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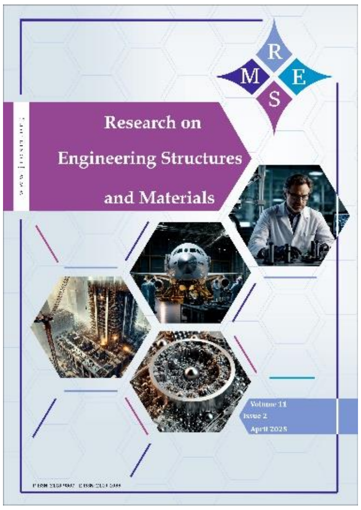

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Research Article

Recycling polypropylene waste to use as material in a 3D printer device

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Abstract

This study investigates the feasibility of mechanically recycling post-industrial polypropylene (PP) waste into homogeneous pellets and 3D-printable filaments for fused deposition modeling (FDM) without the use of chemical additives. The primary objective is to evaluate whether recycled polypropylene can retain sufficient mechanical, thermal, and structural integrity for additive manufacturing applications. The recycled PP was processed using single-screw extrusion to produce pellets and filaments, followed by fabrication of test specimens through injection molding and FDM printing. Mechanical performance was evaluated through tensile testing in accordance with ASTM D638, while thermal behavior and structural integrity were assessed using melting point analysis, Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). The results demonstrate that pellet-based recycled polypropylene retained approximately 90% of the tensile strength of virgin polypropylene, whereas filament-based recycled polypropylene retained approximately 80%. FTIR analysis confirmed preservation of the polypropylene chemical backbone with no significant evidence of oxidative degradation, while SEM observations revealed minor micro voids and interlayer features associated with FDM processing. The successful fabrication of dimensionally stable 3D-printed components further confirms the processability of recycled polypropylene under standard FDM conditions. These findings indicate that mechanically recycled polypropylene can be effectively utilized in additive manufacturing, offering a simplified and sustainable pathway for polymer reuse without chemical modification.

1. Introduction

Polypropylene (PP) is one of the most extensively produced thermoplastic polymers due to its low density, balanced mechanical properties, chemical resistance, thermal stability, and processing versatility. These characteristics have enabled its widespread application in automotive components, packaging systems, consumer products, medical devices, and prosthetic and orthotic applications [1,2]. The continuous growth in polypropylene consumption has consequently led to a substantial increase in polymer waste generation worldwide. The environmental persistence of polypropylene, attributed to its low biodegradability, has intensified concerns regarding solid waste accumulation and long-term ecological impact. Recycling has therefore become a critical strategy for mitigating plastic pollution, conserving raw materials, reducing energy demand, and

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lowering greenhouse gas emissions associated with virgin polymer production [3–6]. Among available waste-management approaches, mechanical recycling remains the most industrially adopted method for polypropylene recovery. Extensive research has evaluated the influence of recycling on the mechanical, thermal, and structural behavior of polypropylene. Previous investigations have shown that repeated thermal processing may induce chain scission, reduce molecular weight, and gradually deteriorate tensile strength and stiffness [8–10,13]. At the same time, polypropylene recycling technologies have been reported to significantly contribute to solid waste reduction and environmental sustainability [11]. Furthermore, studies have demonstrated that recycled polypropylene can be reintegrated into engineering and construction-related applications when appropriate processing strategies are implemented to maintain thermal stability and mechanical resistance [12]. Additional research has examined crystallinity evolution, degradation indicators, emissions during recycling, and composite reinforcement strategies, confirming the continued industrial relevance of recycled polypropylene [14–19].

Although the feasibility of recycled polypropylene has been established across various conventional manufacturing routes, including injection molding, extrusion into bulk products, and composite fabrication, many reported approaches rely on chemical modification, stabilizers, compatibilizers, or filler incorporation to compensate for degradation effects. While these strategies may enhance performance, they increase process complexity and economic cost, which can limit their applicability in simplified or resource-constrained recycling systems. In contrast, the direct use of mechanically recycled polypropylene as feedstock for additive manufacturing—particularly fused deposition modeling (FDM)—has received comparatively limited systematic investigation. Additive manufacturing requires stable melt flow behavior, consistent filament geometry, and sufficient interlayer bonding performance, all of which are sensitive to molecular degradation and thermal history. Therefore, evaluating whether recycled polypropylene can retain adequate structural and mechanical integrity for FDM applications without additional chemical modification is of significant scientific and practical importance. Accordingly, the present study investigates the feasibility of converting post-industrial polypropylene waste into pellets and subsequently into 3D printing filaments through mechanical recycling without incorporating chemical additives or secondary processing treatments. The recycled materials are characterized in pellet and filament forms using tensile testing, melting point analysis, Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM), and their properties are compared with those of virgin polypropylene. The applicability of the recycled filament in additive manufacturing is further demonstrated through the fabrication of functional printed models. By integrating mechanical recycling with additive manufacturing, this work aims to evaluate a simplified and sustainable pathway for polypropylene reuse and to contribute to circular manufacturing strategies that reduce environmental impact while maintaining functional material performance.

2. Materials and Method

The raw material used in this study was post-industrial polypropylene (PP) waste generated during manufacturing processes, including rejected pump molding parts and production remnants. This type of waste was selected due to its known origin, high purity, and absence of foreign polymer contamination, making it suitable for controlled mechanical recycling. The collected polypropylene waste used as the raw material in this study is shown in (Fig. 1).

Virgin polypropylene was also used as a reference material to enable a direct comparison between recycled and non-recycled PP. The fundamental properties of polypropylene reported in the literature, such as density and melting temperature, were used as baseline values for comparison with the recycled material. The fundamental physical properties of virgin polypropylene used as reference material are summarized in Table.1, based on supplier data and literature-reported values.

