic, decreases plastic waste, promotes sustainability, conserves resources, and helps reduce environmental impacts.

Nevertheless, the use of PP in the FFF method remains limited due to processing challenges [5]. Neat PP often requires blending with other polymers or fillers to improve its mechanical properties. Volumetric shrinkage and rheological behavior are the two major challenges, as PP exhibits significant shrinkage during cooling, which leads to warping and dimensional inaccuracies, while its rheological properties make it difficult to achieve optimal printing parameters. In addition, PP shows very low adhesion to other materials, resulting in weak interlayer bonding. These factors restrict the use of PP in 3D printing applications and highlight the need for special modifications and processing techniques to overcome these challenges [6].

Generally, PP is available in two main grades, such as injection-grade and extrusion-grade [7]. The chemical structure of both grades of PP is random copolymer PP, with melting points ranging from 135 to 159°C and densities between 0.904 and 0.908 g/cm^3 [8]. The injection-grade PP is semi-transparent and commonly used for thin-wall applications such as packaging, containers, and medical items. In contrast, extrusion-grade PP exhibits higher clarity, making it suitable for flexible sheets and films that are commonly used in cups, trays, blisters, and flexible packaging films [9]. In terms of mechanical properties, injection-grade PP provides balanced stiffness and flexibility with moderate to high impact resistance and tensile strength of about 25–32 MPa. Conversely, extrusion-grade PP is designed for higher flexibility and impact resistance, though its tensile strength is slightly lower at around 20–30 MPa [10]. Since we aim to recycle and reduce both injection and extrusion-grade PP, it is not feasible to recycle only one grade while leaving the other unused. Furthermore, if post-consumer PP is not sorted by grade, combining both grades directly can lead to variations in material properties across different production batches.

Furthermore, in terms of melt flow index (MFI), injection-grade PP shows a wide range of 1.5 to 100 g/10 min depending on the specific grade, while extrusion-grade PP maintains a lower and more stable MFI of 1.2 to 5 g/10 min [8]. MFI plays an important role in filament extrusion and FFF 3D printing, as it measures how easily a polymer flows when melted under specific conditions. It reflects the material's melted viscosity; however, unsuitable MFI can cause issues such as clogging, warping, or inconsistent filament diameter. For example, a higher MFI indicates lower viscosity and better flowability, while a lower MFI corresponds to a thicker melt [11]. This characteristic directly influences filament quality, print consistency, and extrusion stability, as maintaining an appropriate MFI range ensures smooth production of filaments and high-quality 3D printing [12]. Furthermore, a higher MFI indicates lower viscosity, enabling faster extrusion but risking unstable flow and dimensional inaccuracies. In contrast, low MFI materials require slower speeds to maintain consistent flow and avoid filament breakage or under-extrusion. Proper layer bonding depends on optimal MFI; too low impairs adhesion, while too high may cause sagging. Final print quality is best achieved with a balanced MFI that ensures dense, uniform parts with minimal defects [13]. Therefore, the MFI values of each prepared sample were investigated in this study to evaluate the suitability of the blended rPP for filament production.

In many real-world applications, the post-consumer or post-industrial PP is recycled. Although properties of rPP are not stable, rPP offers potential advantages and obstacles when it comes to achieving desired mechanical qualities [14]. There is no prior literature on combining two different grades of rPP for filament production. Since injection-grade PP generally exhibits a higher MFI, while extrusion-grade PP has a lower and more stable MFI [8]. Therefore, combining injection and extrusion grades with rPP provides a compromise formula with adequate mechanical strength, melt flow for processability, and resilience against the variability typical of rPP streams. Hence, this study focuses on the preparation of 3D printing filaments using post-consumer polypropylene (rPP). Since post-consumer rPP consists of both injection-grade and extrusion-grade materials, this study separates these two grades and investigates how different ratios of injection-grade to extrusion-grade rPP affect the dimensional stability and tensile properties of the 3D-printed filaments.

2. METHODOLOGY

2.1. Overall Research Methodology Flow Chart

Figure 1 shows a flowchart of the preparation process for filaments composed of 100% injection-grade rPP (i-rPP), 100% extrusion-grade rPP (e-rPP), and blends of 60:40, 50:50, and 40:60 of i-rPP to e-rPP. The details of the process are discussed in the subsequent sections.

