MECHANICAL PROPERTIES OF RECYCLED POLYMER WASTE-BASED COMPOSITES WITH A POLYPROPYLENE COPOLYMER MATRIX

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This study examines the valorization of polymer waste from automotive scrapyards by blending it with a polypropylene copolymer (PPC) to promote circular economy practices. Recycled waste, incorporated at 30 wt%, was tested as unsorted raw fractions and selectively recovered materials obtained by flotation. Mechanical testing showed that selective recovery markedly improves tensile strength, impact resistance, and ductility—up to 200%—compared to raw waste. SEM analyses revealed enhanced interfacial compatibility and fracture morphology. The results demonstrate the potential of integrating recycled polymers into PPC matrices for sustainable, high-performance composite materials.

Keywords: recycling polymers, polypropylene copolymer, FTIR, mechanical strength, ductility.

1. Introduction

The management of end-of-life vehicles (ELVs) poses a significant environmental challenge due to the accumulation of non-biodegradable polymeric waste in open-air automotive scrapyards. These plastic residues, originating from various vehicle components, contribute to long-term pollution and emphasize the urgent need for sustainable waste recovery strategies. One promising approach is to reintegrate such materials into the manufacturing cycle through recycling, thereby reducing dependence on fossil-based raw materials and minimizing greenhouse gas emissions.

According to the European Directive 2000/53/EC, 95% of an ELV's mass should be reused or recovered by 2015. However, Schmid et al. [1] demonstrated that this objective was overly ambitious, as the recovery rate reached only 82% by 2013.

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Several studies have investigated the reuse of automotive polymer waste through energy recovery [2], polymer blending [3], and pyrolysis [4–6], yielding valuable fuels and chemical compounds.

Polymeric components such as tires, dashboards, and automotive shredder residues (ASR) have been subjected to both chemical and mechanical recycling. Ramarad et al. [3] and Tian et al. [5] emphasized the influence of waste morphology and interfacial compatibility on the mechanical performance of recycled blends. Vi Kie Soo et al. [4] highlighted the environmental impact of increasing plastic usage in vehicles, rising from 88.45 kg in 1980 to 171.46 kg in 2010, and underscored the necessity of integrating recyclability considerations during product design. Their research also demonstrated that improvements in CO_2 emission reduction are possible through delayed environmental impacts caused by polymeric waste. This further supports the importance of considering material selection and assembly methods to enhance recyclability and comply with legislation targeting ELV waste minimization. The recycling of a luxury vehicle dashboard was studied by Jin Tian et al. [5], who identified a multilayer structure: an outer PVC skin, a polyurethane foam core, and a structural frame composed of a blend of ABS, PP, and PA. Pyrolysis of this composite produced gases such as methane, ethane, ethylene, and propane, which can be recovered as fuels. De Marco et al. [6] focused on the pyrolysis of ASR, while Vermeulen et al. [7] demonstrated that, after upgrading 75% of a vehicle via conventional methods, the remaining 25% could be valorized through pyrolysis and thermo-mechanical transformation.

Bajracharya et al. [8] examined solid plastic waste recovery, which constitutes approximately 16% of municipal waste in Australia, with only a quarter being recycled. Their mechanical characterization of HDPE, HLDPE, and PP fractions showed that the properties of these recycled materials are approximately 90% of those of virgin polymers, and comparable to those of natural wood used in construction. Zheng et al. [9] explored the reuse of non-ferrous scraps from printed circuit boards (PCBs) as reinforcing fillers in a polypropylene matrix. Their mechanical tests indicated increased strength and thermal resistance, with up to 30% filler content remaining within environmental safety limits. Sabin-Chiarilli et al. [10] investigated the ductile-to-brittle transition in ELV-derived polymer blends composed of polypropylene and minor polyamide impurities. They found that polyamide content below 5% by volume did not compromise tensile properties, while higher levels led to embrittlement. Sacchi et al. [11] studied iPP/PA6.6 blends using recycled polyamide fibers, highlighting morphological evolution. Meanwhile, Hermanová et al. [12] analyzed the thermo-oxidative degradation of impact polypropylene copolymers under multiple extrusion cycles, with degradation observed mainly in the homopolymer phase. Sanchez et al. [13] examined the aging behavior of PC/PBT blends used in the automotive sector, demonstrating good post-recycling ductility and stable modulus and tensile strength. Although impact resistance decreased, partial recovery was observed upon recycling.