Fig. 1. The collected polypropylene waste used as the raw material

Table 1. Basic properties of virgin polypropylene used as reference material

Property	Value
Density	0.90–0.91 g/cm^3
Melting temperature	160–170 °C
Polymer type	Homopolymer PP
Physical form	Injection molding grade

2.1. Process of Recycling Polypropylene and Turning it into Homogeneous Spherical Pellets

The recycling of polypropylene waste into homogeneous spherical pellets is achieved through a series of mechanical processing steps designed to convert plastic waste into reusable raw material. The process involves collection, washing, shredding, extrusion, cooling, and pellet formation to obtain uniform pellets suitable for manufacturing applications. The complete sequence of these stages is presented in (Fig. 2).

2.2 Procedures of Recycling Polypropylene to Make Filament to Use in 3D Printing

The recycling of polypropylene waste into filaments suitable for 3D printing involves a series of controlled mechanical processing steps, including shredding, melting, extrusion, cooling, and filament diameter control. The main stages of this process are illustrated in Fig. 3. The overall mechanical recycling process of polypropylene waste, including melting, extrusion, and the production of pellets or filaments, is illustrated in (Fig. 4).

2.3 Tensile Test

The tensile tests were conducted using a universal testing machine (Testometric), as shown in (Fig. 5). Three different types of tensile specimens were prepared for mechanical characterization, namely virgin polypropylene as the reference material (Sample A), recycled polypropylene processed into filament form and fabricated by 3D printing (Sample B), and recycled polypropylene processed into pellet form, re-melted, and subsequently fabricated by 3D printing (Sample C). All tensile specimens were designed and manufactured in accordance with the ASTM D638 standard using Type I specimen geometry to ensure consistency and comparability of the mechanical test results. For Samples B and C, the tensile specimens were fabricated using fused deposition modeling (FDM) 3D printing technology. For Samples B and C, tensile specimens were fabricated using fused deposition modeling (FDM) technology with controlled and reproducible processing parameters.

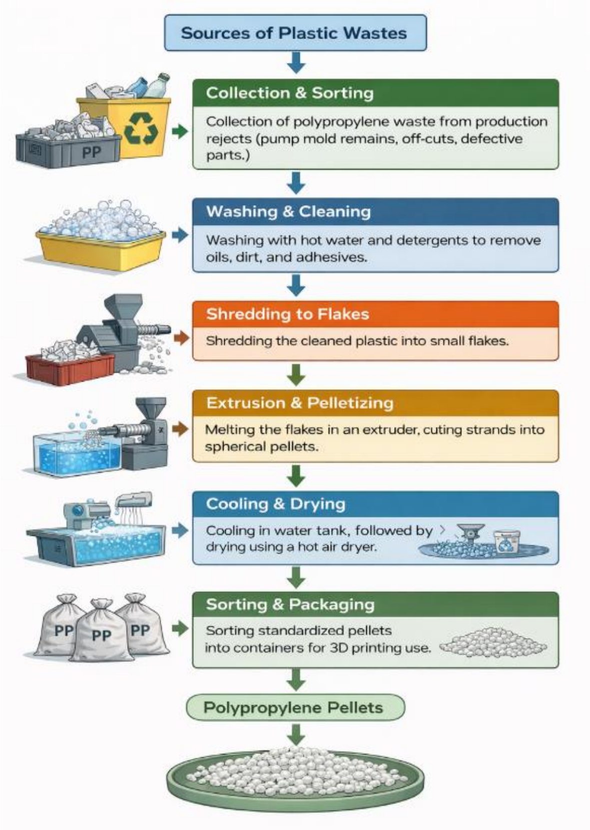

Fig. 2. Flowchart of the mechanical recycling process of polypropylene waste for the production polypropylene pellets

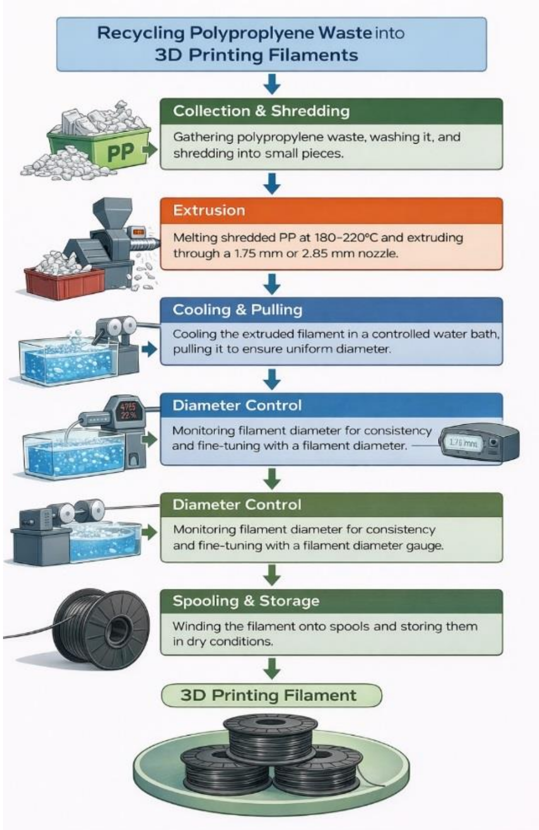

Fig. 3. Flow diagram illustrating the main stages of recycling polypropylene waste into 3D printing filaments

Fig. 4. Stages of recycling polypropylene waste into pellets or 3D-printing filaments

