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


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Article

Air-Assisted Tribo-Electrostatic Separator for Recycling of Shredded Waste Plastics

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Abstract: Waste minimization is a major way to achieve sustainable development. Electrostatic separation is already used in the recycling industry for processing certain mixtures of shredded plastics originating from waste electric and electronic equipment. Standard tribo-electrostatic separators use electric forces to deflect the trajectories of triboelectrically charged particles in the electric field generated between two vertical plate electrodes connected to high voltage supplies of opposite polarities. However, the efficiency of this device is often limited by the impacts between the particles and the electrodes, which diminish the recovery and the purity of the end product. An innovative electrostatic separator was specifically designed to mitigate this risk. The innovation lies in using two rotating co-axial vertical cylindrical electrodes and assisting the movement of the particles with downward-oriented air flow to reduce their impact on the electrodes and improve the quality of the recovered products. The aim of this study was to optimize the operation of the patented electrostatic separator by using experimental design methodology to obtain quadratic polynomial models of the recovery and the purity of the products as functions of the high voltage applied to the electrode system and of the air flow through the device. The experiments were conducted with a granular mixture composed of 88% polypropylene (PP) and 12% high-impact polystyrene (HIPS) particles, extracted from the recycling process of waste electrical and electronic equipment, and triboelectrically charged in a fluidized bed device. A voltage of 50 kV combined with an air flow rate of 1700 m³/min maximized the recovery and the purity of PP and HIPS products collected at the outlet of the separator. These results open promising prospects for expanding the use of tribo-electrostatic separation for efficient recycling of granular waste plastics.

Keywords: electrostatic separation; triboelectricity; plastic waste; fluidized bed



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1. Introduction

The concept of circular economy, which involves keeping materials and resources in a closed loop, is intimately related to the development of innovative and efficient physical and chemical processes aimed at recovering valuable materials from waste streams [1]. This concept, which is most often evoked in relation to the management of waste electrical and electronic equipment, as analyzed by Ongondo et al. in [2], can also be applied—as shown by Scarascia-Magnozza et al. [3]—to the use of plastic materials in agriculture. A systematic literature review of the circular economy in the WEEE industry was published by Bressanelli et al. [4]. In a recent book that provides a broad overview of sustainability as applied to plastics [5], Lee Tin Sin and Bee Soo Tueen pointed out that, over recent decades, the exponential increase in industrial and municipal waste poses significant environmental and health risks. Addressing the global challenge represented by waste accumulation and the growing prevalence of a wide diversity of plastics, more particularly those from

information technology and telecommunication equipment, imposes the integration of advanced recovery technologies, particularly those utilizing electrical and magnetic methods, as demonstrated in the study published by Vermesan et al. [6].

Electrostatic separation (i.e., the use of electric forces for particle sorting) is considered to be a promising technology for the recycling industry. Thus, Tilmatine et al. [7] describe several “standard” applications of this technology to the selective sorting of the constituents of plastic/metal, metal/metal, and plastic/plastic mixtures originating from e-waste. In the book, *WEEE Recycling. Research, Development and Policies*, Dascalescu et al. authored a chapter in which they thoroughly reviewed the most widely used electrostatic separation methods employed for the treatment of this class of waste [8]. In the specific case of waste plastics, the sorting is achieved by tribo-electrostatic separators, as those described by Guiqing Wu et al. [9], Silveira et al. [10] or Achouri et al. [11] use the triboelectric effect to charge the particles in specially designed devices. In some of these devices, reviewed by Zemat et al. [12], the tribocharging is mainly due to collisions between particles themselves, entrained in a turbulent air flow. This is the case of fluidized bed-type devices developed by Calin et al. [13,14] and cyclone-type devices studied by Dobidba et al. [15] and Zemat et al. [16]. In other tribochargers, the impacts between the particles and the walls of the device influence to a greater extent the outcome of the process, as is the case with the vibrated-plate and vibrated-tube devices, similar to those investigated by Higashiyama et al. [17], Blajan et al. [18], and Buda et al. [19]; the rotating-cylinder-type devices designed by Inculet et al. [20] and Achouri et al. [21]; the rotary-blades-type devices conceived by Matsushita et al. [22]; or the propeller-type devices proposed by Miloudi et al. [23]. The choice of the most appropriate tribocharging device depends essentially on the composition of the granular mixture to be separated [8].