Recent advances have enhanced the recovery of recycled polypropylene (rPP) using compatibilizers, hybrid reinforcements, and optimized processing. C. B. Barreto Luna et al. [14] showed recycled copolymer PP can reach properties close to virgin PP, while Hoque et al. [15] demonstrated that jute fiber-reinforced PP maintains improved mechanical performance. Blends with fillers like oxidized polyethylene [16] and fiber-reinforced rPP with short glass [17] or carbon fibers [18] exhibit better dispersion, stiffness, and tensile properties for lightweight applications. Chen et al. [19] highlighted chemical and biological recycling methods, emphasizing hybrid strategies to close the polymer life cycle.

The present study aims to recycle polymer waste collected from open-air automotive scrapyards and reintegrate it into the raw materials cycle. The process involves blending these wastes with a polypropylene copolymer (PPC) matrix. Two types of waste were collected: a bulk (unsorted) sample and a selectively sorted sample obtained through flotation. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify functional groups in neat PPC and in the PPC/waste composites. Differential Scanning Calorimetry (DSC) was conducted at a heating rate of 2 °C/min to assess melting behavior in the various blends. Mechanical performance was evaluated through tensile testing to obtain stress-strain curves, from which Young's modulus, maximum stress, and elongation at break were derived. Impact resistance was assessed through Charpy testing. Fracture surface morphology was examined via Scanning Electron Microscopy (SEM). A comparative analysis was carried out to determine the effects of waste sorting on the microstructure and mechanical properties of the resulting composites.

2. Materials and Methods

2.1. Materials

Polymeric waste was sourced from open-air automotive scrapyards. Two different batches were considered in this study :

The first batch (bulk waste) consisted of unsorted components, namely two fenders (one black and one white), a mudguard, and interior door trims.

The second batch (sorted waste) was selected through a simple flotation test in water, allowing the recovery of parts with a density lower than 1 g/cm^3. Only the interior door trim floated, indicating its compatibility with polyolefin matrices such as polypropylene.

The matrix material used was a polypropylene copolymer (PPC), chosen for its prevalence in automotive applications, where it constitutes over 40% of polymer components.

2.2. Waste Preparation and Composite Formulation

All collected waste was initially washed thoroughly to remove contaminants and residues. The cleaned materials were then mechanically ground to obtain homogeneous granules suitable for compounding. The ground waste was incorporated into the PPC matrix with 30% at weight. Blending was performed in two successive stages:

Cold mixing: carried out using an electric rotary mixer to ensure preliminary dispersion and homogenization of the polymer constituents. Hot processing: performed by extrusion, yielding rods of the composite materials. These extrudates were then re-ground into uniform granules for subsequent processing. We considered two lots. The first bulk batch consisted of two fenders in black and white, a mudguard and the interior trim of the doors. The second batch is made up of waste sorted and selected by a simple flotation test (Fig. 1), in which only the interior door trim floated, due to its lower density than water.

2.3. Characterization Techniques

The produced materials were characterized by using a combination of thermal, spectroscopic, mechanical, and morphological analyses. The melt flow index (MFI) was measured to evaluate the flow behavior and processability of the composite blends. Differential Scanning Calorimetry (DSC) was employed to assess thermal transitions, including melting temperatures and crystallinity variations induced by waste incorporation. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify the main functional groups and detect potential chemical interactions between the PPC matrix and the incorporated waste. Mechanical characterization included tensile testing to determine the Young’s modulus, ultimate tensile strength, and elongation at break, as well as Charpy impact testing to evaluate the impact resistance of the materials. Tensile tests were carried out on a Zwick Roell machine according to NF EN ISO 527-2, with specimens shaped as shown in Fig. 2.a and a crosshead speed of 5 mm/min. Up to five tests were performed to ensure reproducibility, yielding standard deviations below 2% for elongation at break, 7% for tensile strength, and 3.7% for the elastic modulus (relative to the maximum value). Fracture surfaces of selected specimens were then examined by Scanning Electron Microscopy (SEM) in LowVac mode using a Philips ESEM XL30 to evaluate microstructural features and their influence on the mechanical performance of the composites.