A nozzle diameter of 0.4 mm was used. The extrusion (nozzle) temperature was maintained at 205 °C (within a controlled range of 200–210 °C) to ensure adequate polymer melt flow and interlayer diffusion bonding. The build platform temperature was set at 95 °C to minimize warpage and enhance first-layer adhesion. Layer thickness was fixed at 0.2 mm to promote consistent layer stacking and interfacial fusion. Printing speed was maintained at 45 mm/s, corresponding to a controlled material deposition rate compatible with the selected nozzle diameter. A 100% infill density was used, and the printing direction was aligned parallel (0°) to the tensile loading axis to ensure maximum load transfer efficiency and minimize anisotropic strength reduction typically observed in FDM-printed specimens. Cooling was achieved under natural convection without forced fan cooling to allow gradual solidification and improved interlayer bonding. These parameters were selected to optimize interlayer adhesion and ensure repeatability of mechanical performance evaluation. Virgin polypropylene tensile specimens were produced using injection molding under controlled processing conditions. The mold cavity conformed to ASTM D638 Type I geometry. The standard specimen dimensions used in this study are illustrated in Fig. 6. The injection temperature was maintained between 200–220 °C, while the mold temperature was controlled at approximately 40 °C. Injection pressure was approximately 80–100 MPa with moderate injection speed to ensure uniform cavity filling. Cooling time was maintained at 30–40 seconds before specimen ejection. These parameters were selected to minimize residual stresses and ensure dimensional consistency. The printed specimens can be seen in (Fig. 7).

Fig. 5. The Testometric device

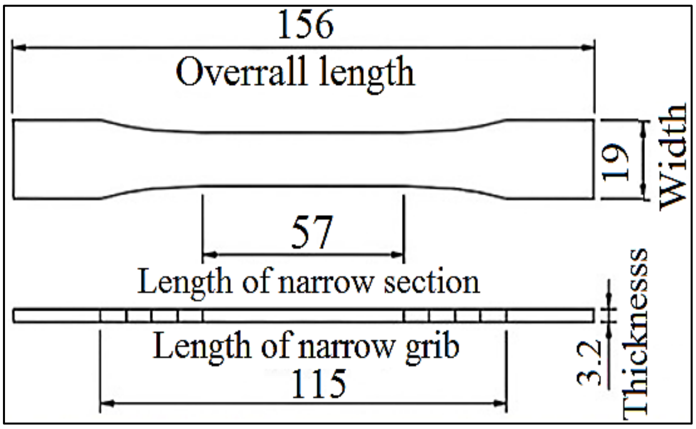

Fig. 6. The standard dimensions according to ASTM D638

While injection-molded virgin polypropylene specimens exhibited smooth and continuous surfaces, the 3D-printed recycled specimens showed clearly distinguishable layer-by-layer deposition patterns. These visible interlayer boundaries are characteristic of FDM processing and contribute to the slight reduction in tensile strength observed in filament-based samples.

Sample A-Raw Polypropylene (Raw PP): Symbolises the initial, which is not recycled. Sample B-Filament recycled Polypropylene: The plastic waste in the form of polypropylene was recycled into filaments that could be used in 3D printing. The test specimens were printed as 100% infill filaments. Sample C- Recycled Polypropylene (Pellet form): The recycled polypropylene was moulded into pelletized spherical form, which was subsequently mixed and re-melted as the feed material to extrude the test specimens with an infill density of 100 per cent by use of 3D printing.

To ensure its accuracy and reproducibility, each of the types of samples was tested at least three times under the same conditions of testing, such as the same tensile speed, ambient temperature, and the same specimen size. Some of the mechanical parameters that were recorded during the testing process are stress, strain, ultimate tensile strength, Young's modulus and the elongation at break. These parameters gave thorough insight into the mechanical behavior of the material before and after recycling. The printed tensile specimens clearly exhibited visible layer deposition lines characteristic of fused deposition modeling, confirming the additive manufacturing origin of Samples B and C.

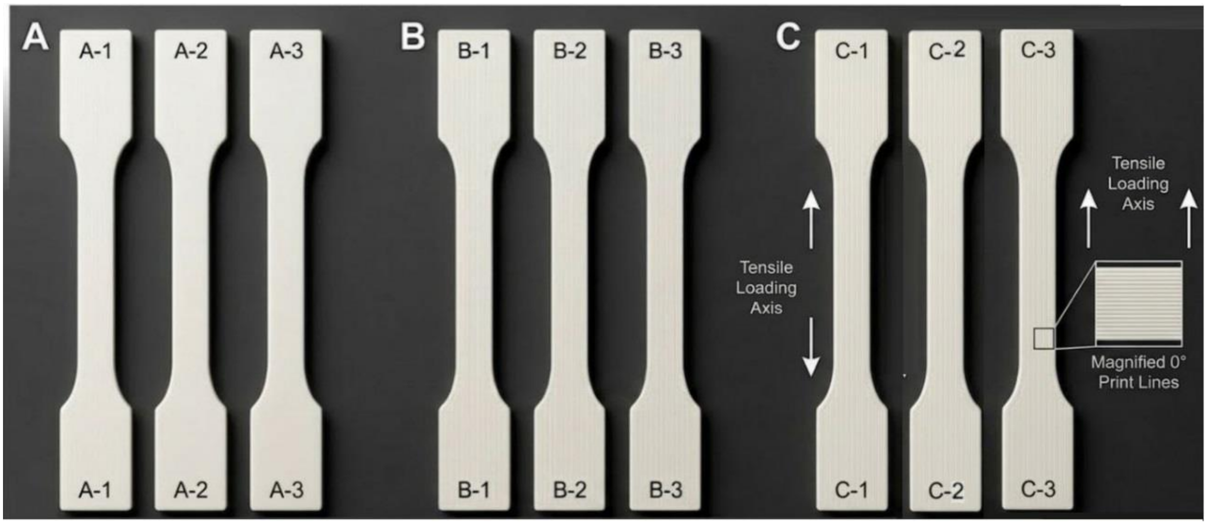

Fig. 7. Tensile specimens for the three groups to be tested

2.4 Test the Melting Point of Recycled Polypropylene by the Stuart SMP1 Device

This test aims to find out the melting point of a recycled polypropylene (PP) and also how much the thermal property is maintained after the recycling process. This breakdown will be critical in knowing whether the material can be reused in the form of thermal manufacturing processes like 3D printing. Equipment Used:

- -Melting point apparatus (Stuart SMP1) as shown in Fig. 8.
- - Fine capillary tubes in which the sample will be placed.
- - The device contains an in-built thermometer.

Fig. 8. Stuart SMP1

A minute amount (in the form of pellets or fine powder) of a recycled polypropylene was removed and inserted into a capillary tube compatible with the Stuart SMP1 device. The heating rate was made slowly, around C/min0 5-10. Heating was commenced, and it was observed manually through the device observation window. The temperature at which the material started changing its state from solid to a liquid was recorded. Other samples were used in repeating the test to demonstrate the accuracy of the results.

2.5 Test Using FTIR of Recycled Polypropylene

FTIR analysis was performed to evaluate the chemical structure of recycled polypropylene and to detect any potential chemical degradation or oxidation resulting from the recycling process.

Recycled polypropylene samples were prepared as thin films and analyzed using an FTIR spectrometer over the spectral range of 4000–500 cm^{-1}. The obtained spectra were compared with those of virgin polypropylene to identify characteristic absorption peaks and assess structural integrity

2.6 Scanning Electron Microscopy (SEM) Analysis

The surface and fracture morphologies of virgin polypropylene and recycled polypropylene (pellet-based and filament-based) samples were examined using scanning electron microscopy (SEM). Small specimens were mounted on aluminum stubs using conductive carbon tape and sputter-coated with a thin layer of gold to enhance electrical conductivity. SEM observations were carried out at accelerating voltages between 10 and 15 kV, with magnifications ranging from 100× to 2000×, allowing detailed assessment of surface texture, porosity, and internal morphology.

3. Results

Representative optical images of the recycled pellets and extruded filaments are shown in (Fig. 9) and (Fig. 10). The pellets exhibited uniform geometry and homogeneous surface texture, indicating stable extrusion and cutting processes. The produced filaments demonstrated consistent diameter and smooth surface continuity suitable for FDM processing.

Fig. 9. The particle of polypropylene recycled

Fig. 10.The filament of polypropylene recycled

The tensile properties of virgin polypropylene and recycled polypropylene in pellet and filament forms were evaluated using uniaxial tensile testing. Representative stress–strain curves for all tested materials are presented in Fig. 11, while the corresponding mechanical properties are summarized in Table 2. Virgin polypropylene exhibited the highest mechanical performance, with an average yield strength of approximately 22 MPa, an ultimate tensile strength of 36 MPa, and a Young’s modulus of about 1.6 GPa. Grain or small pellet recycled polypropylene showed a slight reduction in mechanical properties, recording an average yield strength of approximately 19 MPa and an ultimate tensile strength of 34 MPa. Recycled polypropylene in filament form exhibited a further reduction, with an average yield strength of approximately 16 MPa and an ultimate tensile strength of 33 MPa. Despite the observed reductions, both recycled materials retained a substantial portion of the mechanical properties of virgin polypropylene. The standard deviation values for all measured properties were low, indicating good repeatability and consistency of the experimental results across the tested specimens.

To statistically evaluate the differences in mechanical properties between virgin polypropylene and recycled polypropylene samples, a one-way analysis of variance (ANOVA) was performed using a significance level of $p < 0.05$. The analysis revealed a statistically significant difference in yield strength among the three groups ($p < 0.05$). Post-hoc comparison indicated that filament-based recycled polypropylene exhibited a significant reduction compared to virgin polypropylene. However, the difference between virgin polypropylene and pellet-based recycled polypropylene was less pronounced, indicating that mechanical degradation remains controlled after single-cycle mechanical recycling. These findings confirm that the observed reductions in tensile properties are not due to experimental variability but are statistically supported.