The separation of the tribocharged particles is achieved in the electric field generated by various electrode configurations, energized from DC high voltage power supplies [24]. The voltage is typically higher than 30 kV and may largely surpass 100 kV (absolute values) in industrial electrostatic separators. In this way, the intensity of the electric field, roughly expressed by the ratio between the applied voltage and the distance between the electrodes, is strong enough to guarantee that the electric forces can drive the particles to distinct collecting compartments, in function of the polarity and the level of the charge they carry. The particle size, shape, and mass also influence the particle trajectories.

The rotating-roll-type and the free-fall-type electrostatic separators are the most used for selective sorting of granular waste plastics, as explained by Tilmatine et al. [25]. The industrial application of the former type is somewhat hampered by the fact that the granular mixture should be fed as a monolayer on the surface of the grounded roll-electrode that introduces the particles in the electric field zone [8]. The latter type of electrostatic separators, where the particles fall freely in the electric field generated between vertical or slightly inclined plate electrodes, allows for relatively higher hourly throughputs demanded by the industry.

Despite their mechanical simplicity and modest power requirements, the use of a free-fall separator is also affected by some restrictions, related to the lack of controllability of gravitational force, which is stronger than the Coulomb force for large-sized particles and impedes the separation efficiency, as argued by Calin et al. [26]. Another major drawback of free-fall tribo-electrostatic separators is related to the impact of the particles on the vertical electrodes to which they are attracted. These impacts cause either strong rebound, the consequence of which is their deviation to the compartment of the collector dedicated to the other plastic product, or their attachment to the electrode, in the form of a layer of fine particles, which leads to a reduction in the electric field. In both cases, the efficiency and purity of the separation will be affected.

Inclined, segmented, and screen mesh-type electrodes are sometimes utilized to avoid or at least reduce the impact effect, as shown by Dascalescu et al. [8], Dobidba et al. [15], and Lingtao Zhu et al. [27]. The use of vertical, rotating cylindrical electrodes is another

way to mitigate the impact effect, as suggested by Touhami et al. [28], Reriballah et al. [29], and Kimi et al. [30].

In an electrostatic separator for granular materials, recently patented by Dascalescu et al. [31], the electric field is generated between two rotating co-axial vertical cylindrical electrodes. The main innovation lies in the fact that the movement of the particles is assisted by downward-oriented air flow to reduce their impact on the electrodes and improve the quality of the recovered products.

The separator was designed to be able to adjust several process control variables, including the high voltages applied to the electrodes and the air flow rate. The aim of this study was to optimize the operation of the patented electrostatic separator. To attain this goal, the design of the experiment methodology [32] was used to obtain quadratic polynomial models of the recovery and the purity of the products as functions of the high voltage applied to the electrode system and of the air flow through the device. The results of this experimental study are expected to pave the way to the industrial application of the novel air-assisted tribo-electrostatic separator.

2. Materials and Methods

2.1. Experimental Set-Up

The electrostatic separator is used to sort, separate, and collect the particles triboelectrically charged by collisions between themselves or with the PMMA walls of a fluidized bed device (Figure 1).

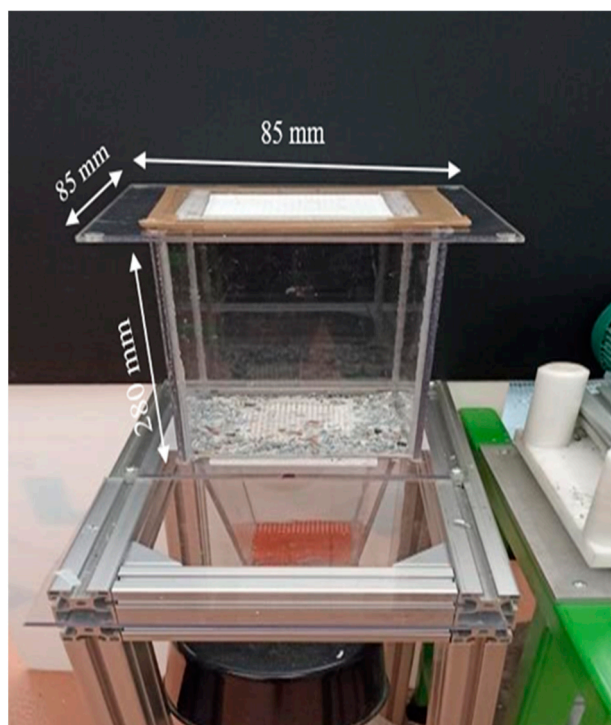


Figure 1. Photograph of fluidized bed triboelectric charger.