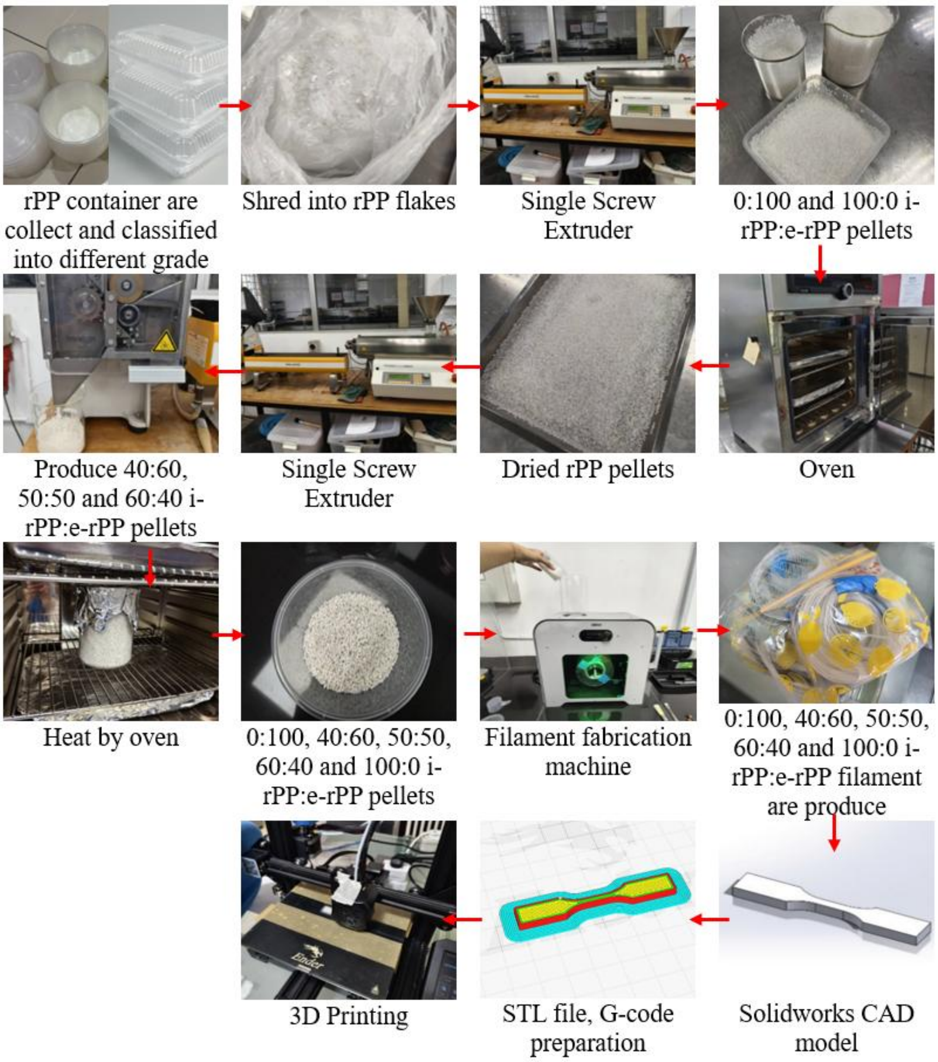

Figure 1. Flowchart of the preparation process for 100% i-rPP, 100% e-rPP, 60:40, 50:50, and 40:60 blends of i-rPP to e-rPP blend filament.

2.2. Materials

Post-consumer PP (rPP) was collected and classified into injected-grade and extruded-grade. After that, the sorted rPP was shredded into flakes by using a plastic crusher. These flakes were subsequently processed through a single screw extruder (TEACH LINE E20T, Collin) to produce rPP pellets.

2.3. Preparation of Filament

The different grades of rPP were mixed in specific ratios and extruded into pellets using a single screw extruder, with the temperature for zone 1 set at 45°C and zones 2-5 set at 170 °C. These rPP pellets were then processed using a *3devo* Composer 350 filament maker to produce 3D printing filaments. The filament extrusion was carried out at a temperature of 175°C for zone 1 and 180°C for zones 2, 3, and 4, with a screw speed of 3.5 rpm. During filament extrusion, the temperature settings were maintained, and the filaments were consistently wound onto a spool with a target diameter of 1.75 mm. The filament diameter was monitored and recorded in real time using DevoVision, a software by *3devo* that enables both live analysis and historical logging of extrusion processes. The different grades of rPP were mixed in specific ratios, which are 100:0, 60:40, 50:50, 40:60, and 0:100.