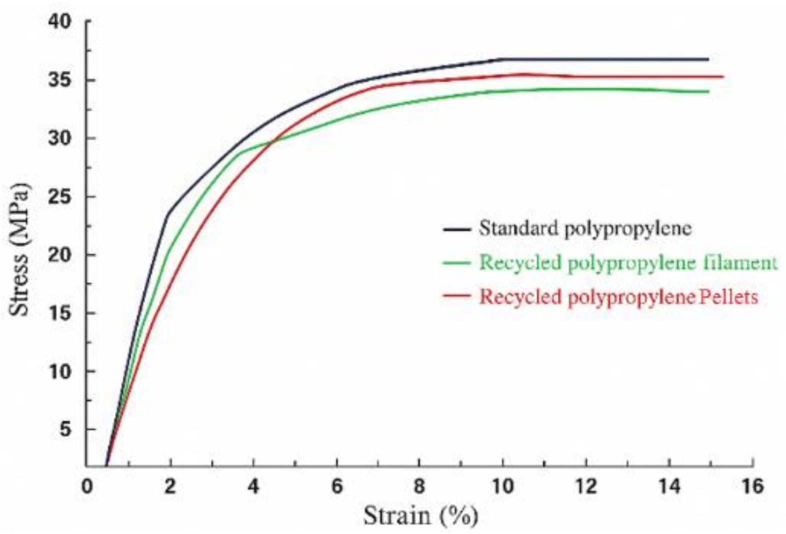

Fig. 11. Stress-Strain curve of standard and recycled polypropylene

Table 2. Summary of mechanical properties of standard and recycled polypropylene

Group	Material Type	Sample	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Young's Modulus (GPa)
A	Standard Polypropylene	1	22.1	36.2	1.6
		2	21.9	35.9	1.59
		3	22	36	1.61
		Mean ± SD	22 ± 0.1	36 ± 0.2	1.6 ± 0.01
B	Recycled Polypropylene Filament	1	19	34.2	1.31
		2	19.1	33.7	1.29
		3	18.9	34.1	1.3
		Mean ± SD	19 ± 0.1	34 ± 0.2	1.3 ± 0.01
C	Recycled Polypropylene Pellets	1	16.1	33.2	1.21
		2	15.9	32.9	1.19
		3	16	33	1.2
		Mean ± SD	16 ± 0.1	33 ± 0.15	1.2 ± 0.01

The tensile strength values obtained for virgin polypropylene in this study fall within the typical range of 30–38 MPa reported in the literature for injection-molded homopolymer polypropylene [10,13]. The slight reduction observed in recycled filament-based specimens is consistent with previously reported degradation effects during reprocessing cycles. Nasir et al. [13] reported gradual decreases in tensile strength and modulus due to chain scission and molecular weight reduction during repeated recycling. Similarly, Infurna et al. [10] observed mechanical performance deterioration in recycled polypropylene blends. The results of the present study align well with these findings, confirming that mechanical recycling without stabilizers may induce moderate but predictable strength reduction.

Table 2 shows yield, ultimate tensile, and Youngs modulus of the virgin and recycled polypropylene (PP) materials. The groups were subjected to three tests (n = 3). The findings have revealed that the raw PP recorded the best mechanical properties, whereas the recycled materials (PP) gave a slightly lower value that depended on the process of recycling. The low standard deviation values are a measure of good repeatability and prove the statistical reliability of the results.

The melting temperatures of recycled polypropylene samples were measured using a Stuart SMP1 melting point apparatus. The recorded melting temperatures for both pellet-based and filament-based recycled polypropylene were in the range of 160–170 °C.These values are comparable to those typically reported for virgin polypropylene, indicating that the recycling process did not cause a significant shift in the melting behavior of the polymer. Repeated measurements showed minimal variation, confirming the reliability of the obtained results.

FTIR spectra of virgin polypropylene and recycled polypropylene in pellet and filament forms are presented in Fig. 12. All samples exhibited the characteristic absorption peaks of polypropylene. Strong absorption bands were observed in the range of 2950–2870 cm^{-1}, corresponding to C–H stretching vibrations of the $–CH_2$ and $–CH_3$ groups. Additional characteristic peaks were detected between 1450 and 1375 cm^{-1}, which are associated with bending and deformation vibrations of these functional groups. The FTIR spectra of recycled polypropylene closely matched that of virgin polypropylene, with no additional peaks indicating the formation of new chemical groups. Minor variations in peak intensity were observed between samples but no significant changes in peak position were detected.

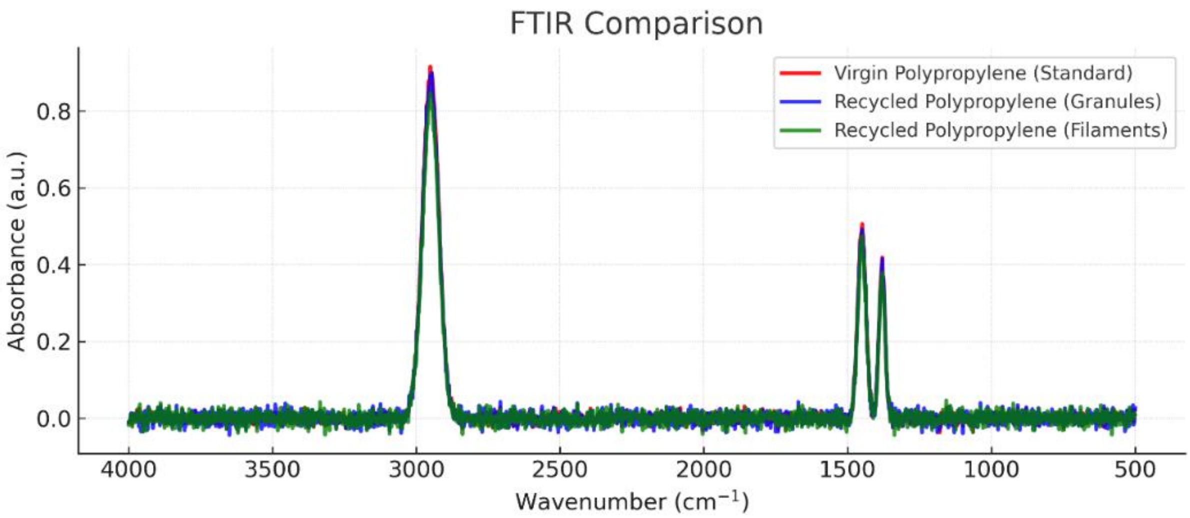

Fig. 12. FTIR spectrum comparison between virgin and recycled polypropylene

The FTIR spectra of recycled polypropylene did not reveal significant new absorption peaks associated with carbonyl groups (~1700–1750 cm^{-1}), which are commonly attributed to thermo-oxidative degradation during processing. This observation suggests limited oxidative damage during the applied recycling procedure. Similar findings were reported by Polachova et al. [8], who indicated that controlled thermoplastic reprocessing does not necessarily introduce severe oxidation if processing temperatures are maintained within stable ranges. The preservation of characteristic PP peaks (e.g., CH_2 and CH_3 stretching vibrations) further confirms chemical structure stability. SEM micrographs revealed relatively homogeneous fracture surfaces in injection-molded specimens, whereas filament-printed samples showed characteristic interlayer boundaries. Comparable fracture morphologies have been documented in FDM-printed polypropylene systems, where interlayer bonding plays a critical role in tensile performance. Previous studies on recycled polypropylene have also reported increased surface roughness and micro void formation associated with thermal history and molecular degradation [15]. The morphological features observed in the present work are therefore consistent with established degradation mechanisms reported in the literature.

