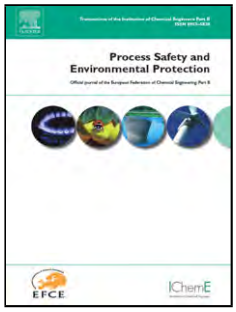

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Authors: A.V.M. Silveira, M. Cella, E.H. Tanabe, D.A. Bertuol

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APPLICATION OF TRIBO-ELECTROSTATIC SEPARATION IN THE RECYCLING OF PLASTIC WASTES

A. V. M. SILVEIRA; M. CELLA; E. H. TANABE; D. A. BERTUOL*

Environmental Processes Laboratory (LAPAM), Chemical Engineering Department, Universidade Federal de Santa Maria – UFSM, Avenida Roraima 1000, 97105-900 Santa Maria, RS, Brazil

A. V. M. SILVEIRA. E-mail address: andrevicente_eq@hotmail.com

M. CELLA. E-mail address: mateus_cella@hotmail.com

E. H. TANABE. E-mail address: edutanabe@yahoo.com.br

D. A. BERTUOL.* E-mail address: dbertuol@gmail.com

*Corresponding author: Chemical Engineering Department, Federal University of Santa Maria – UFSM, Avenida Roraima 1000, 97105-900 Santa Maria, RS, Brazil. E-mail address: dbertuol@gmail.com; Tel.: +55 (55) 3220-8448.

Highlights

- Application of a roll-type electrostatic separator in plastics recycling;
- Determination of the best parameters for tribo-electrostatic separation;
- Use of plastics particles from the selective collection of urban solid waste;
- Alternative process to separate different types of plastic waste;
- Efficient recovery of different types of plastics from a mixture of polymeric waste.

ABSTRACT

In the last decades, increasing industrial development has led to huge consumption of plastic materials, due to their versatility and low cost. Therefore, the implementation of efficient and environmentally friendly recycling technologies is of great importance. This study proposes an alternative separation process for recycling mixtures of plastic wastes, using a tribo-electrostatic separation process. The methodology adopted in this work was firstly characterization of the polymeric wastes, followed by preparation of the wastes using different unit operation processes (washing, drying, and comminution), tribo-charging, and electrostatic separation of different combinations of plastics (HDPE/PP, LDPE/PP, and PET/PVC). Various parameters were evaluated in the tribo-charging process and the electrostatic deflection. Separation of a mixture of HDPE and PP achieved PP recovery of 92.8% (purity of 95.7%) and HDPE recovery of 95.9% (purity of 93.1%). Recovery and purity values higher than 90.2% and 95.9% were obtained for PP/LDPE and PET/PVC mixtures, respectively. These results demonstrated that tribo-electrostatic separation is a promising and efficient method for use in the recycling of plastic wastes. The process studied enabled significant recoveries of the components at high levels of purity.

Keywords: Tribo-electrostatic separation; plastic; recycling; mechanical processing.

1. INTRODUCTION

The quality of life of individuals has improved due to continuous industrial development. Plastics are directly related to this development, due to their reliability, low cost, durability, and lower weight compared to competing materials, besides their great versatility and adaptability in terms of the technical specifications required (Siddique et al., 2008). The world's total consumption of plastics is increasing at an average growth

rate of 5-6% per year (Saisinchai, 2013), and global plastics production reached 322 million tons in 2015.

There are several plastics used in everyday life. The demand is mainly dominated by thermoplastic types such as polypropylene (PP) (19.1%), low-density and linear low-density polyethylene (LDPE and LLDPE) (17.3%), high-density polyethylene, (HDPE) (12.1%), polyvinyl chloride (PVC) (10.1%), and polyethylene terephthalate (PET) (7.1%) (Plastic Europe, 2016). Plastics constitute a significant fraction of urban solid waste, including packagings and discarded goods (Astrup et al., 2009). The correct disposal of plastic waste has become a major issue worldwide, and recycling is an effective way to solve this problem. Plastic products contain chemical substances (additives) that have the potential to contaminate soil, air, water, and food (Hahladakis et al., 2018). Recycling of plastic wastes has numerous benefits, such as reducing the amount of solid wastes that go to incineration and landfill, in addition to reducing the production of virgin plastics from refined fossil fuels (Saisinchai, 2013; Siddique et al., 2008).

A major challenge for producing recycled resins from plastic wastes is that most different plastic types are not compatible with each other, due to their inherent immiscibility at the molecular level and differences in processing requirements at a macro-scale. Rigid containers composed of a single polymer are simpler and more economical to recycle than multi-layer and multi-component packages (Hopewell et al., 2009).

Mechanical recycling is the most widely used method, but can only be used with products containing only one type of resin (PP, HDPE, or PET, etc.). The more mixed and contaminated is the plastic waste, the harder it is to perform the mechanical recycling process. According to Luijsterburg and Goossens (2014), extensive sorting leads to purer waste fractions and better mechanical properties. Pyrolysis is another versatile recycling

method that can produce a range of hydrocarbons potentially useful as chemical feedstocks or energy sources (Al-Salem, 2017). The type of feedstock and its purity are among the main elements that determine the nature of the final product, since they govern the boiling point range of the product that is to be condensed downstream of the process (Al-Salem, 2017). Therefore, an efficient separation of polymeric materials is essential (Al-Salem et al., 2010).

Different techniques have been developed for plastics separation, including optical separation (Arvanintoyannis and Bosnea, 2001), gravity separation (Pascoe, 2006; Pongstabodee et al., 2008), selective dissolution (Achilias et al., 2007), density separation (Briassoulis et al., 2013; Wu et al., 2013), and flotation (Burat et al., 2009; Takoungsakdakun and Pongstabodee, 2007; Wang et al., 2015). Density separation with water can effectively separate polyolefins such as PP, HDPE, and LDPE (the floating fraction) from PVC and PET (the sinking fraction) (Hopewell et al., 2009).

In an industrial chain, considering the main thermoplastic types, after density separation with water there are still some fractions to be separated, such as PET/PVC and PE/PP (including both HDPE and LDPE). A problem is that PVC cannot be separated from PET in this manner, because their density ranges overlap (Hopewell et al., 2009). In addition, the PVC present in a PET recycle stream will degrade the recycled PET resin due to evolution of hydrochloric acid gas from the PVC at the higher temperature required to melt and reprocess PET (Hopewell et al., 2009). In the case of PE/PP, the densities of the plastics are also very close, making it difficult to separate them according to density. PE and PP have been extensively researched in terms of their pyrolysis (Kunwar et al., 2016), with the highest possible purity being necessary to increase the added value of the products obtained using this process. Therefore, an efficient method is required for separation of these different fractions (PET/PVC and PE/PP).

