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Processability of Recycled Polypropylene for More Sustainable Pellet-Based 3D Printing

Peymani Dorna[1,a*] and Strano Matteo[2,b]

Politecnico di Milano, Dipartimento di Meccanica Via Previati 1/c, Lecco, Italy

[a*]Dorna.peymani@polimi.it, [b]matteo.strano@polimi.it

[*]Corresponding author

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Abstract. This study evaluates the processability of recycled polypropylene (rPP) in pellet-based material extrusion (MEX) to support more sustainable additive manufacturing. Virgin polypropylene (PP) and post-consumer rPP obtained from end-of-life woven builder bags were processed in neat form and as PP/rPP blends with increasing recycled content. Melt-flow behavior was characterized using a Technological Melt Flow Index (TMFI), a process-specific metric reflecting the combined effects of temperature and screw rotation. Disk-shaped specimens were printed to assess deposition behavior through the build-up rate (BUR), which integrates shear flow in the extruder and elongational deformation during deposition. TMFI results show that rPP exhibits markedly higher flowability than virgin PP below 200°C, indicating potential for lower-temperature, energy-efficient processing. In contrast, printing experiments reveal that BUR systematically decreases with increasing rPP content. This trend indicates a transition to an elongation-dominated deposition regime, where rPP displays higher resistance to extensional deformation during deposition, resulting in narrower roads and reduced spreading. Regression analysis confirms that BUR is governed primarily by flow-rate setting (F%) and nozzle speed (Sp%), whereas nozzle temperature Te (°C) has only a minor influence within the investigated window. Overall, the results demonstrate the competing rheological effects introduced by recycling and highlight the need for tailored parameter optimization to enable higher rPP incorporation in pellet-based 3D printing.

Introduction

The widespread use of plastics has grown rapidly in recent decades, driven by their low cost, durability, and versatility across nearly all industrial sectors. However, the accumulation of plastic waste, combined with inefficient collection and disposal practices, has created significant environmental concerns. These challenges have intensified the need for effective recycling strategies that can reduce the environmental impact of plastics while conserving raw materials and energy resources [1]. According to the data, the most often used plastics are polypropylene (PP), low density polyethylene (LDPE), poly (vinyl chloride) (PVC), and high-density polyethylene (HDPE) [2].
Mechanical recycling is commonly carried out for thermoplastic polymers such as PP, poly(ethylene terephthalate) (PET), polyethylene (PE), polystyrene (PS), and PVC [3]. This process first sorts the plastic waste, followed by shredding. Shredding consists of breaking down the part into small pellets, granules, or powder forms. The recycled material is processed to produce the final component through material melting and extrusion. The processing techniques primarily involve extrusion and injection molding [4].
Material extrusion (MEX) is an AM process in which a polymer is selectively dispensed through a heated nozzle and deposited layer by layer to form a three-dimensional object [5]. Recycling thermoplastic waste for MEX may lead to reductions in shear viscosity, molecular weight, and thermal or mechanical properties after one or more cycles of processing [6]; however, some of these effects can be mitigated by appropriately adjusting the process parameters [7]. Degradation during recycling also affects the compatibility of polymer blends [8]. Various combinations of process parameters in MEX lead to different fabrication qualities and mechanical properties. Fused Filament

Fabrication (FFF) and Fused Granular Fabrication (FGF) are among the most common additive manufacturing methods based on material extrusion [9]. Unlike traditional filament-based printing, FGF directly processes polymer pellets, enabling the in-line blending of different materials during the printing operation. This capability allows the production of parts that combine multiple functional properties, such as enhanced strength and improved thermal stability, within a single manufacturing process [10].

Recycled polypropylene (rPP) exhibits distinct processing behavior compared to virgin PP, particularly in its Melt Flow Index (MFI), a widely used indicator of material processability [11]. MFI reflects how polypropylene flows during melting and shaping, directly influencing processing stability and final part quality. Recycled PP typically shows higher MFI than virgin PP due to structural degradation during service life and reprocessing, including reductions in molecular weight and melt viscosity, as well as changes in crystallization and mechanical response. The dominant consequence of recycling is chain scission, which lowers melt viscosity and increases MFI, thereby affecting both processing performance and the properties of printed components. Although shear viscosity (η) and MFI are standard metrics for characterizing polymer melts, the MEX 3D-printing process can be influenced by elongational viscosity [12], a relationship for which limited literature evidence is currently available. Given the higher MFI of rPP compared to virgin PP, one might expect that materials with high recycled content could be processed at lower nozzle temperatures. In practice, however, the printability of rPP is often poor. While insufficient interlayer adhesion contributes to this issue, a more significant factor may be the elevated elongational viscosity of recycled polymers [13].