Fig. 13 presents SEM micrographs of three polypropylene samples: virgin polypropylene (Sample A), recycled polypropylene in pellet form (Sample C), and recycled polypropylene in filament form (Sample B). The virgin polypropylene sample exhibited a smooth and dense surface morphology with a nearly circular cross-section and no observable voids, with an approximate diameter in the range of 1.70–1.80 mm. The pellet-based recycled polypropylene sample showed a slightly rougher surface with minor surface irregularities and small voids. The cross-section remained nearly circular, with an approximate diameter of 1.65–1.84 mm, indicating good structural continuity after recycling. The filament-based recycled polypropylene sample exhibited increased surface roughness and the presence of micro void-like features, along with a somewhat irregular cross-sectional geometry. The measured diameter ranged approximately between 1.60 and 1.70 mm. In addition to SEM analysis, the fractured tensile specimens were visually examined at the macroscopic level.

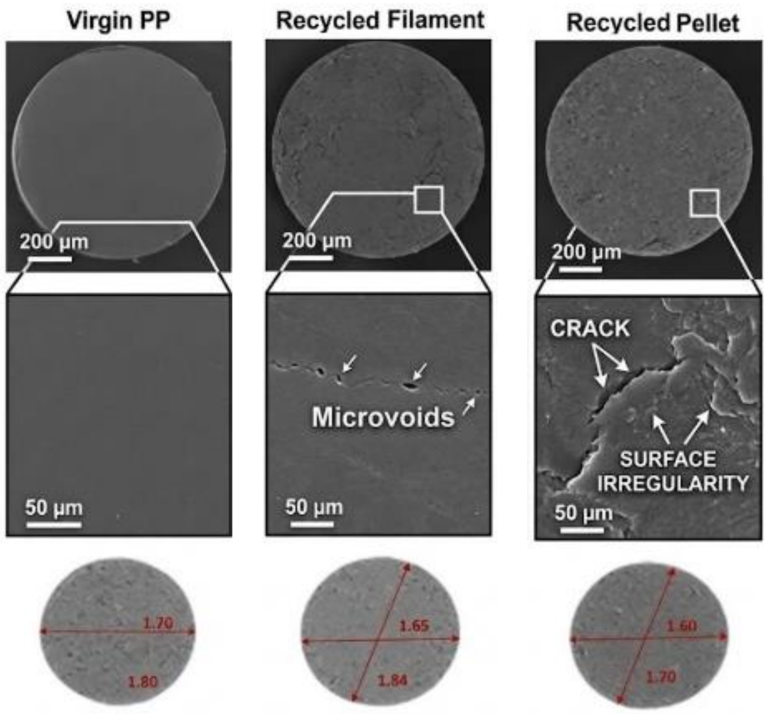

Fig.13. The SEM of virgin PP and recycled PP

Fig. 14. 3D printed model of recycled polypropylene

The fracture surfaces of virgin polypropylene showed pronounced necking and ductile deformation prior to failure, which is characteristic of semi-crystalline thermoplastics. Recycled polypropylene specimens, particularly filament-based samples, exhibited visible stress whitening and localized plastic deformation at the fracture zone. The presence of neck formation confirms ductile failure behavior rather than brittle delamination between layers. Although minor interlayer separation was observed in filament-printed specimens, catastrophic interfacial failure was not detected, indicating acceptable interlayer bonding under the selected FDM parameters. To experimentally validate the processability of recycled polypropylene, the material was extruded into filament and subsequently used in fused deposition modeling (FDM) 3D printing to fabricate a cosmetic hand prototype of a prosthetic limb, as shown in Fig. 14. The printing process was completed successfully without interruption, filament breakage, or dimensional instability. The fabricated prototype exhibited satisfactory shape fidelity and surface continuity, demonstrating the suitability of recycled polypropylene filaments for complex geometries produced by additive manufacturing. This application serves as a proof of concept highlighting the potential of integrating polypropylene recycling with 3D printing technologies for non-load-bearing and demonstrative prosthetic components.

