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Recycling of Polypropylene Recovered from a Composting Plant: Mechanical Behavior of Compounds with Virgin Plastic

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Abstract: The recycling of polypropylene recovered from waste discarded by a composting plant was investigated. The recovery involved a sorting step carried out by means of an optical infrared separator and a subsequent washing treatment. This method of processing allowed us to obtain polypropylene that was only slightly contaminated by other polymeric and inorganic materials. As many tens of tons of polypropylene could be recovered every year in this plant, recycling could be convenient from the economic point of view and beneficial for the protection of the environment. In fact, the landfill of this waste could be reduced in this manner. A possible mechanical recycling route was developed for the recovered plastic. The recycling was carried out by pelletizing the recovered polypropylene, mixing it with a commercial polypropylene feedstock, and manufacturing items by injection molding. In this way, tensile specimens containing different amounts of recycled polypropylene were processed and tested. Their tensile features were compared with those of a commercial polypropylene that was used as a reference. The elastic modulus and tensile strength were slightly worsened when using the recycled plastic, while the strain at failure significantly increased. Nonetheless, the tensile properties of compounds made by mixing recycled and virgin polypropylene were consistent with the characteristics that are expected for polypropylene-based plastics.

Keywords: recycling; polypropylene; waste; composting plant; tensile properties

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1. Introduction

The generation of plastic waste has been constantly increasing in recent decades all over the world because of the increasing use of this kind of material for the industrial production of goods and for packaging. It has been estimated that about 380 million tons of plastics are produced every year and that more than 60% of municipal solid waste is composed of polyolefins, but less than 20% of the plastics produced are presently recycled at the end of their life [1]. The disposal of plastic waste is nowadays considered a key issue that must be faced, with the aim of preventing environmental contamination and climate change, as well as protecting human health from the effect of pollutants, global warming, and soil/water contamination [2,3]. For these reasons, the re-use, recovery, and recycling of plastic is considered essential.

According to the principle of the circular economy, efforts must be spent to progressively reduce the amount of plastic waste introduced into the environment with the objective of the society of the future granting zero plastic waste landfilling and possibly zero waste cities. The recovery and recycling of plastics can be more or less difficult depending on which kind of waste has to be treated, such as industrial scraps, end-of-life

components, and urban waste. Several recycling strategies and related technologies are available today [1,4–6].

The mechanical recycling of industrial scraps, that is the re-introduction of scraps of a single polymer into the production cycle of plastic pellets, is a well-assessed and widely adopted practice. Pellets, flakes, and powders can also be obtained by processing end-of-life plastic components and then used for producing new plastic goods [4,5,7–10]. However, the degradation of plastic components caused by the action of heat, UV radiation, moisture, and contact with other substances worsens the plastic's material characteristics. For these reasons, these recovered plastics are generally used by compounding them with virgin materials [4,8,10].

The recovery of plastics from urban waste is still very challenging [10] because municipal solid waste consists of a mixture of very different components (organic matters, glass, metals, plastics, paper). Separate collection programs that are currently adopted in several countries promote waste recycling. In particular, the separate collection system at the curbside level greatly favors plastic recycling, as the citizens are obliged to separate plastic goods (like bottles) from other waste and place them into specific containers [11]. In this manner, mixtures of plastic waste are recovered. Several technologies are nowadays available for sorting this municipal solid waste (MSW) made of mixed plastics [12]. The same kind of automated sorting methods can also be exploited to recover plastic from mixed waste in central facilities, which are set up for the treatment of MSW where separate collection is not adopted.

Nonetheless, residual or mixed MSW that contains significant quantities of plastics (from 7 to 35% [13]) is collected in many countries. This kind of waste is landfilled or, in the best case, sent to mechanical and biological treatment (MBT) plants for the production of refuse-derived fuel (also called solid recovered fuel) that can be used for energy recovery, stabilized organic waste, and scraps/residues that are disposed in landfills [13]. Unfortunately, some energy recovery processes, like incineration, also have a negative impact on the environment due to the production of air pollutants (CO_x, NO_x, SO_x) and the promotion of the greenhouse effect. The recycling of urban plastic waste can also involve incorporation into bitumen, asphalt mixtures, and concrete [14,15].

In the case of the separate collection approach, an organic fraction of the municipal solid waste (OFMSW) can be valorized by aerobic decomposition in composting plants. A waste fraction containing significant amounts of plastics, in this case, is also discarded and sent to landfills. In principle, plastics should be recovered from the discarded fractions of several treatment plants of municipal waste (MBT, composting plants) as, according to the circular economy model, materials should be recovered from all waste and recycled. In this manner, the amount of plastic waste introduced to the environment should be dramatically lowered or even cancelled. The sorting of plastics from the waste fractions rejected by MBT units or composting plants is very challenging as these waste fractions are very heterogeneous, containing organic components, metals, and polymers mixed with plastic fillers and additives [16]. On the other hand, plastics, in particular polyethylene (PE) and polypropylene (PP), represent a non-negligible fraction of this rejected waste [16].