A highly promising technique that can be employed in plastic waste processing is electrostatic separation. When used in conjunction with a tribo-charging process, this is termed tribo-electrostatic separation. The technique can be applied in the separation of non-conducting materials, such as in polymer recycling (Al-Salem et al., 2009). This technology makes it possible to separate different materials based on the differences in their electrical properties. This process offers high efficiency, low cost, and no concerns regarding secondary pollution (Wu et al., 2013).

The rates of recovery and purity found in the literature indicate that tribo-electrostatic separation is an effective method for the separation of polymeric residues. However, in most studies, the process has been applied to virgin plastics, rather than to post-consumer materials from municipal solid waste (MSW) (Iuga et al., 2005). An important indicator for the separation is the tribo-electric series of the polymers (Park et al., 2008). This series describes the acquired polarities of the charged plastic particles. Some of the main tribo-electric series of plastics are presented in Table 1. In this way, it is possible to rapidly predict the polarity of the charge for the recycling of plastic wastes using tribo-electrostatic separation.

Author	(+) Tribo-electric series (-)
Matsushita et al. (1999)	PS – PET – PE – PP – PVC
Dodbiba et al. (2003)	ABS – PC – PET – PS – PE – PP – PVC
Iuga et al. (2005)	PMMA – PE – PET – PP – PVC
Park et al. (2007)	PMMA – ABS – PET – PEAD – PP – PVC – PTFE
Park et al. (2008)	PMMA – ABS – HIPS – PET – PEAD – PEBD – PP – PVC
Li et al. (2015)	PP – ABS – PVC – PC – PS – PE

Table 1. Tribo-electric series of polymers reported in the literature.

The choice of the tribo-charging mechanism is very important, since it will determine the efficiency of particle separation in the next steps. The literature cites two mechanisms for obtaining electric charge on the particles: solid single phase (vibration, rotary drum, rotary blades, etc.) and gas-solid two-phase (fluidized bed, cyclone, propeller-type tribo-charger, etc.) (Wu et al., 2013).

After the particles have acquired an electric charge, they are subjected to an electrostatic deflection process. Different types of electrostatic separators can be used in this step, including the free-fall, roll, plate, and fluidized bed types (Wu et al., 2013). The free-fall type separator is most widely used for the separation of plastic particles (Aksa et al., 2013; Dodbiba et al., 2003; Tilmatine et al., 2010). In the fluidized bed type separator, the tribo-charging and electrostatic separation occur together (Dascalescu, 2011). The roll type separator, although still little used in the separation of plastic residues, has been used for many years in the separation of conductive from non-conductive materials (Gaudin, 1971; Jiang et al., 2008). The particles are fed onto the surface of the roll, passing through an electrode-generated electric field that only affects the trajectory of positively-charged particles. As a result, particles are accumulated in different collectors at the bottom of the separator (Wu et al., 2013).

This work concerns the application of the tribo-electrostatic technique in the separation of different plastic mixtures from MSW. Gas-solid two-phase tribo-charging was applied using a fluidized bed. Electrostatic deflection was performed with a roll type electrostatic separator, which has previously only been applied a few times in tribo-electrostatic separation. Firstly, the main tribo-charging and electrostatic deflection parameters were evaluated for the separation of HDPE/PP. The best conditions identified

in the HDPE/PP separation were then applied to different plastics mixtures (LDPE/PP and PET/PVC) in order to evaluate the separation efficiency.

2. MATERIALS AND METHODS

Fig. 1 shows the methodology employed in this work. In the first step, a characterization was performed to confirm the plastics composition. In all these procedures, the plastics were first submitted to a washing process in order to avoid interference from contaminants. Mechanical processes were then performed, followed by tribo-electrostatic separation, in order to obtain high recoveries of the plastics at high degrees of purity.

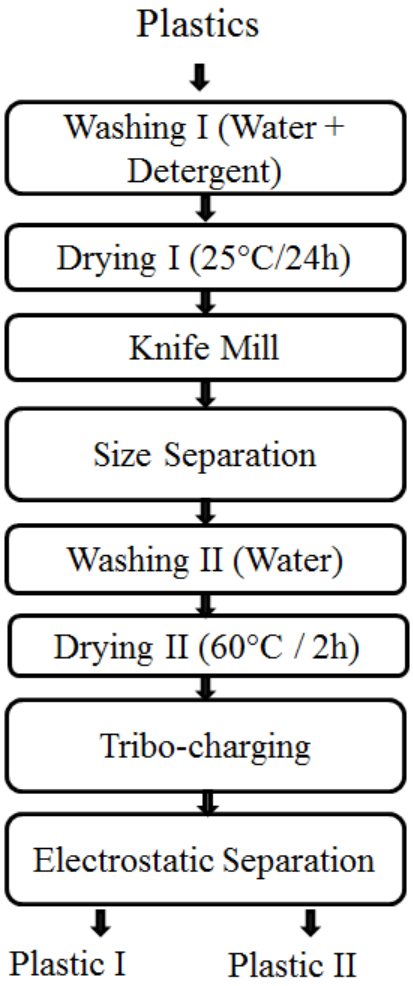

Fig. 1. Flowchart of the process for tribo-electrostatic separation of the plastics mixtures.

2.1 Plastics characterization using DSC

Five types of polymers were selected: PP, HDPE, LDPE, PET, and PVC. These represent the majority of plastic materials found in the selective waste collection in Santa Maria (Rio Grande do Sul, Brazil. The plastics were characterized by differential scanning calorimetry (DSC–60 Plus, Shimadzu). All the analyses were performed in triplicate.

2.2 Mechanical processing

2.2.1 Washing, drying, and comminution

The plastics were washed with tap water and soap to remove the adhered impurities, followed by drying at room temperature (25 °C) for 24 h. This process was required in order to minimize surface contamination of the particles, which would impair the reproducibility and efficiency of the tribo-charging process (Lee and Shin, 2002). The polymers were then ground in a knife mill (N150, RONE) fitted with a 5 mm output sieve.