Dimensional stability of the printed specimens was assessed through visual inspection and diameter measurements of printed tensile samples. Filament diameter variation remained within ±0.05 mm, and no significant warpage or corner lifting was observed during printing or post-cooling. The maintained geometric integrity indicates controlled shrinkage behavior and acceptable dimensional predictability of recycled polypropylene under the selected FDM conditions. Although precise shrinkage percentage was not quantified, the successful fabrication of geometrically stable components suggests reliable dimensional performance for non-load-bearing applications. The use of recycled polypropylene instead of virgin polypropylene offers notable environmental benefits, particularly in terms of energy consumption and greenhouse gas emissions, as reported in life cycle assessment studies. It should be clarified that the energy consumption and emission values presented in this section were not experimentally measured within the scope of the present study. Instead, they are derived from previously published life-cycle assessment (LCA) studies and international environmental reports addressing polypropylene production and recycling systems [16–18]. These literature-based data are included solely for comparative and contextual purposes to highlight the potential environmental benefits of mechanical recycling relative to virgin polymer production. According to published data, the production of virgin polypropylene requires approximately 80 MJ/kg of energy, whereas mechanical recycling of polypropylene into pellets or filaments typically consumes between 25 and 35 MJ/kg. Similarly, carbon dioxide emissions associated with virgin polypropylene production, estimated at around 2.0 kg CO_2/kg, are significantly reduced to approximately 0.6–0.8 kg CO_2/kg when recycled polypropylene is used. In addition, recycled polypropylene can partially replace virgin material, with studies indicating that 50–70% of material demand can be fulfilled using post-consumer polymers. These reported reductions correspond to energy and emission savings of approximately 60–65%, highlighting the potential of polypropylene recycling to lower material demand, reduce plastic waste generation, and decrease the overall carbon footprint of polymer-based manufacturing processes [20-21]. Therefore, the presented environmental comparison serves as a qualitative sustainability indicator rather than a direct experimental outcome of this work.

4. Discussion

The tensile results showed that recycled polypropylene in pellet form retained approximately 86–90% of the tensile strength of virgin PP, while filament-based recycled PP retained around 80–85%. In fused deposition modeling (FDM), mechanical performance is strongly governed by interlayer diffusion bonding rather than bulk material continuity. During deposition, molten polypropylene filaments fuse through thermal diffusion across adjacent layers. The effectiveness of this bonding depends on melt temperature, cooling rate, and polymer chain mobility at the interface. The slight reduction in tensile strength observed in filament-based recycled polypropylene can therefore be attributed to limited interlayer diffusion and the presence of microscopic interfacial discontinuities. Since load transfer in FDM-printed components occurs across these bonded interfaces, any reduction in molecular interpenetration reduces effective stress transfer efficiency. The consistent printing parameters and full infill structure applied in this study minimized structural variability, suggesting that the observed strength reduction is primarily governed by intrinsic interlayer bonding limitations rather than macroscopic defects. The slight reduction in yield strength and Young's modulus can be attributed to thermal reprocessing effects such as chain scission and minor oxidative degradation during extrusion and FDM printing. Similar behavior was reported by Douiri, L. et al., who investigated multiple recycling loops of polypropylene and observed a gradual decrease in tensile strength due to molecular weight reduction and crystallinity changes during repeated thermal cycles. Their study demonstrated that mechanically recycled PP typically maintains 75–90% of its original tensile properties after limited recycling stages, which aligns closely with the retention ratios observed in the present work [22].

The melting temperature of recycled polypropylene (160–170 °C) remained within the characteristic range of virgin PP, indicating preservation of crystalline phase stability after recycling. Although Differential Scanning Calorimetry (DSC) was not performed in the present study, the measured melting temperature range (160–170 °C) remained consistent with typical semi-crystalline polypropylene behavior, suggesting preservation of the crystalline phase structure after recycling. Furthermore, the relatively stable Young's modulus values (1.2–1.3 GPa for recycled samples compared to 1.6 GPa for virgin PP) indicate that no drastic alteration in crystallinity occurred. Since stiffness and shrinkage behavior in polypropylene are strongly correlated with crystalline fraction, the moderate reduction in modulus suggests limited structural disruption rather than significant phase transformation. Future investigations will incorporate DSC analysis to quantify crystallinity changes and correlate them directly with mechanical and dimensional performance The stability of melting behavior suggests that the recycling process did not significantly alter lamellar crystal structure. Comparable findings were reported by Mannheim and Simenfalvi, who demonstrated through life-cycle and thermal evaluation studies that mechanically recycled polypropylene generally preserves its melting transition unless severe oxidative degradation occurs. The thermal stability observed in the present study therefore supports the suitability of recycled PP for repeated thermal processing such as FDM printing [23].

FTIR spectra of recycled PP closely matched those of virgin PP, with characteristic peaks at 2950–2870 cm^{-1} and 1450–1375 cm^{-1} preserved. No additional carbonyl peaks (≈1700–1750 cm^{-1}) were detected, indicating minimal oxidative degradation. Similar spectral stability was observed by Nasir, N.H. et al., who reported that mechanically recycled polypropylene composites retained their fundamental chemical structure with only minor intensity variations in FTIR spectra [24]. Furthermore, Polachova, A. et al. indicated that early-stage thermal degradation of polypropylene is often detectable by slight peak intensity changes rather than the formation of new functional groups, which corresponds with the observations in the current study. These findings confirm that the recycling procedure did not significantly alter the polymer backbone structure [25]. Although Gel Permeation Chromatography (GPC) analysis was not performed to directly quantify molecular weight distribution, several indirect indicators suggest limited chain degradation during recycling. The retention of approximately 80–90% of tensile strength and the absence of significant carbonyl peak formation in FTIR spectra indicate that severe chain scission or oxidative breakdown did not occur. In polypropylene, substantial molecular weight reduction typically results in pronounced decreases in tensile strength and modulus. The moderate mechanical reduction observed in this study therefore suggests partial but controlled molecular weight alteration rather than extensive polymer backbone degradation. Future work will incorporate GPC measurements to quantitatively correlate molecular weight evolution with mechanical performance. Although Melt Flow Index (MFI) testing was not performed in this study, extrusion stability, absence of nozzle clogging, and consistent filament diameter (1.60–1.75 mm) provide indirect indicators of acceptable melt viscosity. Since viscosity behavior is directly related to molecular weight evolution during recycling, future work will include quantitative MFI measurements to establish a direct correlation between rheological changes and mechanical performance. Thermogravimetric Analysis (TGA) was not conducted in this study to quantify decomposition onset temperature and thermal stability margins. However, polypropylene typically exhibits thermal degradation onset above 300 °C, which is substantially higher than the processing temperatures used in extrusion and FDM (200–210 °C). The absence of discoloration, bubbling, or flow instability during repeated processing cycles suggests that no premature thermal decomposition occurred. Nevertheless, future studies will incorporate TGA measurements to evaluate long-term thermal aging resistance and degradation kinetics under multiple recycling and manufacturing cycles.