As mentioned above, several technologies can be used for the recovery of materials from complex mixtures of waste [12]. Automated techniques that exploit some material properties can be utilized; for instance, electric or magnetic properties can be exploited for the separation of metals while flotation or air jets can separate light materials like plastics. These processes are classified as "direct sorting methods", while "indirect sorting methods" employ sensors to detect the presence of recyclables in the waste [12]. Plastics can be recovered by using Laser-Induced Breakdown Spectroscopy, X-ray Fluorescence, or Spectral Reflectance. In this last case, as a specific set of wavelengths of light is reflected by each kind of plastic, sensors (near infrared, middle infrared, Raman) make it possible to identify the kind of plastic; meanwhile, an air jet is used to eject each plastic into its bin. Near infrared range radiation has proven to be very effective for recovering polyethylene and polypropylene from mixed waste [12].

Some of the literature deals with the recyclability of polyolefins [17] and some reports are focused on the use of recycled polypropylene in plastic compounding [8,10]. However, as far as we know, the recovery and recycling of polyolefins from the waste rejected by MBT plants has not been well investigated until now, even though this waste shows potential for the recycling of its components [18]. In this work, the recovery and recycling of PP from a waste fraction rejected by a composting unit has been investigated. The identification and recovery of PP was performed by using reflectance of infrared radiation. The recovered material was then washed and dried, characterized, and finally used for producing compounds with commercial PP. Samples with various concentrations of recycled PP were processed by injection molding and their mechanical features were investigated.

2. Results and Discussion

2.1. Comparison between the Characteristics of the Recovered PP Fraction and a Commercial PP

The polypropylene plastic fraction was sorted from waste rejected by the GAIA composting plant. It was assessed that this waste was a mixture of several polymers (mainly polyethylene, polypropylene, polyethylene therephthalate, polybutylene therephthalate, polyurethane, polyamide, and acrylonitrile-butadiene-styrene), other organic and inorganic components, and water. The NIR separator allowed us to recover a fraction mainly constituted by PP from this complex mixture. However, this recovered sample still contained important quantities of organic and inorganic contaminants, like polyethylene terephthalate, dirt, talc (about 30 wt. %), and humidity (about 13 wt. %). This was due to the fact that water and contaminants formed a slurry that adhered to the surface of the plastic fragments. For this reason, it was necessary to wash the plastic sorted by the NIR separator to take off the contaminants and make the material suitable for recycling. On the basis of the amount of the cleaned PP which resulted from the washing step, it can be estimated that a non-negligible amount of PP could be recovered using the method investigated in this paper. Actually, about 53 tons of PP could be recovered every year from the GAIA composting plant, which was designed to treat about 90,000 tons of waste. Much more important quantities of PP (as well as of other polymers) could be taken back and destined for recycling in the context of the global scenario of existing composting plants. Avoiding leaving this waste in the landfill, which is the current practice, would be advantageous for the environment and human health.

In the following, a comparison between the characteristics of the PP recovered according to the investigated route and those of commercial Moplen HP456H (a homopolymer produced by LyondellBasell Industries) is presented. Several kinds of analyses (XRD, TGA, FTIR, and DSC) were adopted to investigate the purity of the recovered PP and compare it with that of commercial PP. In Figure 1, the XRD patterns of these two materials are compared. Most of the diffraction peaks in these two spectra can be attributed to monoclinic polypropylene. In fact, according to the ICDD database-card 00-050-2397, monoclinic PP shows diffraction peaks placed at 14.19° (110), 17.05° (040), 18.65° (130), 21.36° (111), 21.88° (−131), 25.70° (060), and 43.19° (−123). The peak showing a maximum at about 21.88° is rather broad, and it likely results from the overlapping of several signals; it should be noted that the (111) peak of PP is placed at 21.36° and that high-density polyethylene gives its (110) peak at 21.6°. A strong peak placed at 16° can also be distinguished, but not ascribed to PP. This peak is stronger in the spectrum of commercial PP and could be due to another component of this product. Some additional diffraction peaks in the spectrum of the recovered PP can be tentatively attributed to inorganic contaminants like talc, silica, and calcium carbonate (Figure 1). Moreover, talc is frequently used as a filler in commercial products based on PP.