2.4. Preparation of 3D Printed Specimens

SOLIDWORKS 3D modeling software was used to design the test specimens for tensile testing. All specimen dimensions followed the ASTM D638 Type V standard. The 3D printing parameters were set using Ultimaker Cura slicing software, which generated the corresponding G-code for the printing process. Table 1 shows the detailed printing settings.

Table 1 3D Printing settings

Layer height	0.32mm
Wall thickness	1.6mm
Wall line count	1
Infill density	100%
Infill overlap percentage	30%
Infill layer thickness	0.32mm
Printing temperature	200℃
Build plate temperature	60℃
Material flow	100-130%
Printing speed	50mm/s
Regular fan speed threshold	10s
Support	no
Build Plate Adhesion Type	Brim
Brim width	5mm
Brim line count	7

2.5. Testing and Characterization

2.5.1. Filament Diameter Consistency Inspection

During the extrusion process using the *3devo* Composer 350 filament maker, the filament was continuously monitored and recorded for diameter consistency as it passed through the integrated laser diameter sensor. Real-time measurement and logging were conducted using DevoVision, which enables continuous monitoring and analysis of filament diameter through the extrusion process.

2.5.2. Ovality Inspection

A total of 10 readings were taken along the filament, with each reading spaced at intervals of 10 cm. These values were recorded for subsequent analysis of filament ovality. The nominal diameter was set at 1.75 mm. The ovality was calculated using Equation (1), as shown below:

$$Ovality\ (\%) = \frac{Maximum\ Diameter - Minimum\ Diameter}{Nominal\ Diameter} \quad (1)$$

2.5.3. Melt Flow Index Analysis

Melt flow index (MFI) analysis was carried out by following the ASTM D1238 standard to identify the flowability of the prepared filaments. Prior to testing, the filament specimens were cut into small pieces. The test was conducted at a temperature of 230°C, using a 2 mm die with an applied load of 2.41kg. During the test, the extrudate was automatically cut every 15 seconds. The mass of each extrudate was measured using a digital scale, and the readings were recorded. The results were reported in g/10min.

2.5.4 Tensile Test

The test specimens were designed and printed according to the Type V specimen dimensions in ASTM D638 standard. Tensile tests were carried out using Shimadzu Universal Testing Machines to measure elastic modulus and tensile strength. A 10kN load cell was used with a crosshead speed of 30 mm/min, and all tests were conducted at room temperature.

3. RESULT AND DISCUSSION

3.1. Filament Diameter Consistency Inspection

According to Shukri et al. (2025), the ideal filament diameter range is between 1.65 and 1.85 mm [15]. This range serves as a reference for evaluating the consistency and processability of each rPP material. In this study, the filament diameter of rPP produced with various i-rPP to e-rPP ratios of 100:0; 60:40; 50:50; 40:60, and 0:100 was investigated.

Figure 2 shows the filament diameter values of rPP made with 100% i-rPP. This filament showed the highest variability, with several sharp peaks and drops, indicating lower process stability. However, Figure 3 presents the filament diameter values of rPP with an i-rPP to e-rPP ratio of 60:40, which shows relatively better consistency, although some data point still falls outside the ideal range. Figure 4 presents the filament diameter values of rPP with an i-rPP to e-rPP ratio of 50:50, where most data points remain within or near the ideal range, which shows the most consistent filament diameter compared to 100:0 and 60:40. Figure 5 shows the filament diameter for rPP with a 40:60 injection-to-extrusion ratio, and Figure 6 presents rPP with 100% extrusion-grade, where both fluctuations are low and most values fall within the ideal range, indicating improved stability compared to injection-dominant blends. This can be attributed to the lower MFI of e-rPP, which provides a slower extrusion flow and leads to better filament uniformity.