Air is injected into the 85 mm × 85 mm × 280 mm fluidized bed chamber using a 1.5 kW blower, controlled by a variable speed drive within a range from 1000 rpm to 4000 rpm. The fluidized bed is equipped with a porous ceramic plate to ensure uniform air distribution through a honeycomb structure. A textile filter is also placed at the top of the chamber to prevent particles from escaping. In this experiment, a charging time of 5 min was used to allow the particles to be well charged before the separation process began.

The principle of the patented air-assisted tribo-electrostatic separator is shown in Figure 2. The stainless steel hopper of a vibratory feeder receives the charged particles and diffuses them using the air flow descending between the two co-axial cylindrical electrodes.

Attracted by the aluminum electrodes of opposite polarities, the particles adhere to their surfaces. Particles of opposite polarity to the outer electrode are drawn into the peripheral compartments and the others into the inner compartments of the collector. The cyclone-type suction device then transfers the particles to separate trays.

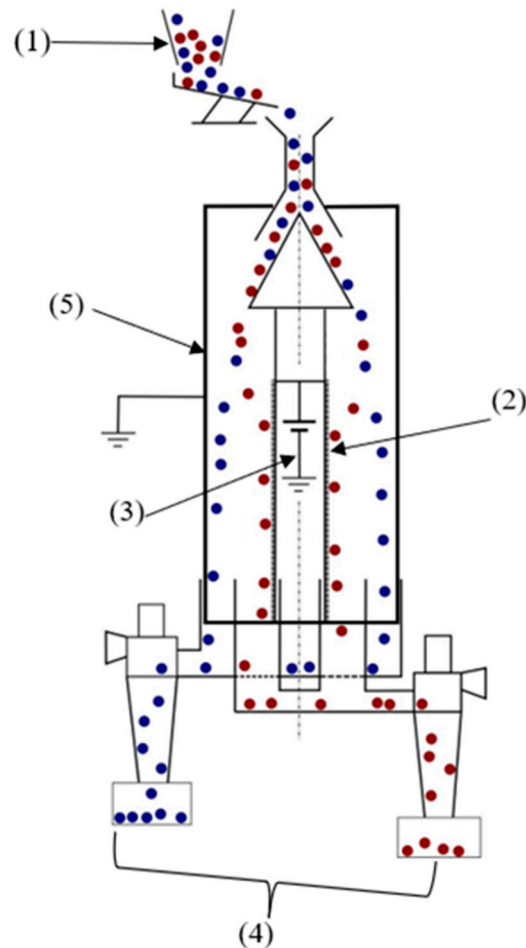


Figure 2. Schematic representation of air-assisted electrostatic separator equipped with two rotating vertical cylindrical electrodes. 1: Vibratory feeder; 2: internal cylindrical electrode; 3: high voltage supply; 4: collecting system; 5: external cylindrical electrode. (red dots: negatively-charged particles; blue dots: positively-charged particles).

In the particular embodiment of the principle of the newly patented electrostatic separation method, the electric field is generated between two rotating co-axial vertical cylindrical electrodes, (2) and (5) in Figure 2. The internal electrode (2), with a radius of 12.5 cm, is connected to a high voltage supply (3) of positive polarity and the external electrode (5), with a diameter of 50 cm, is grounded. At the upper end of the separator, a vibratory feeder (1) receives the particles previously charged in the fluidized bed device and—by means of a conical diffuser—introduces them as a cylindrical curtain at mid-distance from the two electrodes. In the descending air flow generated by the cyclones of the collecting system (4), the particles are subjected to the combined action of electrical, gravitational, and aerodynamical forces.

Attracted by the cylindrical electrodes of opposite polarity, some of the particles adhere to their surfaces, from which they are removed by rotating brushes (not represented in Figure 2). The other particles, in function with the polarity of their charge, are directly collected into either the peripheral or the inner compartment of the collector.