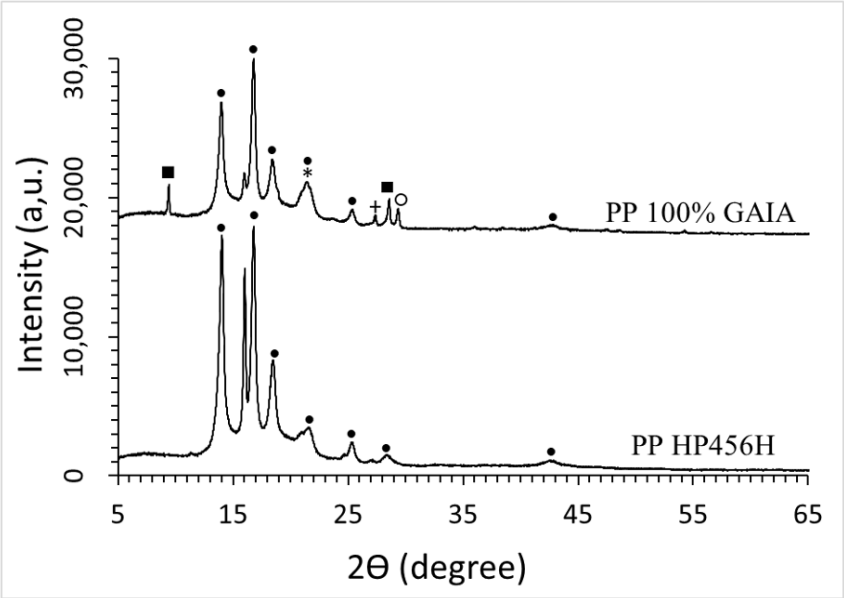


Figure 1. XRD: o = $CaCO_3$, ■ = $Mg_3Si_4O_{10}(OH)_2$, + = SiO_2, * = HDPE, ● = PP.

The TGA curve of the recovered PP and the relevant derivative curve, depicted in Figure 2 alongside those of the commercial PP, are consistent with TGA analyses reported in the literature for polypropylene [19]; the literature also reported small modifications of TGA curves resulting from reprocessing [20,21].

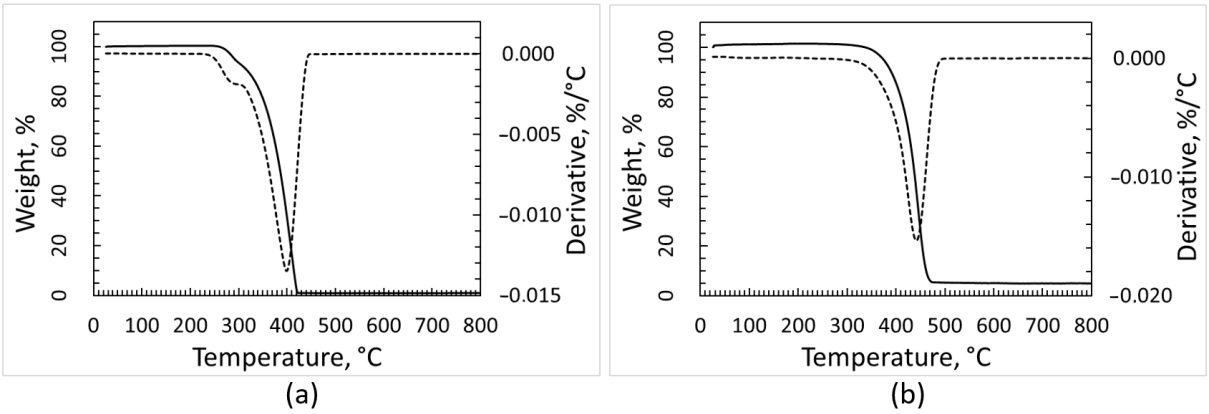


Figure 2. TGA (continuous line) and DTGA (dotted line) curves: commercial PP HP456H (**a**), PP recovered from GAIA waste (**b**).

The TGA analysis also strengthens the hypothesis that the recovered PP contains inorganic contaminants that cannot burn during the temperature scan under an oxidative environment. In fact, the residue left at the end of the analysis was close to zero in the case of commercial PP (Figure 2a), while a solid residue representing the 5 wt. % of the initial sample was left by the recovered PP at the end of the temperature scan (Figure 2b). In addition, some differences can be noticed in the trend of the curves belonging to the commercial and recycled PP. The recovered PP showed a progressive weight loss during the temperature scan with a maximum oxidation rate just below 445 °C, while the TGA curve of the commercial PP is more structured. In this last case, the oxidative degradation starts at a lower temperature (around 276 °C) than in the case of recovered PP, and the derivative curve shows two maximum points at 290 °C and 405 °C. On the other hand, additives are currently used in the formulation of commercial plastic products.

The IR spectra of the two samples of PP, reported in Figure 3, look very similar. The most important peak characteristics of the PP can be seen at 1375 cm^{-1}, 1457 cm^{-1},

2838 cm^{-1}, 2916 cm^{-1}, and 2950 cm^{-1}. A weak peak, that could be due to another organic component, is placed at 2865 cm^{-1}. This signal is consistent with the stretching of methyl and methylene groups contained in saturated aliphatic compounds [22].