The present paper aims to demonstrate these effects to advance understanding of the underlying extrusion mechanisms and to support future improvements in the energy efficiency of 3D printing with recycled materials. The paper therefore investigates the flow behavior and processing response of recycled polypropylene (rPP) in comparison with virgin PP under material-extrusion conditions. To this end, the flow behavior of both materials was examined under controlled variations of nozzle temperature and screw speed, and a series of PP/rPP blends was prepared to explore the potential for increasing recycled content while maintaining stable printing performance.

Materials and Equipment

In this work, a virgin random-copolymer polypropylene (PPR 3260, TotalEnergies) was used in pellet form, with a Melt Flow Index (MFI) of 1.8 g/10 min (230°C/2.16 kg, ISO 1133) and a density of 0.902 g/cm³, representative of a standard extrusion-grade material. The recycled random polypropylene (rPP) was supplied by Gamma Meccanica (Bibbiano, Italy) and produced from post-consumer end-of-life woven builder bags. The rPP is available in three different colors: brown, pine (dark green), and light green. This material exhibits a substantially higher MFI, although the specific value was not measured by the supplier. The materials were processed in their neat forms and in controlled blends to assess how increasing rPP content influences melt rheology and printability under MEX conditions.

Both virgin and recycled polypropylene were supplied in pellet form and required drying prior to extrusion, as PP can absorb small amounts of moisture that cause voids, bubbles, surface defects, and reduced mechanical performance. To ensure consistent material quality, all pellets were dried using a rotating-drum dehumidifying dryer (3devo Precision Pellet Dryer), whose continuous stirring ensures uniform heating. Drying was conducted at 80 °C for three hours, effectively removing moisture while avoiding thermal degradation.

All tests were performed using a pellet-extrusion printer (Direct3D F30 Pro), equipped with a dedicated granular screw extruder and a 0.8 mm nozzle. The system employs a Cartesian frame with linear guide rails, enabling stable deposition and precise control of extrusion dynamics. Printing parameters were controlled through the open-source slicing software Super Slicer.

In the slicer software, all G-code files were generated with a nominal transverse printing speed of 20 mm/s. However, this value can be overridden at the start of each print using the Sp% parameter, which increases or decreases the programmed feed rate. The machine firmware (Marlin) then determines the corresponding screw rotational speed (RPM) required to achieve the commanded nozzle speed. The printer software also allows independent adjustment of the screw's reference rotational speed through the flow-rate percentage parameter F%, which proportionally modifies the targeted material throughput. In practice, neither Sp% nor F% can be increased indefinitely, as the extruder is subject to motor torque and power limitations; therefore, the relationship between these parameters and the actual flow-rate is not linear and may reach saturation at high settings. Moreover, at elevated screw speeds, wall slip may occur, meaning the true material flow-rate does not necessarily continue to increase with higher Sp% or F%.

Melt Flow Characterization

The flow behavior of the polypropylene feedstocks was experimentally characterized under processing conditions representative of FGF.
In this study, the term Technological Melt Flow Index (TMFI) denotes a process-specific flow metric obtained directly from the pellet extruder, with the print head held stationary and positioned far above the build plate. Extrusion tests were thus performed by vertically extruding material into air. Unlike the standard MFI defined by ISO 1133 or ASTM D1238—which measures polymer flow under low-shear, fixed-temperature conditions that differ significantly from those in pellet-based extrusion, this metric reflects melt output under the actual thermo-mechanical conditions of the process. The TMFI is calculated by normalizing the extruded mass to the measured extrusion time and reporting the result in g/10 min to facilitate comparison across processing conditions.
The TMFI was computed as:

$$\text{TMFI (g/10 min)} = \frac{\text{Extruded Mass M (g)}}{\text{Extrusion time t (s)}} \times 600 \quad (1)$$