Overall, a higher content of e-rPP resulted in lower MFI values and improved filament production with a more uniform diameter. Based on filament diameter consistency, the 50:50 blend ratio started to show improved uniformity and was therefore selected for 3D printing the tensile testing specimens. In detail, the average filament diameter with skewness of each prepared filament is presented in Figure 7. The results show that the 0:100, 60:40, and 100:0 ratios showed negative skewness, meaning the distributions were left-skewed, with most filament diameters staying at higher values. Nevertheless, the 40:60 and 50:50 ratios exhibited positive skewness, indicating right-skewed distributions, where most of the filament diameters were thinner, with some thicker outliers. Based on the results in Figure 7, while extrusion-grade PP improves flow stability and helps maintain the filament within the ideal range, it reflects a trade-off between filament consistency and dimensional uniformity.

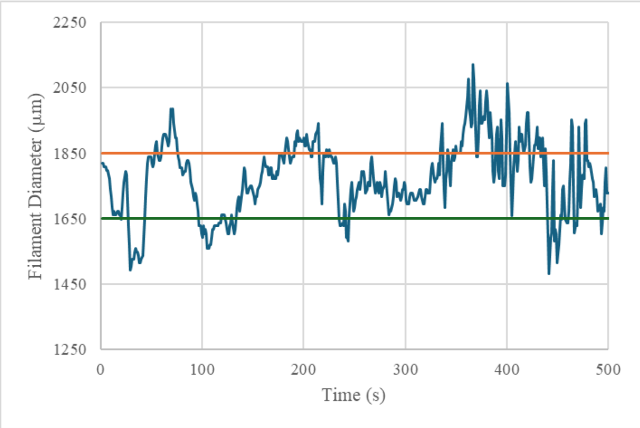

Figure 2. Graph of filament diameter of 100% i-rPP.

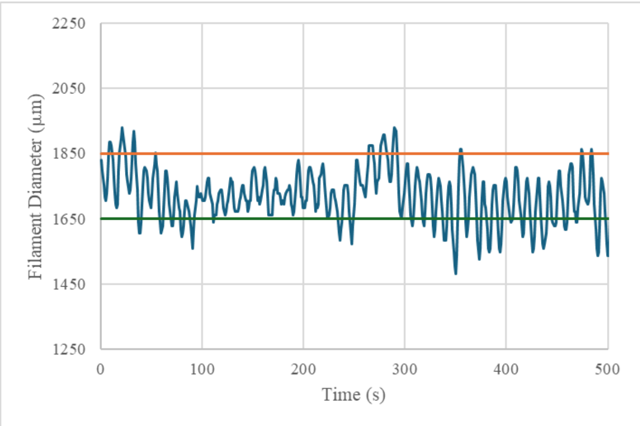

Figure 3. Graph of filament diameter of rPP with 60:40 injection-grade to extrusion-grade.

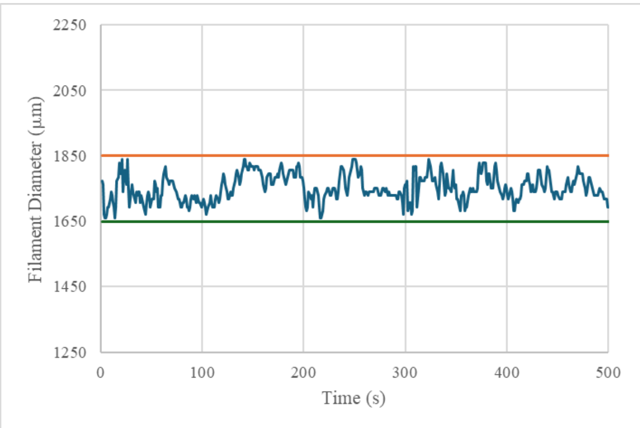

Figure 4. Graph of filament diameter of rPP with 50:50 injection-grade to extrusion-grade.

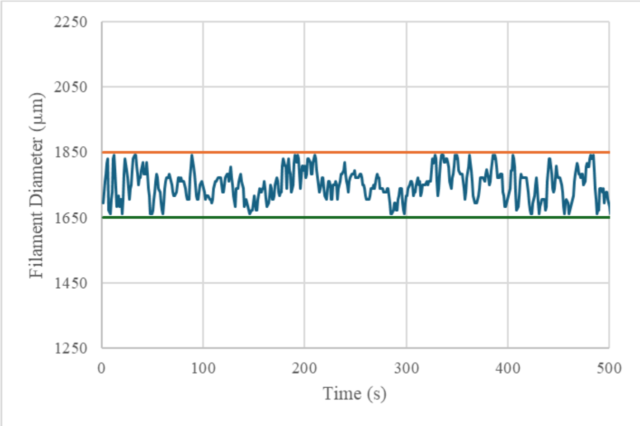

Figure 5. Graph of filament diameter of rPP with 40:60 injection-grade to extrusion-grade.