2.2.2 Sieving

Studies have shown that particle size has a direct effect in tribo-electrostatic separation (Dodbiba et al., 2005; Tilmatine et al., 2010). Therefore, a granulometric separation was carried out using sieves coupled to a vibratory agitator. The sieves used were Tyler 9 and 7 (2.0 and 2.8 mm, respectively). The average size obtained was -2.8 / +2.0 mm.

According to Tilmatine et al. (2010), the roll type electrostatic separator is more suitable for the separation of polymeric particles with average diameter greater than 2.0 mm. Dodbiba et al. (2005) reported that particles with average diameter greater than 3 mm suffer minor deviation from the electrodes. When the particle size increases, the electric field strength required for the electrostatic deflection of the particles increases exponentially. Therefore, particles with mean size in the range from 2.0 to 2.8 mm were selected in the present work.

2.2.3 Secondary washing and drying

During the comminution and sieving processes, the plastic particles can acquire surface charges. This affects the charging efficiency and influences the purity and recovery of the products resulting from the overall process (Wu et al., 2013). One way to neutralize these charges is by using washing and drying processes that help to discharge the plastic particles (Trigwellet al., 2003). Washing processes (using water only) and oven drying at 60 °C for 2 h were performed to promote electric neutralization of the particles. As a result, the particles sent to the tribo-charging stage remained neutral, favoring the reproducibility of the process.

2.3 Tribo-electrostatic separation

2.3.1 Materials used in the tests

The plastics mixture used in the initial study of tribo-electrostatic separation consisted of PP and HDPE. These were chosen because of the difficulty involved in separating them. PP has a density of 0.9-0.91 g/cm^3, while HDPE has a density of 0.94-0.97 g/cm^3. Hence, it is very difficult separate these polymers according to their densities,

because the values are very similar. In addition, in the tribo-electric series presented in the literature, HDPE (or PE) and PP are adjacent in most distributions (Table 1).

2.3.2 Tribo-charging

A mixture of 10 g of PP and 10 g of HDPE (50/50) of different colors, with average size of -2.8 / +2.0 mm, was used for this step. Two tribo-charging mechanisms were tested, with set parameters defined in preliminary experiments (Silveira, 2016; Tilmatine et al., 2010). First, a solid single-phase tribo-charger was tested using a vibration system (total displacement = 0.12 inches and t = 10 min). The results were then compared to two-phase gas-solid tribo-charging using a fluidized bed system (air velocity = 3.5 m/s, t = 10 min, and air temperature = 20 °C). The material used in the manufacture of both systems was PP (Fig. 2).

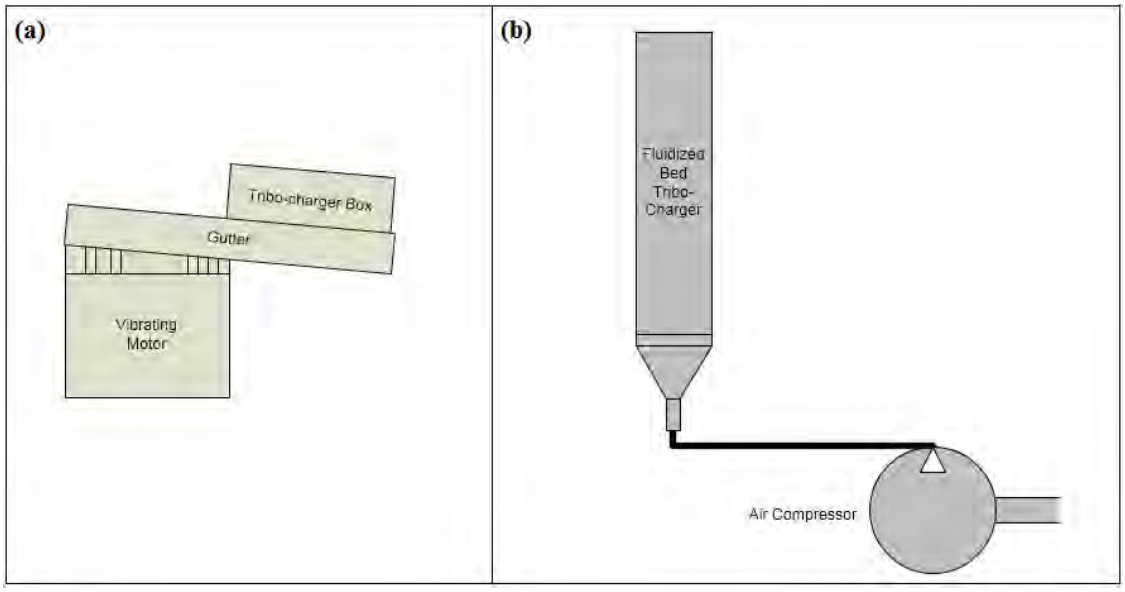

Fig. 2. Tribo-charging systems: (a) vibration in a PP box; (b) fluidized bed of PP.

After selection of the tribo-charging mechanism, other parameters were studied. The influence of relative humidity (42, 52, 60, and 77%) on the tribo-charging of the particles was tested. The humidity was measured using a digital hygrometer. Evaluation

was also made of the influence of time (2.5, 5, 10, 15, and 20 min) on the tribo-charging performed in the fluidized bed of PP (air velocity = 3.5 m/s and air temperature = 20 °C). The separation efficiency was evaluated in terms of the amount of material recovered, as well as its purity. The best time was selected for use in the subsequent tests.

For all the tribo-charging tests, the electrostatic separator (ES) parameters were as follows: tension (U) = 30 kV; roll speed (n) = 10 rpm; electrostatic electrode distance (D) = 3 cm; electrostatic electrode angle (Θ) = 45°; deflector angle of the collector (Â) = 0°; and feed rate of 1 kg/h. The initial parameters were based on preliminary tests and the study by Tilmatine et al. (2010).

2.3.3 Electrostatic separation

The roll-type electrostatic separator shown in Fig. 3 was employed for separation of the plastics mixtures. After the tribo-charging process, the different materials acquired electric charges with different polarities (positive, negative, or neutral), enabling the collection of each material in a separate collection box, depending on the charge. The particles were collected in three different compartments, as shown in Fig. 3. Negative particles remained adhered to the roll and were collected in the first collector. Neutral particles were collected in the second collector, while positive particles were attracted to the electrostatic electrode and were collected in the third collector.