SEM analysis of recycled polypropylene specimens revealed a rougher and more porous fracture surface compared to the relatively smooth morphology of virgin PP, especially in filament-based samples that underwent extrusion and 3D printing. These morphological irregularities, such as micro voids and interlayer gaps, can weaken interfacial bonding and act as stress concentrators, leading to the reduction in tensile strength observed in recycled specimens. A similar effect was reported in a recent study on recycled polypropylene for additive manufacturing, where the fracture surfaces of 3D-printed recycled PP showed pronounced interlayer cavities and porosity, which were directly linked to diminished mechanical performance due to reduced effective load-bearing area and poorer interlayer adhesion. This confirms that microstructural defects induced during processing (e.g., extrusion and printing) contribute to the mechanical degradation of recycled PP parts [26-28]. Although SEM observations were primarily qualitative, comparative analysis of fracture surfaces indicates that filament-based recycled polypropylene exhibited a higher density of micro void-like features relative to pellet-based samples. The presence of these voids reduces the effective load-bearing cross-sectional area and can act as localized stress concentrators during tensile loading. While quantitative porosity measurements were not performed, the observed morphological differences correlate consistently with the measured reduction in tensile strength and modulus. Future investigations will include image-based porosity quantification and microstructural statistical analysis to establish a direct numerical relationship between void fraction and mechanical durability. The present study intentionally excluded the use of antioxidants or thermal stabilizers in order to evaluate the baseline mechanical and structural performance of mechanically recycled polypropylene. While stabilizer integration is commonly employed in industrial recycling to mitigate oxidative degradation and extend long-term durability, the objective here was to assess intrinsic material retention without chemical modification. The retained mechanical performance (80–90%) suggests that limited degradation occurred under the selected processing conditions. Future optimization studies will investigate the incorporation of stabilizing additives to further enhance long-term structural reliability and storage stability of recycled polypropylene filaments.

It should be acknowledged that the present study focused primarily on tensile characterization. For prosthetic and orthotic applications, materials are typically subjected to cyclic loading, bending stresses, and occasional impact forces during real-world use. Therefore, additional mechanical evaluations such as Charpy or Izod impact testing and three-point bending tests are recommended to comprehensively assess long-term structural reliability. The current tensile results demonstrate promising baseline strength retention; however, future investigations will incorporate impact resistance and flexural behavior analysis to further validate suitability for load-bearing biomedical components.

5. Conclusions

This study demonstrated the feasibility of mechanically recycling polypropylene waste into pellets and filaments suitable for fused deposition modeling (FDM) 3D printing without the use of chemical additives. The recycled polypropylene retained a substantial proportion of the mechanical properties of virgin polypropylene, with pellet-based recycled material showing slightly higher performance than filament-based recycled material due to reduced thermal reprocessing. This observation highlights the influence of repeated thermal cycles on the mechanical stability of thermoplastic polymers and emphasizes the importance of minimizing unnecessary processing steps during recycling.

Thermal analysis confirmed that the melting behavior of recycled polypropylene remained within the typical range of virgin polypropylene, indicating preservation of the polymer's crystalline structure after recycling. FTIR results showed that the characteristic chemical structure of polypropylene was maintained, with no evidence of significant chemical degradation. These findings suggest that the mechanical recycling method applied in this study did not lead to severe polymer chain scission or oxidation reactions. SEM observations revealed increased surface roughness and micro voids in recycled samples compared to virgin polypropylene; however, no critical structural defects were observed that would significantly compromise the integrity of the printed components.

The successful fabrication of 3D-printed specimens and a cosmetic prosthetic hand prototype further demonstrated the processability of recycled polypropylene using standard FDM conditions, serving as a proof of concept for additive manufacturing applications. The printed components showed stable extrusion behavior and acceptable dimensional consistency, indicating that recycled polypropylene filament can be processed reliably under typical printing parameters. These results highlight the potential of integrating recycled thermoplastics into additive manufacturing workflows for practical engineering and biomedical prototype applications.

From an environmental perspective, the use of recycled polypropylene provides clear sustainability advantages. Recycling plastic waste reduces the need for virgin polymer production, which is associated with significant energy consumption and greenhouse gas emissions. Reported literature data indicate that the use of recycled polypropylene can significantly reduce energy consumption, carbon dioxide emissions, and virgin material demand compared to conventional polypropylene production. Therefore, converting plastic waste into functional 3D printing filament supports circular economy principles and contributes to more sustainable materials management.

Although the results are promising, some limitations should be acknowledged. Advanced characterization techniques such as melt flow index analysis, differential scanning calorimetry for detailed crystallinity quantification, and molecular weight distribution measurements were beyond the scope of the present study. Future research could incorporate these analyses to better understand the rheological behavior, crystallization mechanisms, and long-term stability of recycled polypropylene during repeated processing cycles.

Overall, the findings confirm that recycled polypropylene is a viable material for additive manufacturing of non-load-bearing components, offering a practical route to reduce plastic waste and support more sustainable polymer processing while maintaining acceptable mechanical and structural performance.

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