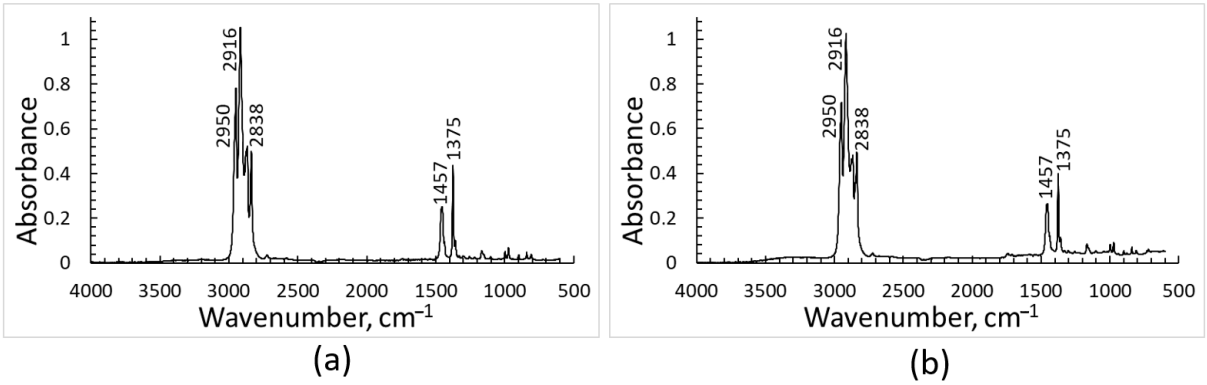


Figure 3. FTIR-ATR spectrum: commercial PP HP456H (**a**), PP recovered from GAIA waste (**b**).

The DSC traces (Figure 4) show the presence of endothermic effects which occurred during heating, with a main peak at 166 °C, and exothermal effects which occurred during cooling in the range between 115 °C and 128 °C. The thermal effect at 166 °C is consistent with the melting of crystalline PP and it is the only signal that can be appreciated in the heating curve of the commercial PP (Figure 4a). The cooling curve of this product shows a sharp exothermal effect at around 115 °C caused by the crystallization of the molten polymer. Differently, two signals can be observed either during heating or cooling in the DSC traces of the recovered PP (Figure 4b). In the heating trace, in addition to the melting of the PP at 166 °C, a very weak additional endothermic effect at 125 °C is observed. This last peak could be due to the melting of high-density polyethylene. The cooling trace also shows two thermal effects, and the main one at 128 °C could be attributed to the crystallization of the PP, while the second feeble one, tentatively, could be attributed to the crystallization of the PE. These features suggest that the recovered PP probably contains small amounts of PE. Unfortunately, this finding cannot be confirmed, neither by the IR analysis nor by XRD. In fact, in the IR spectrum, the strong peaks typical of PE at 2915 cm^{-1} and 2847 cm^{-1} should be superimposed on the peaks of the PP that are placed in the same region. Similarly, in the XRD pattern of the PE, its strongest peak (110) lies in the same region of the (111) and (−131) reflexes of PP.

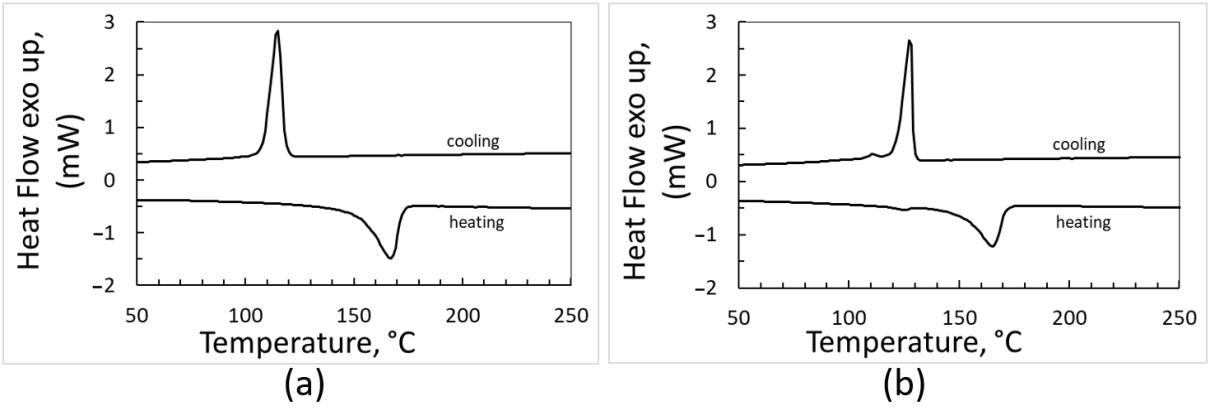


Figure 4. DSC recorded under nitrogen atmosphere: commercial PP HP456H (**a**), PP recovered from GAIA waste (**b**).

It is worth noting that the main exothermal effect attributed to crystallization from the melt is not placed at the same temperature in the DSC patterns of the commercial and

recovered PP. However, the recovered PP also contains inorganic contaminants that could act as a nucleating agent and promote crystallization.