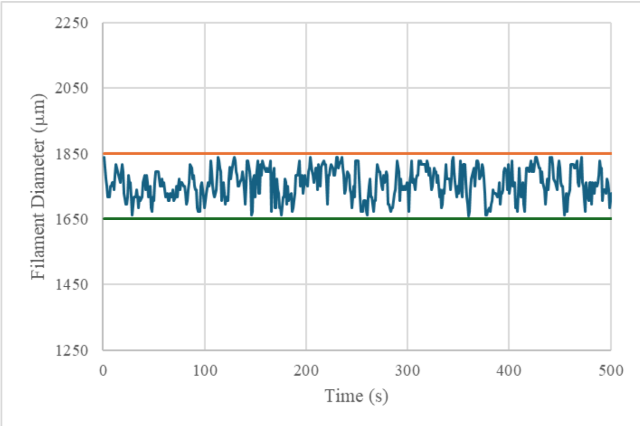

Figure 6. Graph of filament diameter of 100% e-rPP.

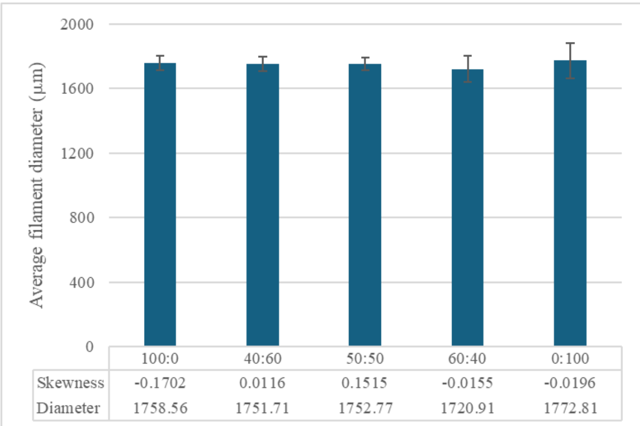

Figure 7. Graph of average filament diameter and skewness.

3.2. Visual Inspection

Figure 8 displays rPP filaments produced using various ratios of i-rPP and e-rPP. The filament made from 100% i-rPP shows significant inconsistency in diameter, with visible variations along its length, indicating poor process stability during extrusion. This inconsistency could be related to the MFI of the i-PP. The injection-grade polymeric materials are generally unsuitable for filament extrusion due to their unfavorable flow characteristics [9]. In contrast, the filament produced with a 50:50 ratio of i-rPP to e-rPP showed uniform and consistent in diameter, suggesting that this ratio provides a balance between flowability and melt strength for filament production. Similarly, the 40:60 and 0:100 i-rPP to e-rPP ratios also showed more consistent filament diameters. The observation aligns with the previous section 3.1. Overall, increasing the proportion of e-rPP improves filament stability. Consequently, the 50:50 ratio was selected for comparison in tensile properties with the 3D printed specimens made from commercial PP, serving as a benchmark.

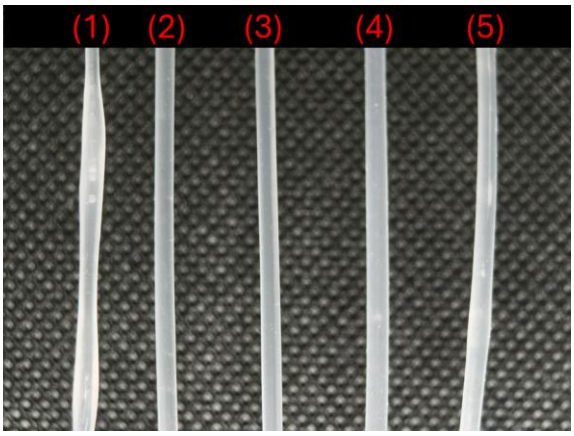

Figure 8. rPP filaments produced with different injection-grade to extrusion-grade ratios: (1) 100:0, (2) 40:60, (3) 50:50, (4) 60:40, and (5) 0:100.