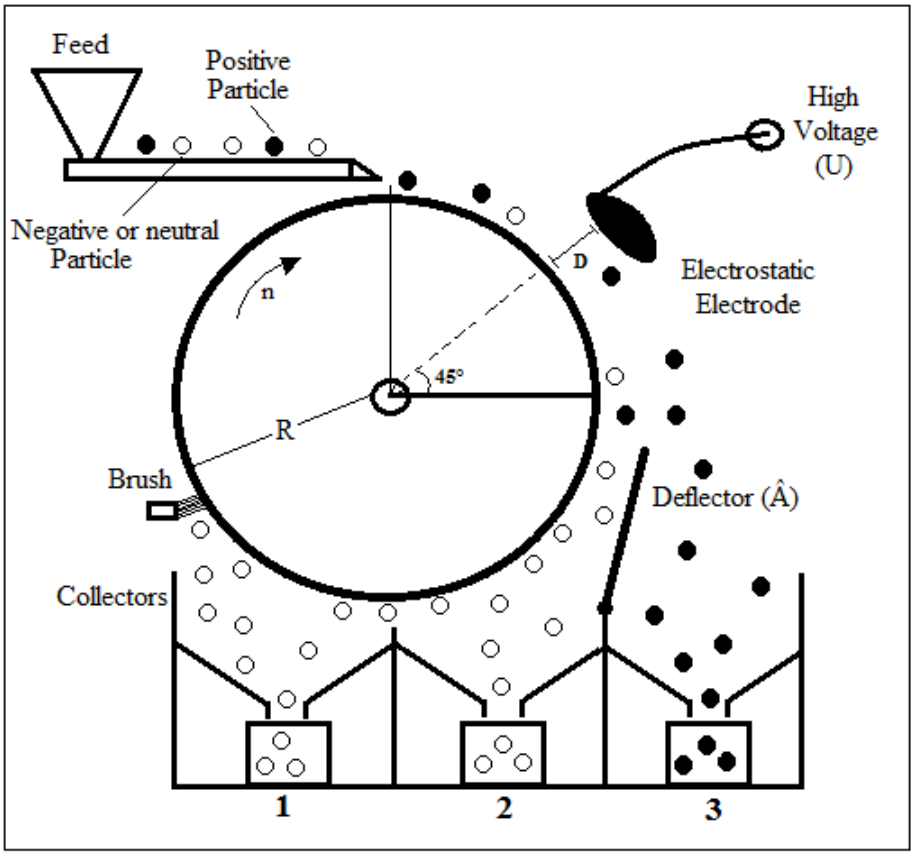

Fig. 3. Operation scheme of the electrostatic separator.

The electrostatic separator parameters studied are shown in Table 2. The material used in this step was a mixture of 10 g of PP and 10 g of HDPE (50/50) of different colors. The electrostatic electrode angle was maintained constant at 45°, in accordance with earlier research (Tilmatine et al., 2010). All the experiments in this step were performed using tribo-charging in the fluidized bed, with a residence time of 5 min and air humidity of 42±3%, as established in the tribo-charging tests.

Parameter	Values	Unit
Deflector angle (Â)	0, 2.5, 5, 7.5, 10	°
Electrostatic electrode distance (D)	2, 3, 4, 5, 6, 7	cm
Electrode tension (U)	10, 15, 20, 25, 30	kV
Roll speed (n)	5, 10, 20, 30, 40, 50	rpm

Table 2. Parameters studied in the tribo-electrostatic separation of PP and HDPE.

The plastic particles from each collector were separated manually using tweezers and spatulas. This separation was possible because of the different colors of each type of plastic and resulted in two groups of particles (plastic 1 and plastic 2) for each collector. The particles of each material were weighed on an analytical balance. The recovery and purity of each material were determined using Equations 1 and 2, respectively:

$$\textbf{\textit{Recovery}}\ \textbf{(\%)} = (m_{ic} / m_{it}) \times 100 \quad (1)$$

$$\textbf{\textit{Purity}}\ \textbf{(\%)} = (m_{ic} / m_{tc}) \times 100 \quad (2)$$

where m_{ic} is the mass of polymer *i* that was collected in the collection box intended for it, m_{it} is the total mass of polymer that was fed into the electrostatic separator, and m_{tc} is the total mass of polymers in the specific collection box for each material.

After determination of the best operational conditions for the tribo-electrostatic separation, these parameters were applied in triplicate in order to evaluate the reproducibility of the process. The best conditions were also applied in tribo-electrostatic separation of other plastics mixtures (PP/LDPE and PET/PVC).

3. RESULTS AND DISCUSSION

3.1 Plastics characterization

The DSC analyses were performed for each type of plastic. The HDPE showed a characteristic melting peak at 131 °C, confirming its composition (Fig. 4a). For LDPE, a melting peak was obtained at a slightly lower temperature of 125 °C, characteristic of this plastic (Tsukame et al., 1997). The difference in melting temperature can be explained by the different structures of these two polymers. LDPE has a branched structure, while

HDPE has a linear structure that leads to greater compaction of the polymer chains and consequently a higher melting point. The PP showed a melting temperature of 165 °C, in agreement with the literature and confirming its composition (Manivannan and Seehra, 1997).