Four polypropylene feedstocks were examined: one virgin PP and three recycled variants distinguished by color (brown, pine, and green). Each material was extruded at three temperatures Te (170, 200, and 230°C) and two screw-rotation speeds RPM (30 and 60 rpm) summarized in (Table 1). For consistency across trials, each extrusion run comprised exactly 50 screw revolutions. Five replicates were produced for every material–temperature–screw-speed combination, resulting in 120 samples in total. Parameter combinations were alternated throughout the testing sequence to minimize systematic effects associated with temperature drift or residence-time variation within the extruder.
After cooling, each extruded strand was weighed, and its TMFI was calculated. The resulting dataset, comprising material type, Te, RPM speed, and flow response TMFI, was analyzed using the statistical software JMP. A standard least squares regression model was built to evaluate the main and interaction effects governing melt-flow behavior.

Table 1. Processing parameters for melt flow characterization of polypropylene feedstocks.

Material	Nozzle temperature (°C)	screw-rotation speeds (rpm)
Virgin PP	170 / 200 / 230	30 / 60
Recycled PP (brown, pine, green)	170 / 200 / 230	30 / 60

3D Printing of specimens with mixtures

To experimentally evaluate the printability of recycled polypropylene (rPP), a series of PP/rPP blends with increasing recycled content were prepared. Starting from a 100% virgin PP baseline, additional mixtures were produced, in which 25%, 35%, and 50% of the total material weight was replaced by recycled PP. The aim was to explore whether higher fractions of recycled material can be incorporated in a sustainable manner while maintaining stable material-extrusion performance. All mixtures were processed into small disk-shaped specimens with nominal dimensions of 28.2 × 28.2 × 0.6 mm (Fig. 1), which were selected as a representative test geometry for systematically probing extrusion behavior.

For each formulation, three printing parameters were varied: nozzle temperature Te (°C), Printing speed factor Sp%, and the imposed flow-rate percentage F%.
The disk-shaped specimens were printed under the conditions reported in Table 2.

Table 2. Printing parameters for disk-shaped specimens.

Parameter	Value
Printing method	FGF
Materials	Virgin PP / rPP blends (100/0, 75/25, 65/35, 50/50)
Nozzle diameter	0.8 mm
Layer thickness	0.3 mm
Nozzle temperature (°C)	164–225
Printing speed factor, Sp%	25–200
Flow-rate percentage, F%	2500–9000

These settings were selected to investigate how thermal input and deposition rate influence the flow behavior and extrusion stability of the blends. During each print, the mass flow-rate (MFR) was recorded as the primary output variable, serving as an operational analogue to melt-flow index under processing-relevant conditions, while the resulting deposition behavior was subsequently quantified through the build-up rate (BUR).
The MFR data were analyzed to quantify the sensitivity of flow behavior to changes in temperature, flow-rate setting, speed and blend composition.

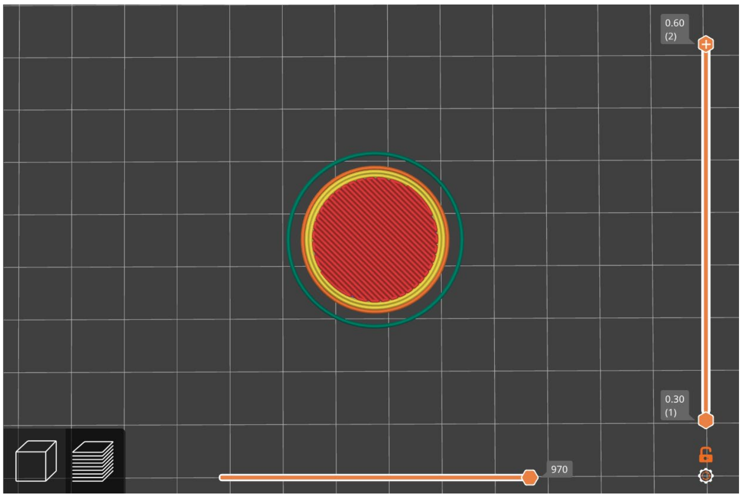

Fig. 1. Disk-shaped specimen geometry used in the 3D-printing experiments.

Results and Discussion

Thermo-Mechanical Effects on Melt Flow Behavior.