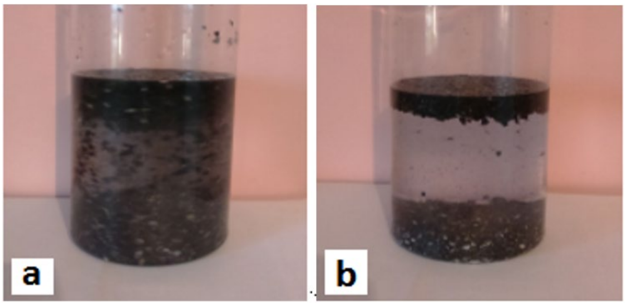

Fig. 1 : Flotation test (a) before settling, (b) after settling.

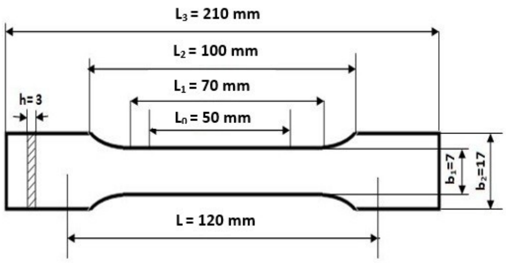

Fig. 2.a : Shape and dimensions of tensile specimens (NF EN 527-2).

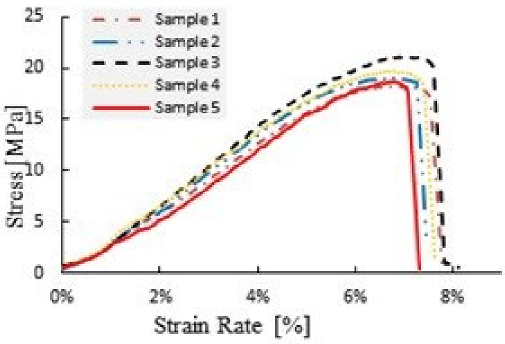

Fig. 2.b : Reproducibility of tensile tests and typical result, case of the PP-30% Bulk Waste.

3. Results and discussion

The calculation of the fluidity index of our materials, determined using a plastometer in accordance with EN/ISO1133-2.2011, shows that the addition of sorted and selected waste reduces this index from 76.98 g/10mn for the PPC matrix (100%) to 59.04 g/10mn for the composite containing 30% of this waste. We have found that bulk waste mixtures are not suitable for this test, due to the inclusion of constituents with high melting temperatures, and that they do not melt during the test (at a pre-set 230°C). To identify these non-melting components, we carried out analysis using Fourier-IR spectroscopy and DSC.

Figure 3 shows the superimposed FTIR spectra of the materials produced. The spectrum of the PPC used shows that it is indeed polypropylene, whose main absorption bands are given in Table 1. The absorption bands recorded for the 30% raw waste composite reveal the presence of an amide and a sulfone, whose main functional groups are listed in Tables 2 and 3 respectively. For the sorted and selected waste, we found a similarity in the spectra with the presence of an absorption peak at 1638 cm-1 attributed to the C=O group, most likely due to the presence of a small amount of polyamide.

Figure 4 presents the overlaid Differential Scanning Calorimetry (DSC) thermograms of virgin PPC, PPC/Selected Waste, and PPC/Bulk Waste composites, all containing 30 wt% of waste. The measurements were performed up to 400 °C at a heating rate of 2 °C/min under inert atmosphere. All three samples exhibit a primary endothermic peak around 166 °C, corresponding to the melting point of the polypropylene matrix, indicating that the addition of polymer waste did not significantly affect the melting temperature. The onset of thermal degradation occurs at different temperatures depending on the composition. Virgin PPC begins to degrade at approximately 220 °C and completes degradation around 240 °C. The PPC/Selected Waste blend shows an earlier degradation onset at 205 °C, while the degradation ends at the same temperature as virgin PPC (240 °C).

The PPC/Bulk Waste composite exhibits a delayed degradation onset at 225 °C, with complete degradation occurring at a significantly higher temperature of 290 °C.

Despite the similar final degradation temperature between virgin PPC and PPC/Selected Waste, the heat flow values associated with degradation differ markedly. Virgin PPC displays an exothermic peak of 28 mW, whereas the PPC/Selected Waste blend shows a lower degradation of energy of 18 mW, indicating a reduced energy demand for breaking polymer chains—likely due to molecular aging and environmental degradation (e.g., UV exposure, thermal cycling) of the selected waste.