2.2. Experimental Procedure

Mixtures of granules of irregular shapes and with sizes ranging between 2 mm and 5 mm (Figure 3), consisting of 88 g of polypropylene (PP) and 12 g of high-impact polystyrene (HIPS), were triboelectrically charged in the fluidized bed device. The different colors of PP (orange) and HIPS (black) facilitate the visual evaluation of the quality of the products of the electrostatic separation process.

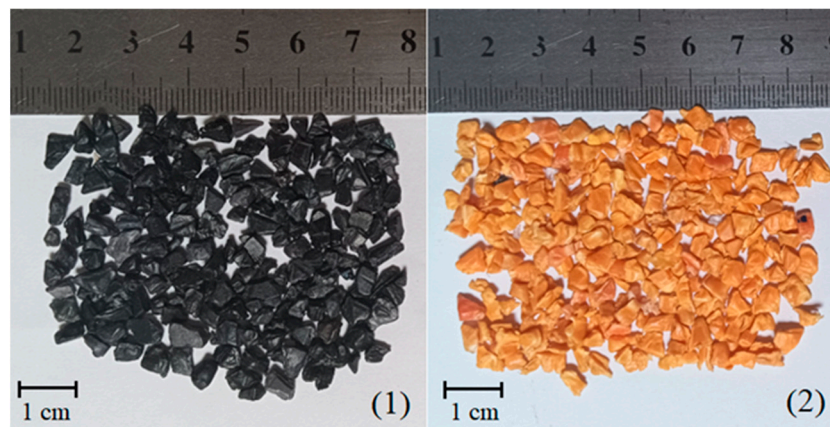


Figure 3. The shape and size of the (1) HIPS and (2) PP granules used in the experimental study of the air-assisted tribo-electrostatic separation process.

Particle size plays a crucial role in the tribocharging stage achieved in the fluidized bed tribocharger. It can influence the fluidity of the fluidized bed and the distribution of electrical charges, which impact the separation of particles according to their response to the electrostatic field. By choosing a specific particle size range (2 mm to 5 mm), this study takes into account the effect of size on electrostatic separation in the separator.

To obtain an accurate assessment of the purity of the separated products, it would be ideal to analyze all the particles recovered in a collecting compartment, but this procedure would be extremely time-consuming. A material divider (Figure 4) was used for extracting 5 g samples representative of the collected products and simplifying the purity measurement. The orange (PP) and black (HIPS) granules contained in a sample were manually sorted and then distinctly weighted for estimating the purity of the collected products. Each time, the experiments were triplicated to allow for the statistical interpretation of the results.



Figure 4. The material divider for sampling the products of the electrostatic separation experiments.

Environmental conditions during the experiments were kept relatively stable, with a relative humidity of $57\% \pm 1.5\%$ and a temperature of $18.2\text{ }^\circ\text{C} \pm 0.4\text{ }^\circ\text{C}$. The steps of the experimental methodology were as follows:

- (1) Turn on the variable air flow rate.
- (2) Switch on the high voltage (HV) power supply.
- (3) Use an electronic balance with a resolution of 0.01 g to measure the total mass of the product recovered from each box.
- (4) Take samples of the recovered product from each bucket to determine their purity using the method described above.

In the first series of preliminary experiments, the air flow rate F was gradually increased from $1200\text{ m}^3/\text{min}$ to $2200\text{ m}^3/\text{min}$, and the applied high voltage U was progressively adjusted to values ranging from 20 kV to 70 kV.

In the second series of experiments, carried out in accordance with a centered-faced composite factorial design, the two factors under studies were fixed at three distinct levels, $1500\text{ m}^3/\text{min}$, $1700\text{ m}^3/\text{min}$, and $2200\text{ m}^3/\text{min}$, for the air flow F , and 30 kV, 50 kV, and 65 kV, for the applied high voltage U . This part of the study was conducted in accordance with the experimental design methodology [32], which offered the possibility of selecting the number and conditions of tests to be carried out according to a precise objective. This approach made it possible to take several factors into account at the same time, to reduce the dispersion of the results associated with measurement and to evaluate the effects of factors and their interactions.