A clear distinction is observed between virgin PP and the rPP feedstocks across the investigated processing window (Fig. 2). At low nozzle temperatures, particularly at 170°C, virgin PP exhibits markedly reduced flowability, resulting in substantially lower TMFI values compared to all recycled materials. In contrast, the rPP streams maintain moderate mass flow under the same conditions, reflecting their intrinsically lower melt viscosity. This behavior is consistent with the reduction in molecular weight typically associated with mechanically recycled polypropylene, arising from chain scission during service life and reprocessing.
As nozzle temperature and screw rotational speed increase, the flow response of the materials diverges significantly. At low shear rates, polymer chains remain in a highly entangled configuration, leading to elevated viscosity and limited flow. With increasing thermal and mechanical input, the

polymer chains experience enhanced deformation, promoting disentanglement and alignment along the flow direction, which in turn reduces the effective viscosity of the melt.
Under aggressive processing conditions (230°C and 60 RPM), virgin PP undergoes a pronounced increase in TMFI, ultimately exceeding the flow-rates of all recycled variants. This crossover behavior indicates a stronger sensitivity of virgin PP to the combined effects of temperature and shear, suggesting a dominant shear-thinning response at elevated shear rates. In contrast, the recycled materials exhibit a more gradual and near-linear increase in TMFI with increasing temperature and rotational speed, pointing to a more constrained rheological response.
The statistical analysis of the TMFI dataset confirms a strong and systematic dependence of melt flow behavior on material type, nozzle temperature, and screw rotational speed. The regression model demonstrates an excellent overall fit ($R^2 = 0.91$), indicating that the selected processing parameters successfully capture the dominant mechanisms governing mass flow during pellet-based extrusion. Diagnostic evaluation confirmed the robustness of the model, with no evidence of significant outliers or systematic deviations.

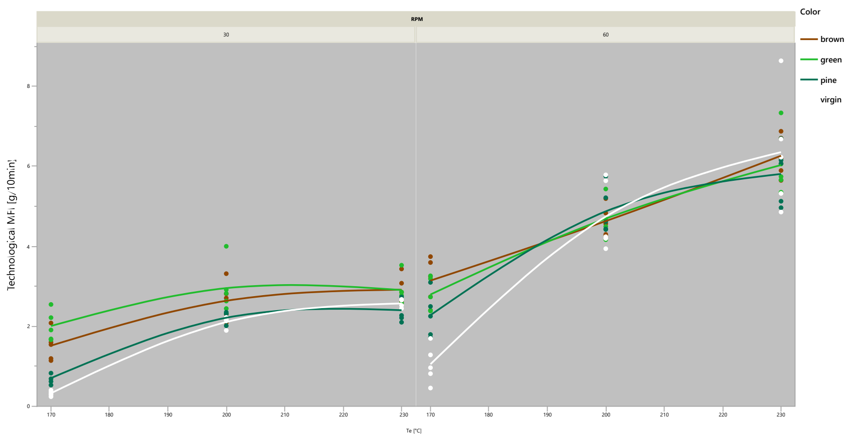

Fig. 2. TMFI response of virgin and recycled polypropylene as a function of Te (°C) and RPM.

The regression analysis further highlights the significant interaction between Te (°C) and RPM. Temperature increments exert a substantially greater influence on TMFI when the extruder operates at higher rotational speeds, whereas at lower speeds the same temperature increase produces a comparatively modest effect. This interaction reflects the coupling between thermal softening and mechanically induced shear, which together governs the effective viscosity of the melt during extrusion.
While quantitative differences in TMFI are observed among the brown, pine, and green recycled PP streams, their overall flow responses follow similar trends, indicating that processing conditions exert a stronger influence on melt flow behavior than feedstock-specific variations within the investigated range.
At higher screw speed of 60 RPM, this ordering is no longer systematically preserved across the investigated temperature range. Under increased shear input, virgin polypropylene exhibits a more pronounced shear-thinning behavior, resulting in a rapid decrease in melt viscosity and a corresponding increase in TMFI. Consequently, the blend does not necessarily maintain an intermediate melt flow response at elevated screw speeds, highlighting the strong process dependence of melt flow behavior in polypropylene systems.
In conclusion, according to the TMFI data, the rPP should allow significantly higher flow-rate if printing below 200 °C, potentially allowing energy efficiency improvements over the virgin counterpart.