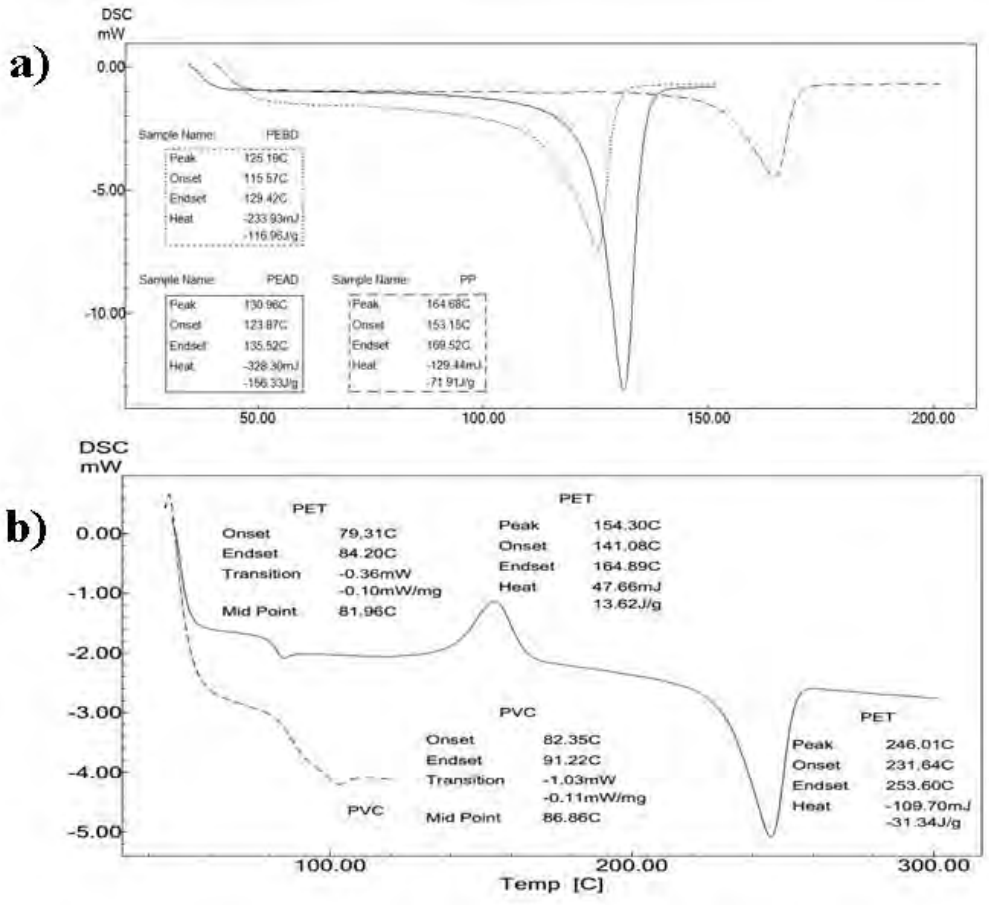

Fig. 4. DSC patterns: (a) HDPE, LDPE, and PP; (b) PVC and PET.

The PET and PVC particles were also characterized by DSC (Fig. 4b). The PET showed a baseline change at 82 °C (glass transition temperature), an exothermic peak at 154 °C (crystallization temperature), and a melting peak at 246 °C, characteristic of this plastic (Jenekhe et al., 1983). The PVC showed a characteristic baseline change at 86.8 °C, corresponding to the glass transition temperature of the plastic (Gong et al., 2004).

Hence, the compositions of all the plastics employed were in agreement with the literature.

3.2 Comminution and size separation

A batch of plastics that had been previously washed and dried was comminuted and subjected to a granulometric separation process. The particles with mean size of -2.8 / +2.0 mm were selected (Fig. 5).

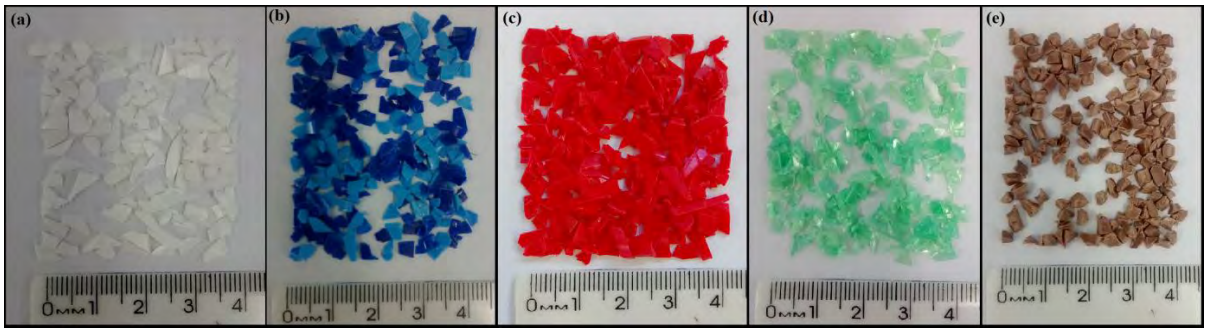

Fig. 5. Plastic particles obtained after the washing, drying, comminution, and size separation processes: (a) HDPE; (b) PP; (c) LDPE; (d) PET; (e) PVC.

3.3 Tribo-charging tests

3.3.1 Tribo-charging mechanism

Tribo-charging performed in a fluidized bed (gas-solid, two-phase) resulted in the highest process efficiency (Fig. 6), enabling recoveries of 95.95% of PP (purity of 93.9%) and 94.0% of HDPE (purity of 96.9%). Tribo-charging with the vibration system (solid single phase) resulted in recoveries of 84.5% of PP (purity of 90.1%) and 90.5% of HDPE (purity of 85.1%).

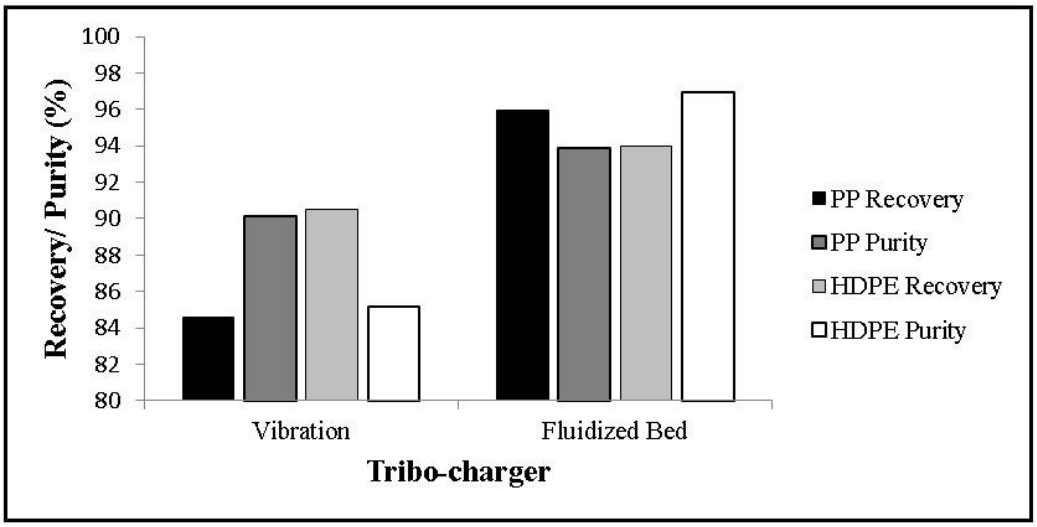

Fig. 6. Performance achieved using the different tribo-charging methods.