Thus, using this methodology, the process under study was modeled using statistical and analytical rules, which enabled the minimization of the experimentation time, as well as the detection and quantification of the measurement errors. Based on the experimental data, the MODDE 5.0 software (Umetrics, Sweden) [33] built regression models using MLR (multilinear regression) or PLS (partial least squares) algorithms. It also enabled the search for the optimum point using the so-called ‘‘Simplex’’ methodology.

The mass of the two types of particles that were present in the samples extracted from each compartment was measured using an electronic balance and the purity and recovery were calculated using the following formulas:

$$P_{HIPS}(\%) = \frac{M_{HIPS}}{M_{total}} \times 100 \quad (1)$$

$$P_{PP}(\%) = \frac{M_{PP}}{M_{total}} \times 100 \quad (2)$$

$$R_{HIPS}(\%) = \frac{M_{HIPS}}{\sum M_X} \times 100 \quad (3)$$

$$R_{PP}(\%) = \frac{M_{PP}}{\sum M_X} \times 100 \quad (4)$$

M_{HIPS} : Is the mass of the product HIPS.

M_{PP} : Is the mass of the product PP.

M_{total} : Is the total mass in the collector.

M_X : Is the mass of product x (PP or HIPS) collected in the different collectors.

Quadratic mathematical models for each response were obtained by analyzing the composite factorial design data using MODDE 5.0 software (Umetrics, Sweden) [33]. These models were evaluated using the following two indices: R^2 , which measures their fit to the experimental data, and Q^2 , which measures their predictive capacity for new conditions. Values close to 1 for these metrics indicate good quality models.

3. Results

Preliminary tests were carried out (Table 1) to select and evaluate the feasibility of the electrostatic separation (Figure 5) and establish the domain of variation for the applied high voltage U and the air flow F .

Table 1. Preliminary tests.

Test	U (kV)	F (m ³ /min)	PP		HIPS	
			Rec (%)	Pur (%)	Rec (%)	Pur (%)
1	20	1200	29.0	33.2	34.1	41
2	25	1300	36.3	41.5	42.5	51
3	30	1400	43.6	49.8	50.8	61
4	35	1500	59.9	58.1	60	72
5	40	1600	45.4	51.9	44.1	53
6	45	1700	51.7	59.0	47.5	57
7	50	1800	68.7	78.5	35	42
8	55	1900	45.4	51.9	37.5	45
9	60	2000	35.2	40.5	32.5	39
10	65	1900	46.3	52.9	60.8	73.7
11 *	70	2100	/	/	/	/
12 *	75	2200	/	/	/	/

* No separation occurred in these situations.

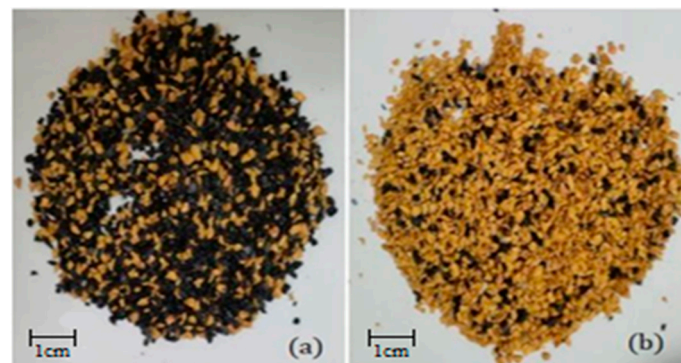


Figure 5. Photograph of recovered products: (a) HIPS; (b) PP.

At 35 kV and above, the performance of the separator improved considerably. Recovery results are particularly satisfactory in the 35 kV to 65 kV range at flow rates between 1500 rpm and 1900 rpm. To optimize the operation of the separator, a face-centered composite experimental design was conducted using MODDE 5.0 software. The results of the experiments reported in Table 2 were processed with MODDE 5.0 software to obtain quadratic polynomial models, including first-order interactions.