Results of 3D Printed Specimens with Mixtures

The fabrication of disk-shaped specimens enabled evaluation of melt-flow behavior under deposition-dominated MEX conditions. In this regime, the polymer flow response is determined not only by shear deformation within the extruder but also by the elongational stretching and spreading of the

melt during deposition. Accordingly, the measured BUR represents an effective mass-flow metric that integrates the melt's rheological characteristics with the deformation imposed during printing.
Regression analysis of the experimental dataset shows that BUR is primarily controlled by the imposed flow-rate percentage F% and the nozzle travel speed Sp%, while the influence of nozzle temperature Te (°C) is comparatively weak within the investigated processing window.
A key observation is the systematic decrease in BUR as the recycled polypropylene content increases (Fig. 3). This trend contrasts with the shear-dominated behavior seen in TMFI measurements and indicates a shift toward an elongation-dominated flow regime during deposition. As the melt exits the nozzle, it undergoes significant elongational deformation driven by nozzle motion. Despite its lower shear viscosity, recycled polypropylene appears to resist elongational flow more strongly, producing narrower extruded roads, reduced lateral spreading, and consequently a lower mass build-up rate.

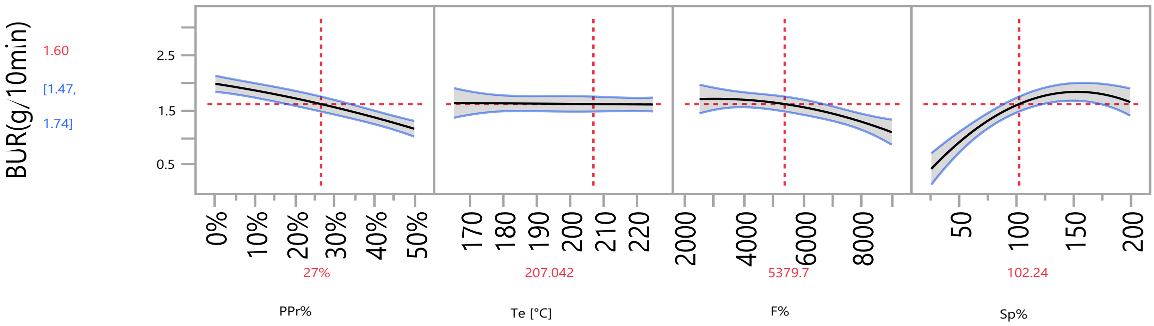

Fig. 3. Effect of recycled polypropylene content and processing parameters on the BUR.

Across the examined temperature range, Te (°C) exerts only a minor influence on BUR, confirming that all materials were processed under fully molten conditions in which temperature is not the dominant governing variable. Instead, extrusion behavior is dictated by the combined effects of deposition kinematics and the material's elongational rheology.

Summary

This work investigated the thermo-rheological behavior and 3D-printing performance of virgin and recycled polypropylene under pellet-based material extrusion. TMFI measurements showed that recycled polypropylene (rPP) exhibits substantially lower shear viscosity and higher mass-flow capability than virgin PP at temperatures below 200 °C, indicating potential for reducing nozzle temperature and associated energy consumption. Under high thermal and shear inputs, however, virgin PP displays a stronger shear-thinning response, ultimately exceeding the flowability of all recycled variants.
In contrast, 3D-printing experiments revealed an opposing trend: increasing recycled content leads to a systematic decrease in build-up rate (BUR). This behavior demonstrates that deposition dynamics in material extrusion are not governed solely by shear viscosity, as reflected by TMFI, but are strongly influenced by elongational rheology during deposition. Despite its higher melt-flow index, recycled polypropylene exhibits greater resistance to elongational deformation, resulting in reduced lateral spreading, narrower extruded roads, and consequently a lower effective BUR.
Across the investigated processing window, nozzle temperature was found to have only a minor influence on BUR, confirming that all materials were processed under fully molten conditions and that deposition kinematics, together with elongational flow behavior, dominate the printing response.
Overall, the results indicate that:
1. Recycled polypropylene can enhance shear-driven flow behavior and enable lower-temperature processing in pellet-based extrusion.
2. The same recycled content can hinder deposition performance by increasing elongational resistance, reducing build-up rate, and narrowing the stable processing window.
3. Sustainable integration of rPP in material extrusion requires balancing these competing effects through optimized control of screw speed, flow-rate setting, and printing kinematics.

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