Tribo-charging performed using the fluidized bed provided more efficient charging, due to greater collision among the particles. The vibration system was simpler, but resulted in poorer separation of PP and HDPE. Therefore, all the tests carried out in the next steps were performed with tribo-charging using a fluidized bed of PP.

3.3.2 Relative humidity

The relative humidity (RH) of the air directly affects the tribo-charging process, with the recovery and purity of the plastics being greatly reduced with increasing RH. The best results were obtained at RH of 42% (Fig. 7a), with recovery values of 95.9% (purity of 93.9%) and 94.0% (purity of 96.05%) for PP and HDPE, respectively. At RH of 52%, the recoveries and purities decreased to levels of around 80±2% for both plastics. At higher relative humidity (77%), the recovery of PP was only 24.8%.

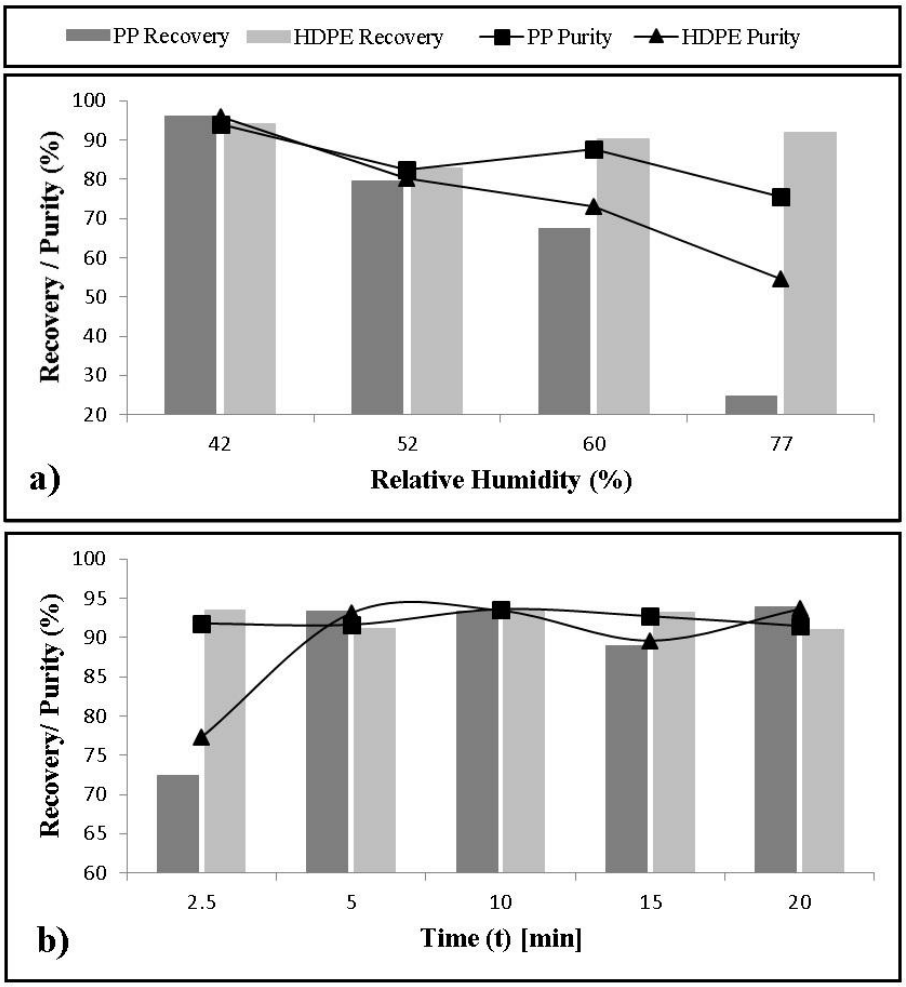

Fig. 7. Effects of (a) relative humidity and (b) residence time on the tribo-charging of the PP and HDPE particles.

Li et al. (2015) studied the effect of relative humidity on the tribo-charging of ABS, PS, and PVC particles in a cyclone tribo-charger composed of PMMA. The highest charge acquired by the plastics studied occurred at RH between 45% and 55%, with higher humidities being unfavorable for tribo-charging of the particles. Park et al. (2008) reported that the charge density was altered by relative humidity because water disturbed the surface polarization among the particles and reduced the charge density, hence discharging the charged particles. Therefore, in the present work, the subsequent experiments were conducted at a relativity humidity of 42%.

3.3.3 Tribo-charging time (t)

The residence time of the particles inside the tribo-charger is a very important variable in the tribo-charging process. A time of 2.5 min was insufficient for tribo-charging of the particles, as shown in Fig. 7b. At this residence time, very low PP recovery of around 72.4±1.6% was obtained, although the recovery of HDPE was 93.5±0.1%. However, a residence time of 5 min resulted in a significant increase in the recovery of PP, with values of 93.4±1.6% (purity of 91.6±2.3%) and 91.2±2.8% (purity of 93.1±1.4%) for PP and HDPE, respectively. For the other times of 10, 15, and 20 min, the efficiency of the process remained constant, with values very close to those obtained for 5 min.

Dascalescu et al. (2005) reported that the particle charge increases with increasing residence time and becomes saturated after very long periods. Therefore, extended residence times are not necessary, since the charge acquired by the particles will be the same. Fig. 9 shows that for times of 5 min or longer, the separation efficiency was the same, so a time of 5 min was selected for the tribo-charging process.

3.4 Electrostatic separation

The parameters evaluated in this study were the angle of the deflector (Â), the distance of the electrostatic electrode (D), the electrode tension (U), and the roll speed (n).

3.4.1 Deflector angle (Â)

The first parameter studied was the angle of the deflector (Â). The other parameters were maintained constant, with electrostatic electrode distance (D) of 3 cm, electrostatic electrode tension (U) of 30 kV, and roll speed (n) of 10 rpm.