These findings are supported by Figure 3, which shows the superimposed FTIR spectra of PPC and PPC/Selected Waste. The spectra confirms that the selected waste is composed predominantly of polypropylene, though altered by aging phenomena. In contrast, the PPC/Bulk Waste blend exhibits a more intense exothermic peak (55 mW) at 290 °C, suggesting the presence of higher melting point polymers, such as polyamides. This is corroborated by the FTIR analysis shown in Figure 2, which highlights several characteristic absorption bands:

A broad N–H stretching band around 3294 cm^{-1}.

An N–H bending vibration at 1537 cm^{-1}.

A prominent C=O stretching band at 1636 cm^{-1}.

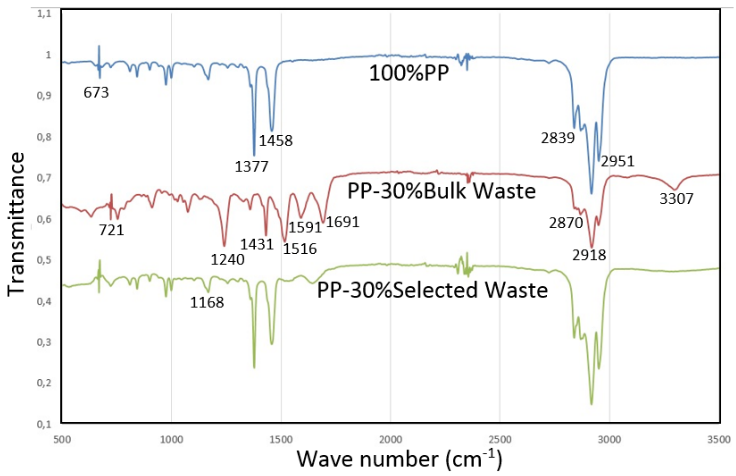

Fig. 3 : FTIR Spectra of virgin PP, PP-30% Bulk Waste and PP-30% Selected Waste

These spectral features are consistent with the presence of polyamide structures, specifically polyamide PA46, whose repeating unit chemical structure is presented below.

$$(-\underset{H}{\underset{|}{N}}-(CH_2)_4-\underset{H}{\underset{|}{N}}-\underset{O}{\underset{\|}{C}}-(CH_2)_4-\underset{O}{\underset{\|}{C}}-)_n$$

Table 1

Polypropylene's main infrared absorption bands

Vibration frequency (cm^{-1})	Assignment
2951	CH3 Asymetrical elongation
2918	CH2 Asymetrical elongation
2839	CH3 Symetrical elongation
1456	CH2 Shear
1377	CH3 Symetrical deformation
1167	CH3 Rocking

Table 2

An amide main infrared absorption bands

Vibration frequency (cm^{-1})	Assignment
3294	NH stretching
1636	C=O
1537	N-H Deformation
1186-1067	C-N Stretching

Table 3

A sulfone main infrared absorption bands

Vibration frequency (cm^{-1})	Assignment
1020	S=O
1304-1377	SO2
690	C-S stretching

This PA46 is widely used in the automotive industry, with a melting temperature of 294°C close to the degradation temperature of the PPC/bulk waste mixture.

The melt flow index (MFI) values and melting temperatures obtained from the preliminary thermal analyses confirmed the suitability of injection molding for specimen fabrication. Based on these results, the processing parameters of the injection molding machine were optimized accordingly, as summarized in Table 4.

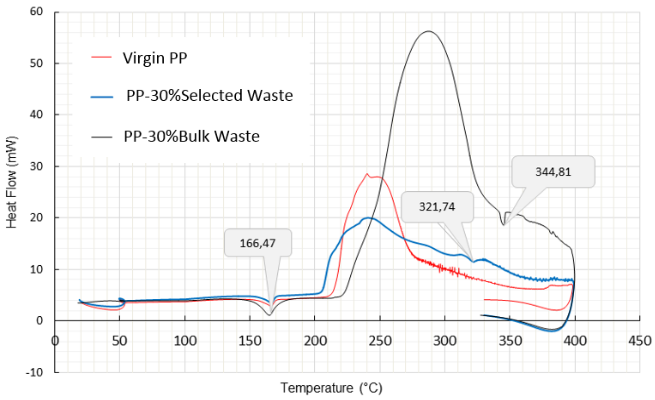

Fig. 4 : DSC Analysis of virgin PP, PP-30% Bulk Waste and PP-30% Selected Waste.