3.3. Ovality Inspection

The ovality graph illustrates the average filament ovality produced from various ratios of i-rPP to e-rPP. Ovality measures the deviation of filament cross-sections from a perfect circle, where higher values indicate lower dimensional uniformity. From Figure 9, it can be observed that ovality slightly decreases with an increasing proportion of e-rPP. The orange reference line at 8% represents the ideal ovality threshold; however, all tested samples exceeded this target. Notably, the filament composed of 100% i-rPP displayed the greatest inconsistency in dimensional stability. This observation aligns with the results presented in the previous section 3.1, where the 100% i-rPP showed greater diameter fluctuations, suggesting unstable flow behavior during the extrusion process. Furthermore, all the rPP filaments showed higher ovality values, which may be due to the inconsistent melt flow resulting from the blending of i-rPP and e-rPP. These variations can lead to irregular flow properties during filament extrusion, causing the filament to have an oval or uneven cross-section. Moreover, the presence of impurities and contaminants in the post-consumer polymeric material could further contribute to this problem. The impurities or contaminants can interfere with the uniform melting and flow ability of the polymeric material through the extrusion die, thereby reducing the dimensional uniformity of the filament.

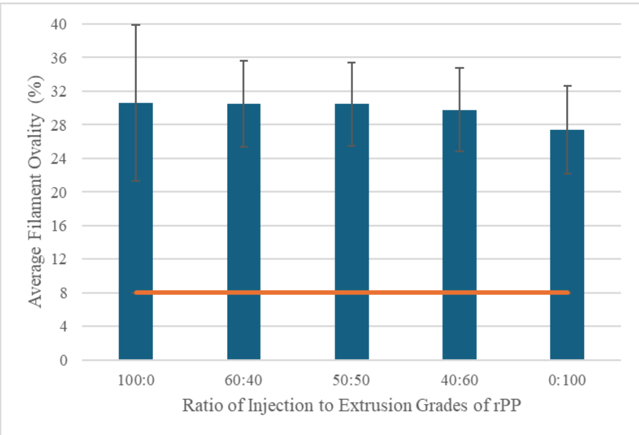

Figure 9. Filament ovality of different ratios of injection to extrusion grades of rPP.

3.4. Melt Flow Index (MFI) Analysis

Figure 10 shows the melt flow index (MFI) of rPP filaments with different i-rPP to e-rPP ratios. The filament made from 100% i-rPP exhibited the highest MFI, approximately 60 g/10 min, indicating high flowability. As the proportion of e-rPP increased, the MFI decreased significantly. The 50:50 blend presents an MFI of 14 g/10 min, while the 100% e-rPP showed an MFI of 10 g/10 min. This trend suggests that e-rPP has inherently lower flowability compared to i-rPP. The blending of the i-rPP and e-rPP effectively moderates the melt behavior, making it more suitable for filament production. The MFI below 10 g/10min is associated with improved extrusion quality, reduced filament diameter fluctuations, and higher dimensional accuracy and precision [12]. This observation aligns with the present findings, where filaments contain a higher e-rPP, and hence lower the MFI values, reduced ovality, and greater diameter consistency, indicating improved extrusion stability and processability.

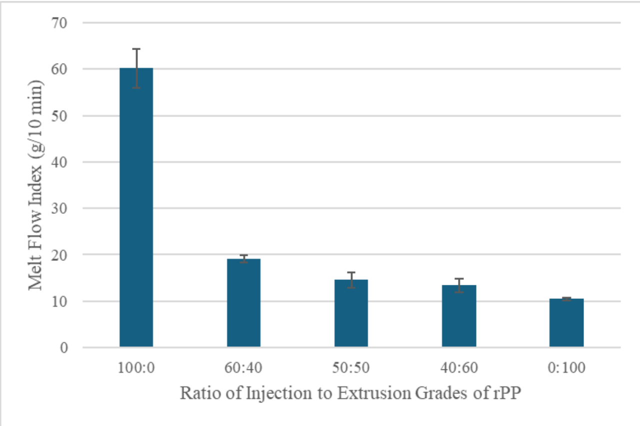

Figure 10. Graph of MFI with different i-rPP to e-rPP ratios.