2.2. Microstructure and Tensile Behavior of Samples Containing Recycled PP

The microstructure of the tensile specimens is compared in Figure 5. The microstructure of the samples produced using the commercial PP looks homogeneous in the microscopic examination. On the contrary, the presence of inclusions and areas with different shades of color and an elongated shape is well evident in the microstructure of the specimens produced by using only the PP recovered from waste (Figure 5i,j). This is consistent with the characterization of the virgin and recovered PP that is presented in the previous section, and which evidences some differences in their composition. The XRD analysis shows the presence of inorganic residual contaminants in the recovered PP, while the DSC results indicate the presence of a small amount of other polymeric materials (likely PE). The content of these impurities in the microstructures of the tensile specimens made by blending virgin and recovered PP progressively increases with the content of the recycled material (Figure 5c–h).

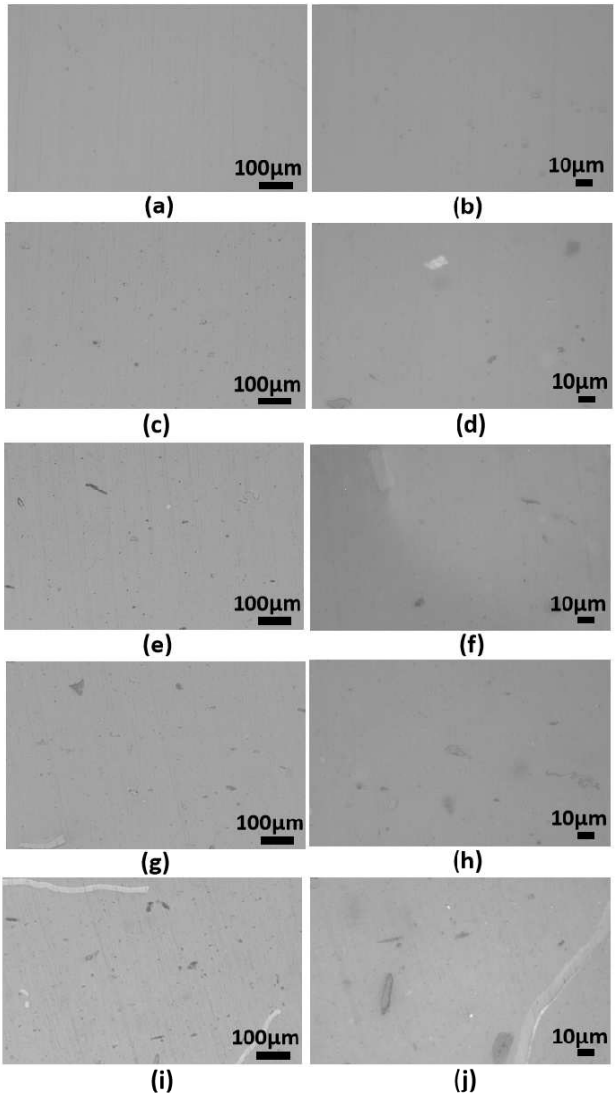


Figure 5. Microstructure of PP tensile specimens: commercial HP456H (**a**,**b**), compound containing 25 wt. % of recycled PP (**c**,**d**), compound containing 50 wt. % of recycled PP (**e**,**f**), compound containing 75 wt. % of recycled PP (**g**,**h**), and 100 wt. % of recycled PP (**i**,**j**).

The density also depends on the composition, as shown in Table 1.

Table 1. Density of PP materials: commercial HP 456H, fully recovered from GAIA waste, and compounds between commercial and recovered PP. Each material is labeled by indicating the source and the content (wt.%) of recovered PP.

PP	HP 456H	25 GAIA	50 GAIA	75 GAIA	100 GAIA
Density, [g/cm^3]	0.9021	0.9109	0.9164	0.9222	0.9290

The HP 456H PP showed a density of 0.9 g/cm^3, which fully agrees with the technical datasheet of the producer. The density values progressively increased with the percentage of the recycled material in the compounds, reaching a maximum value of about 0.93 g/cm^3 for the specimens produced using 100 wt. % of the recycled PP. Inorganic impurities are expected to increase the density. The possible effect of the presence of PE should greatly depend on its crystallinity degree instead; in fact, the density of PE progressively increased from a bit less than 0.9 g/cm^3 to a bit less than 1 g/cm^3 with the increase in its crystalline degree.

The differences reported above for the composition and the microstructure of the tensile specimens should result in different mechanical features. The stress–strain curves of the commercial HP456H polypropylene are compared with those recorded for the materials containing 25 wt. %, 50 wt. %, 75 wt. %, and 100 wt.% of recycled polypropylene in Figure 6a–e.