Table 4

Parameters used for the injection of our materials

Temperatures			
Feeding	Plasticizing	Pumping	Die
165°C	180°C	190°C	200°C
Pressures			
Injection	Holding	Back-pressure	
100 Bar	80 Bar	16 Bar	
Time			

Table 5

Mechanical properties obtained for virgin PPC and composites contained 30% of Bulk Waste and Selected Waste.

Characteristic	Virgin PPC	PPC-30%Bulk Waste	PPC-30%Selected Waste
Elasticity modulus (MPa)	879	840	673
Elongation at break (%)	20.95	7.44	66.65
Stress (MPa)	25	18	24
σ/σmax (%)	100	71.31	93.57
ε/εmax (%)	100	35.51	318
Resilience (kJ/m^2)	8.25	3.98	10.81

Table 5 summarizes the main mechanical characteristics of PPC and composites with 30% bulk and selected waste.

At first glance, we can see that the elongation at break of the composite containing 30% selected waste has increased to 68%, whereas it is 21% for virgin PPC, while the stress only decreases by 1 MPa (from 25 to 24 MPa). The fracture stress ratios σ/σmax, despite the fact that they decrease with the addition of recycled waste, up to 71.31% and 93.57%, respectively for raw and selected waste, show that composites based on selected waste exhibit better mechanical behavior. In this case, the relative deformation ratio ε/εmax increases up to 318% even though the modulus of elasticity decreases to 673 MPa (by almost 200 MPa). This increase in relative deformation at break is also reflected in an increase in impact strength, which rises from 8.25 kJ/m^2 for virgin PPC to 10.81 kJ/m^2 for the composite with 30% selected waste. These changes in mechanical properties give an indication of the significance of the results obtained, and suggest that composite materials made from recycled waste are suitable for a number of industrial applications.

In order to demonstrate the manifestation of these characteristics during the deformation of our materials, the fracture surface of the most representative specimens was observed using an Environmental Scanning Electron microscope (ESEM) using Secondary Electron mode (Fig. 5).

Fractographic analysis of tensile specimens revealed distinct fracture behaviors depending on the type of waste incorporated. Blends containing bulk (unsorted) waste exhibited a predominantly brittle fracture mode, characterized by smooth, flat surfaces and limited plastic deformation. In contrast, specimens incorporating sorted and selected waste showed a ductile fracture behavior, evidenced by rougher fracture surfaces, fibrillation, and pronounced necking—indicative of higher energy absorption and improved deformability.

6. Conclusions

In this study, we investigated the recovery of polymeric waste derived from automotive scrapyards. Given that more than 40% of a vehicle's polymeric components consist of polypropylene, the waste was incorporated into a polypropylene copolymer (PPC) matrix at a fixed proportion of 30 wt%. Two strategies were evaluated: one using unsorted (bulk) waste, and the other employing waste sorted by a flotation-based selection method.

The results demonstrate that the proposed recycling approach is effective. In particular, the incorporation of sorted and selected waste into the PPC matrix led to a remarkable improvement in mechanical performance. Compared to virgin PPC, the PPC/selected waste composite showed an increase in elongation at break exceeding 200% and an enhancement in impact resistance by more than 30%, without any significant deterioration in Young's modulus or yield stress.

These findings indicate that the recovered composites can match or even outperform virgin PPC in certain mechanical aspects, highlighting the technical and environmental relevance of this recovery strategy. Fractographic analysis of tensile specimens revealed distinct fracture behaviors depending on the type of waste incorporated. Blends containing bulk (unsorted) waste exhibited a predominantly brittle fracture mode, characterized by smooth, flat surfaces and limited plastic deformation. In contrast, specimens incorporating sorted and selected waste showed a ductile fracture behavior, evidenced by rougher fracture surfaces, fibrillation, and pronounced necking—indicative of higher energy absorption and improved deformability.