3.5. Tensile Testing

As presented in section 3.1, the filament consistency graphs revealed that higher proportions of i-rPP led to inconsistent filament diameters, making them unsuitable for reliable feeding in 3D printing. Conversely, among all the prepared filaments with different i-rPP to e-rPP ratios, the 50:50 exhibited the favorable performance, thus ensuring stable printability, reducing under-extrude or nozzle clogging. Although higher e-rPP contents, such as the 40:60 and 0:100 ratios, also performed well in 3D printing, the 50:50 ratio was exhibited as the critical starting point where printability and filament stability were consistently achieved. For this reason, the 50:50 formulation was selected for filament fabrication and tensile testing, as it offered consistent and suitable material properties for 3D printing applications.

Commercial PP filament was used as a benchmark, and both 50:50 i-rPP to e-rPP and commercial PP filaments were 3D printed into tensile specimens. The tensile properties results obtained from the tensile test enable a direct comparison between post-consumer PP and virgin PP filaments, thereby validating the suitability of the 50:50 rPP formulation for practical 3D printing applications.

Figures 11 and 12 exhibit a comparison of elastic modulus and tensile strength between 3D printed 50:50 i-rPP to e-rPP and commercial PP, with both tested at a 90-degree orientation. In Figure 11, the elastic modulus of commercial PP is higher than the 50:50 rPP blend. This indicates that commercial PP possesses greater stiffness and resistance to elastic deformation under tensile loading.

Based on Figure 12, commercial PP shows a higher tensile strength compared to the 50:50 rPP blend, indicating that commercial PP can withstand greater tensile loads before failure. This was expected since commercial PP is a virgin material and typically has a more uniform molecular structure and fewer impurities than the post-consumer polymer blends. The performance gap can be attributed to material degradation during the recycling process and the structural heterogeneity introduced by combining different grades of rPP. However, the 50:50 rPP blend may still be suitable for applications where slightly lower mechanical performance is acceptable in exchange for the environmental and sustainability advantages of using post-consumer materials. Figure 13 shows the 3D printed TAR UMT keychain fabricated using the 50:50 rPP blend filament.

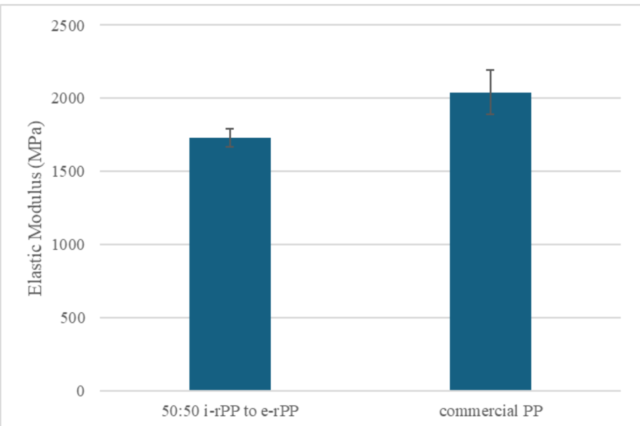

Figure 11. Elastic modulus of 3D printed 50:50 rPP blend and commercial PP filaments.

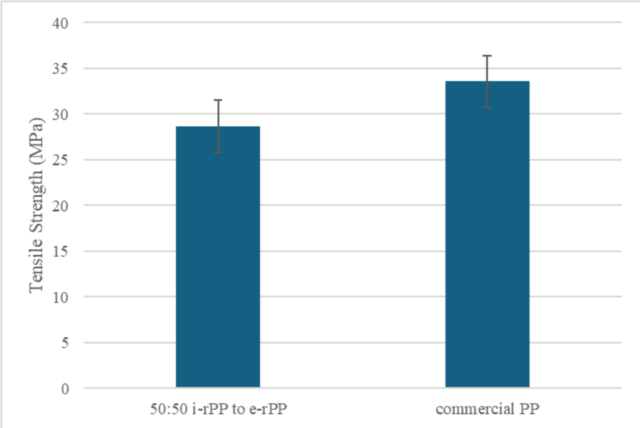

Figure 12. Tensile strength of 3D printed 50:50 rPP blend and commercial PP filaments.

Figure 13. 3D printed TAR UMT keychain fabricated using filament made from a 50:50 rPP blend.