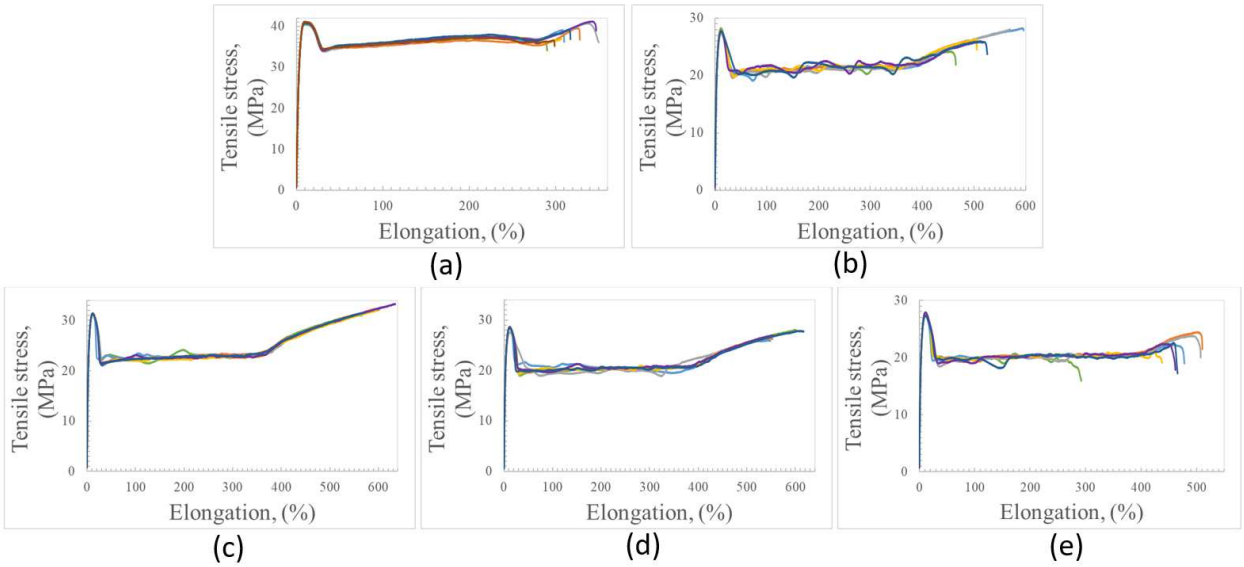


Figure 6. Stress–strain curves for tensile test specimens: 100 wt.% commercial HP456H (**a**), 100 wt. % recycled PP (**b**), compound containing 25 wt. % of recycled PP (**c**), compound containing 50 wt. % of recycled PP (**d**), and compound containing 75 wt. % of recycled PP (**e**).

Several tensile curves with different colors are shown for every specimen composition. The curves for each kind of material (content of recycled PP) are widely superimposed on the relevant figures, showing that they are very similar at least in their initial part. The trend of these stress–strain curves is the same for all of the materials under investigation. After a linear elastic tract, plastic deformation starts and a maximum stress is reached at the yielding, after which the stress suddenly falls, and then progressive plastic deformation occurs. Meanwhile, the stress slightly increases until breakage.

The similar tensile behavior shown by all of the materials under investigation is consistent with the XRD, IR, and calorimetric analyses that prove that both commercial and recovered plastic, as well as their compounds, are mainly composed of polypropylene. The average values of the tensile strength, modulus, and maximum strain are reported in Table 2 with the relevant standard deviations.

Table 2. Tensile strength, modulus, and strain at fracture of PP specimens.

PP Samples	Tensile Strength	Elastic Modulus	Strain at Fracture
	$\sigma_{max} \pm$ SD, [MPa]	E $\pm$ SD, [GPa]	$\varepsilon \pm$ SD, [%]
PP HP 456 H 100 wt. %	40.9 $\pm$ 0.2	1.582 $\pm$ 0.069	318.6 $\pm$ 21.7
PP GAIA 25 wt. %	32.1 $\pm$ 0.7	1.436 $\pm$ 0.050	588.1 $\pm$ 28.9
PP GAIA 50 wt.%	28.4 $\pm$ 0.4	1.329 $\pm$ 0.023	570.6 $\pm$ 26.8
PP GAIA 75 wt. %	27.6 $\pm$ 0.2	1.203 $\pm$ 0.036	450.4 $\pm$ 74.3
PP GAIA 100 wt. %	28.0 $\pm$ 0.3	1.279 $\pm$ 0.050	524.2 $\pm$ 44.6

The specimens produced by using only recycled PP show lower values of strength and stiffness but a significantly higher strain at failure with respect to the commercial product used as a reference. It can be inferred that the contamination of PP recovered from waste with other polymeric materials like polyethylene is responsible for the strength and modulus decrease. Moreover, the DSC results show that such a kind of contamination happens. The presence of impurities in the recovered PP, evidenced by X-ray diffraction and clearly visible in the microstructure of the specimens containing this material (Figure 5c–j), does not negatively affect the ductility. On the other hand, inorganic inclusions and rather wide zones containing PE are randomly present in some sections of the tensile specimens, and could act as initiator sites for the failure process. The more relevant standard deviation for the strain at failure observed for specimens containing recycled PP, and then its impurities, strengthens this hypothesis.