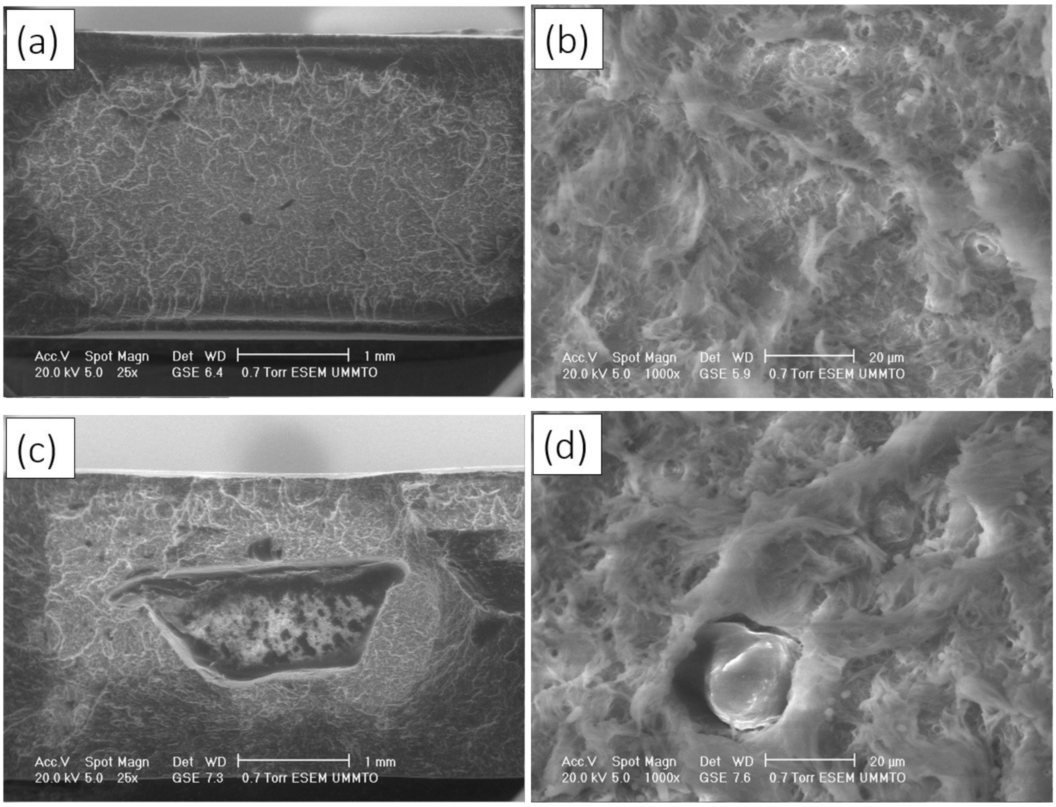

Fig. 5 : SEM micrographs of the fractured surfaces : (a) general view of 100%PP sample and (b) magnified view highlighting material tear-outs, (c) general view of PP-30%Bulk Waste sample and (d) zone including inclusion in PP-30%Bulk Waste.

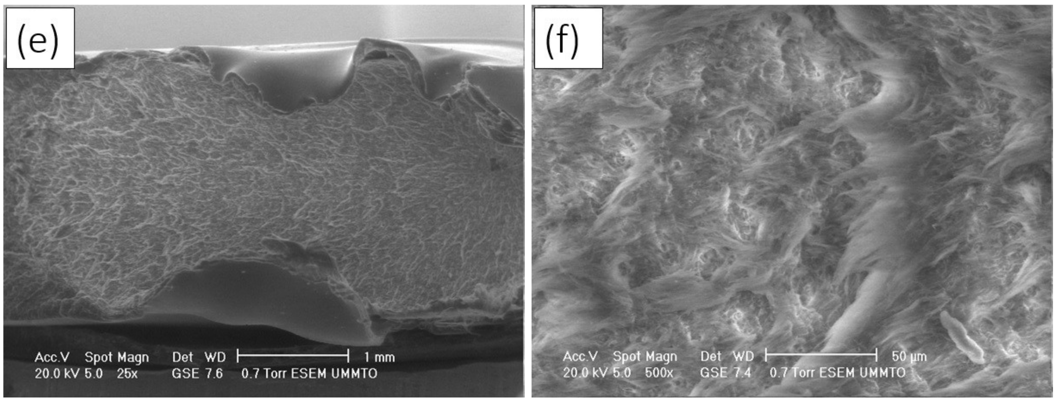

Fig. 5 (continued) : SEM micrographs of the fractured surfaces : (e) general view of PP-30% Selected Waste sample and (f) close-up of a zone showing material tear-outs.

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