The deflector angle (Â) has a major influence, since it depends on the trajectory of the particles attracted by the electrostatic electrode. This trajectory determines whether the particles will fall into collector 2 or 3. The best result was achieved with an angle of 2.5° (Fig. 8a), which resulted in recoveries of 92.8% (purity of 95.7%) and 95.9% (purity of 93.1%) for PP and HDPE, respectively. An angle of 0° resulted in recoveries of 92.2% (purity 93.2%) and 93.2% (purity 92.1%) for PP and HDPE, respectively. When the deflector angle was increased to 5°, 7.5°, or 10°, there was lower recovery of HDPE, because with higher angles the HDPE particles were unable to exceed the deflector and therefore fell into the wrong box.

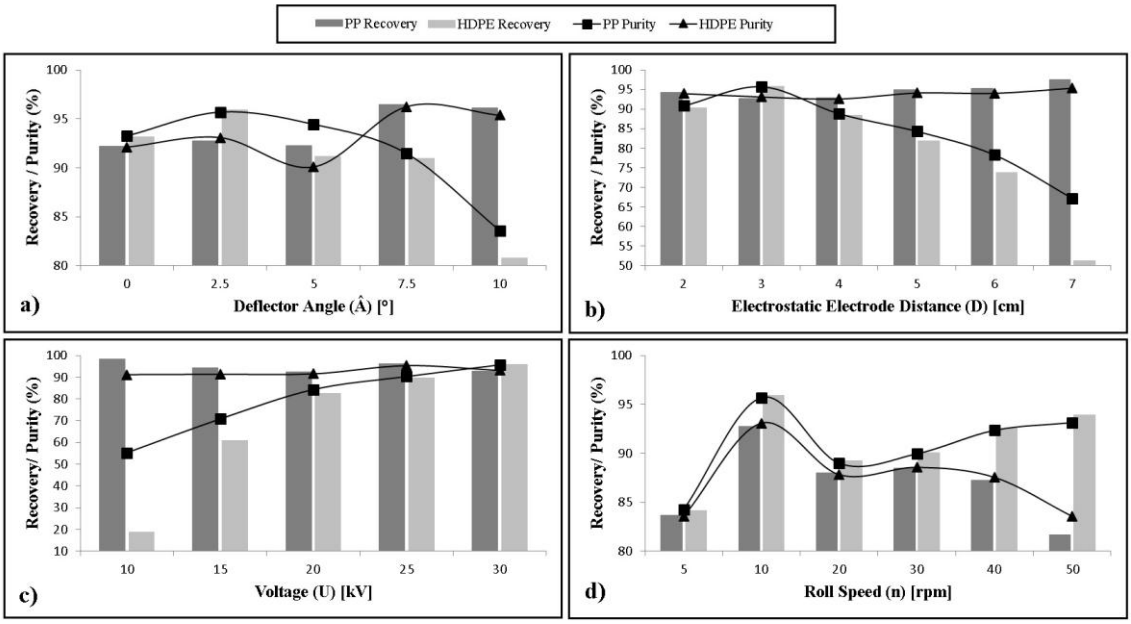

Fig. 8. Effects of different electrostatic separation parameters on the separation of PP and HDPE particles: (a) deflector angle (D = 3 cm; U = 30 kV; n = 10 rpm); (b) electrostatic electrode distance (Â = 2.5°; U = 30 kV; n = 10 rpm); (c) voltage (Â = 2.5°; D = 3 cm; n = 10 rpm); (d) roll speed (Â = 2.5°; D = 3 cm; U = 30 kV).

The separation of plastic materials in a roll-type electrostatic separator has been very little discussed in the literature. Tilmatine et al. (2010) studied the separation of

plastics particles by this technique, using virgin resins of HDPE and LDPE, but did not mention the effect of the collector deflector angle as a process parameter. In the present case, a deflector angle of 2.5° was defined as the optimum.

3.4.2 Distance of the electrostatic electrode (D)

Evaluation was made of the effect of the distance (D) between the roll surface and the electrostatic electrode (Fig. 8b). This parameter is directly related to the voltage applied to the electrodes. The best results were obtained at a distance of 3 cm, with recovery of PP of 92.8% (purity of 95.7%) and recovery of HDPE of 95.9% (purity of 93.1%). The recovery of HDPE decreased at greater distances, with a value below 90% at 4 cm. This could be explained by the fact that a greater distance (D) requires a higher voltage applied to the electrode in order to attract the positively charged particles (HDPE, in this example). Consequently, the HDPE particles end up being collected in the collector intended for the PP, causing the purity of the PP to also decrease significantly with the increase of the electrode distance.

At a distance of 2 cm, the recoveries of PP and HDPE were 94.3% (purity of 90.8%) and 90.3% (purity if 93.9%), respectively. However, with a very small distance (2 cm), sudden large electric discharges of the electrostatic electrode could occur on the roll, which were identified by small flashes. Hence, a distance of 2 cm could not be considered, since the occurrence of electric discharges would affect the operation of the electrostatic separator.

The results obtained in this step were in agreement with the work of Tilmatine et al. (2010), where it was concluded that the most efficient separation distance was 3 cm. However, in the earlier work only two distances were tested (3 and 7 cm), so the effect of gradually increasing the distance was not revealed.

3.4.3 Electrode tension (U)

The tension applied to the electrodes (U) is the most important parameter in tribo-electrostatic separation. It is the most studied variable in tribo-electrostatic separation of plastic particles, especially using free-fall type separators (Aksa et al., 2013; Dodbiba et al., 2005; Park et al., 2008). As shown in Fig. 8c, lower voltages applied to the electrode led to lower recovery of HDPE and lower purity of PP. The best results were obtained at a voltage of 30 kV, with PP recovery of 92.8% (purity of 95.7%) and HDPE recovery of 95.9% (purity of 93.1%). At a voltage of 25 kV, there were decreases in HDPE recovery (89.6%) and PP purity (90.3%), and the values continued to decrease at lower voltages of 20, 15, and 10 kV.

The voltage required for the separation of plastic particles is directly related to the charge density that the particles acquire in the tribo-charging process. According to Park et al. (2007), if the charge density of the particles is high, they can be easily deflected by a low voltage. When the charge density of the particles is low, a high voltage is required for them to be deviated. Therefore, the separation of a mixture of PP and HDPE requires a high tension, due to the difficulty of tribo-charging these plastics.