The changes in the tensile features resulting from the adoption of recycled material are shown in Figure 7. The decrease in strength and modulus with the increase in the amount of recycled PP in the specimens seems not to occur in a linear manner. The addition of the recycled material up to a 50 wt. % appreciably worsens the strength and modulus, while the samples containing from 50 wt. % to 100 wt. % of recycled PP show rather similar features. The presence of recycled PP mainly affects the strength, in fact it decreased by 22% and 31% when using 25 wt. % and 50 wt. %, respectively, of the recycled material. Smaller changes were observed for the elastic modulus, which decreased by 9% and 16% when using 25 wt. % and 50 wt. % of the recovered PP. The trend of the strain at break against the composition shows that the addition to virgin PP of rather small amounts of recovered material suddenly modifies the ductility. The use of recycled PP, which also entails a lack of homogeneity due to the presence of impurities, also enhances the dispersion of the experimental results for the strain at failure.

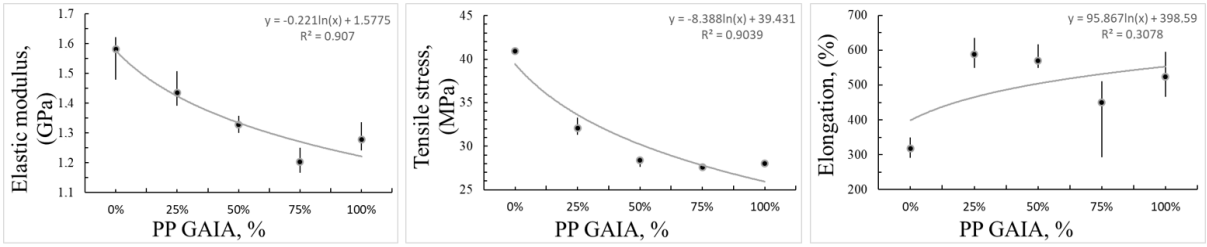


Figure 7. Effect of the content of recycled PP on tensile properties.

3. Materials and Methods

Polypropylene was sorted from a waste fraction, discarded, and usually landfilled by the waste treatment plant of the GAIA company (San Damiano d'Asti, Italy). The GAIA plant is currently constituted by an anaerobic section for biogas production and an aerobic one which is dedicated to the stabilization of the incoming waste and the production of agricultural-grade compost. The compost production process is structured according to several steps. Firstly, an adequate mixture of the organic fraction of municipal solid waste (OFMSW), mowings, and prunings is created, then this mixture is submitted to an aerobic biologic degradation process inside biocells. An initial process of maturation lasts

approximately 50 days and, at the end, some contaminants are removed by sieving. The sieving machine consists of two subsequent rotating drums equipped with holes. The first drum sieves the product at 9 mm (real compost) while the second drum, whose holes measure 50 mm, allows for separating a falling fraction of real waste which is mainly composed of plastic residues, gravel, glass, organic matter, and water.

Polypropylene was separated from this waste fraction by means of an innovative near-infrared (NIR) separator developed by the Entsorga company (Tortona, Italy). This plant allowed us to identify several kinds of polymers using a hyperspectral camera. The waste (a 1.5-ton batch) was placed on a belt conveyor and the PP fragments, identified by the NIR apparatus, were blown away by a compressed air ejection system and collected in a bin. According to this process, a PP sample of 15.7 kg was selected. After sample homogenization by mechanical grinding, a representative sample of 1.5 kg was taken and used for recycling. The polymer-based material was, afterward, washed using laboratory facilities. The sample was dispersed in water under mechanical stirring and the PP was separated by flotation [23]. This operation was repeated several times and then the plastic was dried in an oven at 100 °C for 4 h, obtaining a sample of 850 g. The plastic fraction was analyzed by using several techniques: Fourier Transformed Infrared Spectroscopy (FT-IR), Differential Scanning Calorimetry (DSC), Thermal Gravimetric Analysis (TGA), and X-ray diffraction (XRD).

Infrared spectra were obtained in the range of 500–4000 cm^{-1} by using a Bruker Tensor 27 ATR-FTIR spectrometer, 2 cm^{-1} resolution, MCT detector cooled by liquid nitrogen, 32 scans for each spectrum. A DSC 214 Polyma Equipment (Netzsch Group, Selb, Germany) was used for calorimetric tests. The samples were heated from 20 °C to 300 °C under nitrogen atmosphere (gas flow 40 mL/min, heating rate 10 °C/min) and then cooled; heating and cooling curves were recorded. Thermal gravimetric analyses were conducted with a Mettler Toledo TGA/SDTA851 instrument in oxidizing atmosphere (air flow; 50 mL/min), heating the samples from 25 °C to 300 °C with a heating rate of 10 °C/min. X-ray diffraction analysis was carried out by using a Malvern Panalytical X'PERT PRO PW3040/60 diffractometer with Cu Kα radiation at 40 kV and 40 mA.

The recovered polypropylene was compounded with virgin PP according to the process summarized in Figure 8.