4. CONCLUSION

In conclusion, 3D filaments were successfully developed using post-consumer polypropylene (rPP) for fused filament fabrication (FFF). The results showed that blending i-rPP and e-rPP effectively influenced the filament's melt flow properties. This composition improved dimensional stability, likely attributed to the enhanced flowability achieved by balancing the different grades of rPP. The 50:50 blend ratio served as the starting point among the prepared filaments that exhibited balanced performance, showing greater consistency in filament diameter compared to the 100% i-rPP and 60:40 ratios. Further increasing the e-rPP content, such as 40:60 and 0:100 ratios, also showed to be suitable for 3D printing applications, as the higher proportion of e-rPP led reduction in MFI, contributing to better extrusion stability and maintaining consistent filament diameter. Moreover, although the 50:50 rPP blend showed lower elastic modulus and tensile strength than commercial polypropylene, it still maintained acceptable mechanical performance for applications where slightly reduced strength is tolerable in exchange for environmental sustainability.

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REFERENCES

[1] Y. Shaik, J. Schuster, and A. Shaik, "A scientific review on various pellet extruders used in 3D printing FDM processes," *Open Access Library Journal*, vol. 8, no. 8, pp. 1–19, 2021.

[2] M. S. S. A. Zaki, M. T. Taib and M. H. A. Bakar, "The Analysis of the Effect of Printing Orientation Parameter on the Surface Roughness of 3D Metal Printed Specimens," International Journal of Nanoelectronics and Materials (IJNeaM), vol. 17, no. December, p. 255–268, 2024.

[3] S. Ishutov, K. Hodder, R. Chalaturnyk and G. Zamb, "A 3D printing Short Course: A Case Study for Applications in the Geoscience Teaching and Communication for Specialists and Non-experts," Frontiers in Earth Science, vol. 9, no. 0, p. 0, 2021.

[4] A. Alsabri, F. Tahir and S. Al-Ghamdi, "Environmental impacts of polypropylene (PP) production and prospects of its recycling in the GCC region," Materials Today Proceedings, vol. 56, no. 0, p. 2245–2251, 2021.

[5] M. Blaj and G. Oancea, "Fused deposition modelling process: a literature review," IOP Conference Series Materials Science and Engineering, vol. 1009, no. 1, p. 012006, Jan 2021.

[6] M. Bertolino, D. Battegazzore, R. Arrigo and A. F, "Designing 3D printable polypropylene: Material and process optimisation through rheology," Additive Manufacturing, vol. 40, p. 101944, Mar 2021.

[7] J. Montoya, "Choosing the Right Polypropylene Grade," Plastics Engineering, 2024.

[8] L. Jmerson, "PP Plastic | Material Series for Product Design," First Mold, 04 Jun 2024.

[9] Adreco, "Polypropylene Plastic Uses (PP) | Plastic Properties & Applications," Adreco Plastics, 2022.

[10] K. Yang, Y. Liu, Z. Yan, Y. Tian and Y. Liu, "Enhanced Morphology-Dependent Tensile Property and Breakdown Strength of Impact Polypropylene Copolymer for Cable Insulation," Materials, vol. 13, no. 18, p. 3935, 2020.

[11] E. Pritchard, "MFI Testing: A key validation step for novel filament extrusion," 3devo.com, 2024, 18 Mar 2024.

[12] P. Ellie, "Understanding how MFI influences your filament extrusion | 3devo," 3devo.com, 202, 7 May 2024.

[13] R. Dewi, N. Sylvia, Zulnazri and M. Riza, "Melt flow Index (MFI) analysis of sago based thermoplastic starch blend with polypropylene and polyethylene," sciencedirect, vol. 87, no. 2, pp. 396-400, 2023.

[14] W. Zhang, Jun Shen, Xiaogang Guo, Ke Wang, Jun Jia, Junting Zhao and Jinshuai Zhang, "Comprehensive Investigation into the Impact of Degradation of Recycled Polyethylene and Recycled Polypropylene on the Thermo-Mechanical Characteristics and Thermal Stability of Blends," Molecules, vol. 29, no. 18, p. 4499–4499, 2024.

[15] A. Y. M. Shukri, A. M. Abdullah, S. Shuib and D. Mohamad, "Preparation and Characterization of PLA Filaments for FDM 3D Printing," Journal of Mechanical Engineering, vol. 22, no. 1, p. 223–232, 2025.