3.4.4 Roll speed (n)

The last parameter studied was the influence of the roll speed (n). A speed of 5 rpm did not result in satisfactory recovery and purity (Fig. 8d). This was because at such a low speed, the roll did not present continuous stable rotation, exhibiting small speed variations that affected the results. The best speed was 10 rpm, which enabled PP recovery of 92.8% (purity of 95.7%) and HDPE recovery of 95.9% (purity of 93.1%). At higher velocities of 20, 30, 40, and 50 rpm, there were clear decreases in PP recovery and HDPE

purity, because as the roll speed increased, the neutral PP particles were collected in the collector intended for the HDPE.

Tilmatine et al. (2010) reported that considering speeds of 40, 80, and 120 rpm, the most appropriate for the separation of HDPE and LDPE was 40 rpm. However, the study did not show whether slower speeds might be more efficient. In the present case, a speed of 10 rpm was selected as most appropriate for the process studied. This not only enabled separation of the positive (HDPE) and negative particles (part of the PP), but also separation of the neutral particles (part of the PP) from the positive particles (HDPE).

3.5 Application of the best conditions for the separation of HDPE and PP in order to confirm the reproducibility of the process

The best conditions for the tribo-electrostatic separation of the HDPE and PP particles are shown in Table 3.

Parameter	Condition
Tribo-charging mechanism	Fluidized bed
Relative humidity (RH)	~42%
Residence time (t)	5 min
Deflector angle (Â)	2.5°
Electrostatic electrode distance (D)	3 cm
Electrostatic electrode angle (Θ)	45°
High voltage (U)	30 kV
Roll speed (n)	10 rpm

Table 3. Best conditions for the tribo-electrostatic separation process.

Tests in triplicate were performed using the conditions shown in Table 3, in order to confirm the reproducibility of the process. In this step, PP presented a recovery of

91.9±1.1% (purity of 93.5±2.1%) and HDPE presented a recovery of 93.5±2.2% (purity of 92.0±1.2%). The efficiency of the separation process could be easily observed from the color differences of the plastics (Fig. 9), which clearly revealed the separation of the PP particles (light blue and dark blue) from the HDPE particles (white).

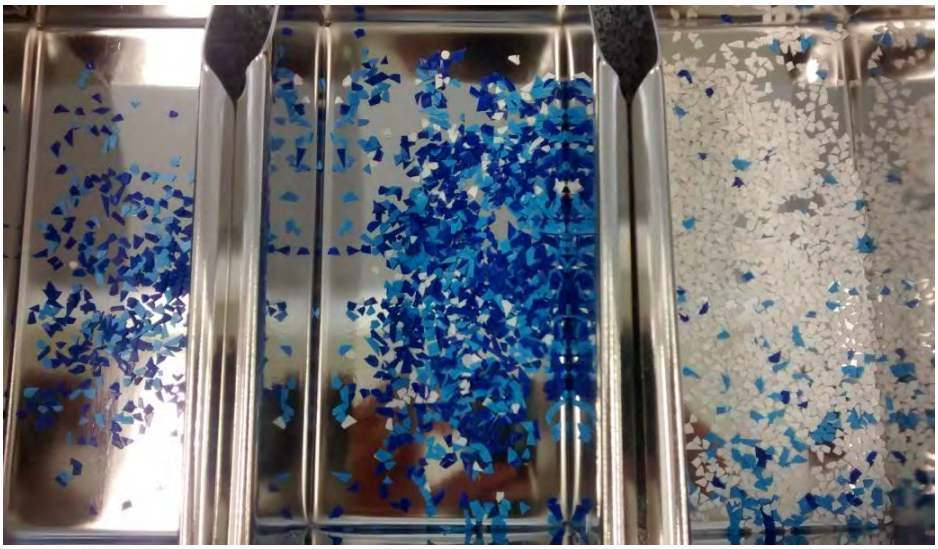

Fig. 9. Separation of PP (light blue and dark blue) and HDPE (white) using the best conditions.

3.6 Application of the best separation conditions for other plastics mixtures

New tests were performed using the previously defined conditions, with the objective of evaluating the efficiency of the process for the separation of other plastics mixtures.

3.6.1 Separation of PP and LDPE

The tribo-electrostatic separation of PP and LDPE followed the same separation principle as PP and HDPE, since the polyethylenes are adjacent in most tribo-electric series (Table 1). Hence, the PP particles acquired negative or neutral charge, while the LDPE particles acquired positive charge and were attracted to the electrostatic electrode.

This separation step resulted in PP recovery of 90.7±0.5% (purity of 91.8±1.7%) and LDPE recovery of 92.1±1.9% (purity of 91.1±0.3%).

3.6.2 Separation of PET and PVC

In the separation of the PET and PVC mixture, the PET particles acquired a negative charge and adhered to the roll. The PVC particles acquired a positive charge and were attracted to the electrostatic electrode. Thus, the tribo-electric series obtained in this study was as follows: (+) PVC - PP - PET (-). This difference can be explained by the fact that most of the tribo-electric series presented in Table 1, such as those of Li et al. (2015) and Park et al. (2008), were obtained from the tribo-charging of only one type of polymer at a time. In the present work, the series was obtained from the tribo-charging of a mixture of PET and PVC in a fluidized bed of PP. The separation resulted in PET recovery of 97.1±0.6% (purity of 95.9±1.0%) and PVC recovery of 95.9±0.5% (purity of 96.8±0.5%).

4. CONCLUSIONS

Recycling is one strategy for the end-of-life waste management of plastic products. In this work, characterization of the different plastics using DSC analyses confirmed the compositions of HDPE, LDPE, PP, PET, and PVC. The best mechanism of tribo-charging for the separation was a fluidized bed, rather than the vibration method. The relative humidity strongly affected the tribo-charging process and needed to be kept at low levels. The best conditions for the tribo-charging and electrostatic separation process were successfully defined.

Satisfactory separations of the plastics mixtures were achieved, with recovery and purity values exceeding 90.2% for all the separations studied, demonstrating the

effectiveness of the tribo-electrostatic process in separating a mixture of polymers. The results showed that was possible to obtain fractions with high purity, in addition to high recovery. Therefore, the tribo-electrostatic separation process is fully feasible for the recovery of plastics from selective waste collection. This process offers a good alternative to mechanical segregation and recycling of plastics from MSW.

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