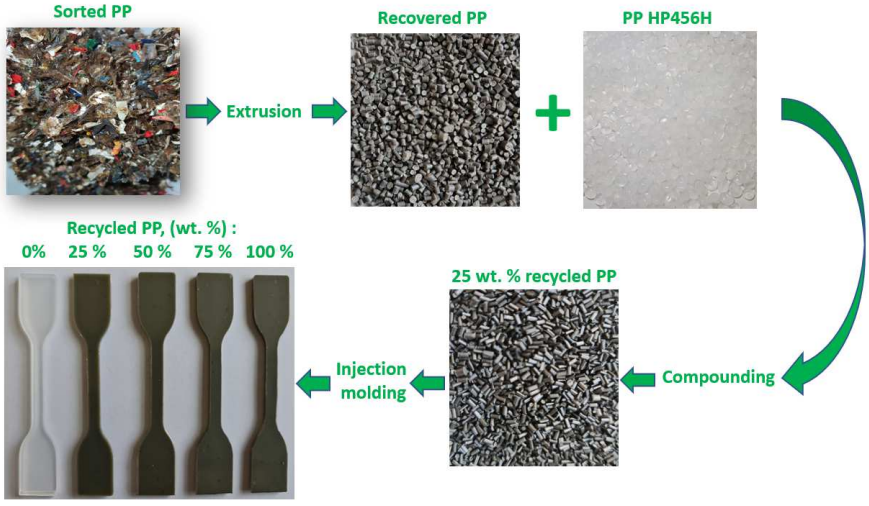


Figure 8. Reprocessing of recovered PP by compounding it with virgin material.

Pellets of recovered PP were produced by using a co-rotating twin screw extruder LEISTRITZ ZSE 18/40D with the following characteristics: diameter Φ = 18 mm and L/D ratio = 40. The extrusion flow rate was maintained at 3 kg/h. The barrel temperature was set at 190 °C, at 400 rpm with a spinning pressure of 20 bar. The recovered PP plastic was then mixed with commercial virgin PP (polypropylene homopolymer, Moplen HP456H, LyondellBasell Industries), thus obtaining compounds with different percentages

of recycled material. An Internal Mixer, W50E of Brabender, was used for this purpose and then the compounds containing 25, 50, and 75 wt. % of recycled PP were pelletized by using a small-size granulator (Piovan G17). Pellets made of a mixture of recovered and virgin PP, and containing 25 wt. % of recovered material, are depicted in Figure 8 as an example.

Specimens for tensile tests (dog-bone shape, size 75 × 4 × 2 mm^3, standard UNI EN ISO 527-1,-2) were processed by injection molding using a Babyplast 610P Standard machine, from CRONOPLAST SL (Abrera, Spain). Injection molding was performed in the following conditions: operating temperature of 190 °C, first injection time of 20 s at 90 bars for filling the mold, second injection time of 20 s at 80 bars for maintenance.

Seven tensile specimens for each formulation (100% recycled PP, compounds containing recovered PP, neat commercial PP) were tested with a MTS Criterion Model 43 dynamometer (with 5 kN load cell) equipped with a contact extensometer. A strain rate of 1 mm/min was adopted for the measurement of the elastic modulus, while stress–strain curves were recorded with a strain rate of 10 mm/min. Cut down parts of tensile specimens, obtained by sectioning them transversally, were mounted in epoxy resin and their surfaces were examined by Leica DMI 5000 M optical microscope after polishing with diamond pastes (1 μm surface finishing). The density of the dog-bone samples was measured according to the ASTM C604 standard by means of a helium pycnometer (Ultrapyc 5000 gas pycnometer Anton Paar GmbH, Graz, Austria).

4. Conclusions

A processing method that is suitable for the recovery and the recycling of polypropylene contained in waste rejected by a composting plant that treats the organic fraction of municipal solid waste was developed. A polypropylene fraction was sorted by using a NIR apparatus and then impurities were taken away by flotation. At the end of the process, only a small quantity of polyethylene and inorganic impurities contaminated the recovered plastic, which was found to be suitable for recycling. This plastic fraction and the compounds obtained by its blending with commercial polypropylene were pelletized and then subjected to injection molding for the manufacturing of tensile specimens. The tensile features of the plastic containing recycled polypropylene were found to be rather similar to those of several commercial products, in spite of the content of residual impurities that was not eliminated during the recovery process. Moreover, the content of impurities, reasonably, could be further lowered in the case of the washing of the dirty plastic separated by NIR being carried out by exploiting industrial facilities instead of laboratory equipment. However, the use of recycled PP in compounds was found to affect both their microstructure and mechanical behavior. In fact, the strength and the stiffness of the samples fully made of recovered plastic were 31.5% and 19.2%, respectively, lower than those of the commercial product that was used as a reference. As a consequence, the addition of recovered polypropylene lowered the tensile strength and the elastic modulus of the commercial product used for the compounding process. For instance, the addition of 25 wt. % of the recovered material caused a decrease of 22% in the tensile strength and a decrease of 9% in the elastic modulus. The recycling of polypropylene in compounds resulted in a significant increase in the strain at failure. The presence of impurities in the blends containing recycled material probably also affected the final breakage, and resulted in an increase in the dispersion of values of the strain at failure. However, the process of recovery produced polypropylene that is suitable for recycling this material in compounds with virgin plastic, as these compounds showed rather satisfactory mechanical features.

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