For the factors considered in the present study, the quadratic model of the responses will take the following form:

$$y = a_0 + a_1 U^* + a_2 F^* + a_{12} U^*F^* + a_{11} U^{*2} + a_{22} F^{*2} \quad (5)$$

In this formula, U^* and F^* are the normalized centered values of the high voltage U and of the air flow F , defined as follows:

$$U^* = (U - U_{av})/\Delta U; F^* = (F - F_{av})/\Delta F \quad (6)$$

with:

$$U_{av} = (U_{max} + U_{min})/2; \Delta U = (U_{max} - U_{min})/2; \quad (7)$$

$$F_{av} = (F_{max} + F_{min})/2 \Delta F = (F_{max} - F_{min})/2 \quad (8)$$

where U_{av} , U_{max} , and U_{min} are, respectively, the average, maximum, and minimum values of the applied high voltage U ; U_{av} , F_{max} , and F_{min} are, respectively, the average, maximum, and minimum values of the air flow F ; ΔU is half of the interval of variation in the applied high voltage U ; and ΔF is half of the interval of variation in the air flow F .

These models, characterized by high R^2 (i.e., excellent fit to the experimental data), and Q^2 (i.e., good predictive capacity) (Figure 6) represent the recovery and purity of the products as functions of the voltage U^* and the air flow F^* (Figures 7 and 8).

$$R_{PP} = 84.18 + 0.92 U^* - 2.54 F^* + 0.05 U^*F^* - 18.41 U^{*2} - 2.52 F^{*2} \quad (9)$$

Table 2. The recovery and purity rates obtained for PP and HIPS in each of the 11 runs of the face-centered composite experimental design.

Test	U (kV)	F (m ³ /min)	PP		HIPS	
			Rec (%)	Pur (%)	Rec (%)	Pur (%)
1	35	1500	50.9	62.1	60.0	72.3
2	65	1500	50.9	58.2	57.5	69.1
3	35	1900	45.5	52.0	62.5	75
4	65	1900	46.3	53	60.8	73.3
5	35	1700	53.4	61.1	60.8	73.7
6	65	1700	55.1	63.0	60	72.6
7	50	1900	80.1	91.6	43.3	52
8	50	1700	85.1	97.3	50	60
9	50	1900	80.5	92.1	43.3	52.7
10	50	1700	84.8	97.1	47.5	57.4
11	50	1700	84	96	45.8	55.6

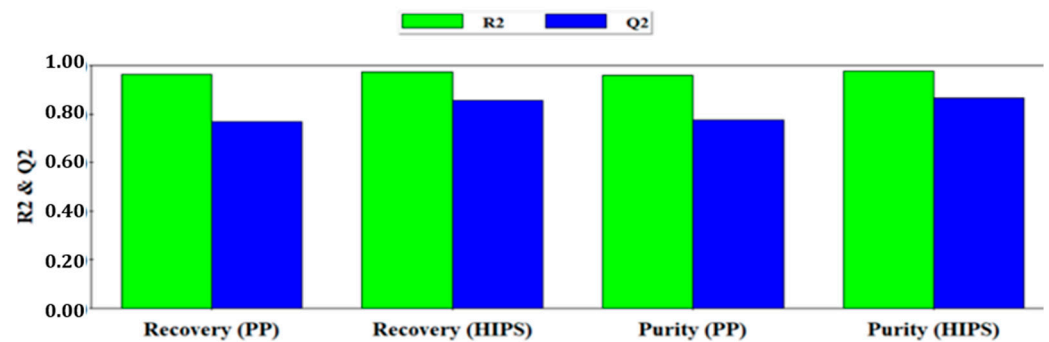


Figure 6. Goodness of fit R^2 and goodness of prediction Q^2 of model.

$$R_{HIPS} = 45.8 - 0.48 U^* + 1.32 F^* + 0.04 U^*F^* + 8.6 U^{*2} + 0.16 F^{*2} \quad (10)$$

$$P_{PP} = 97.04 + 0.27 U^* - 3.95 F^* + 0.49 U^*F^* - 22.02 U^{*2} - 2.35 F^{*2} \quad (11)$$

$$P_{HIPS} = 56.42 - 1.05 U^* - 3.95 F^* - 0.05 U^*F^* + 0.47 U^{*2} - 1.62 F^{*2} \quad (12)$$

PP achieved a remarkable purity of 97.3%, at a recovery rate of 83.2%. For HIPS, a mass of 7.2 g was recovered from 12 g contained in the input, at a purity of 75%.

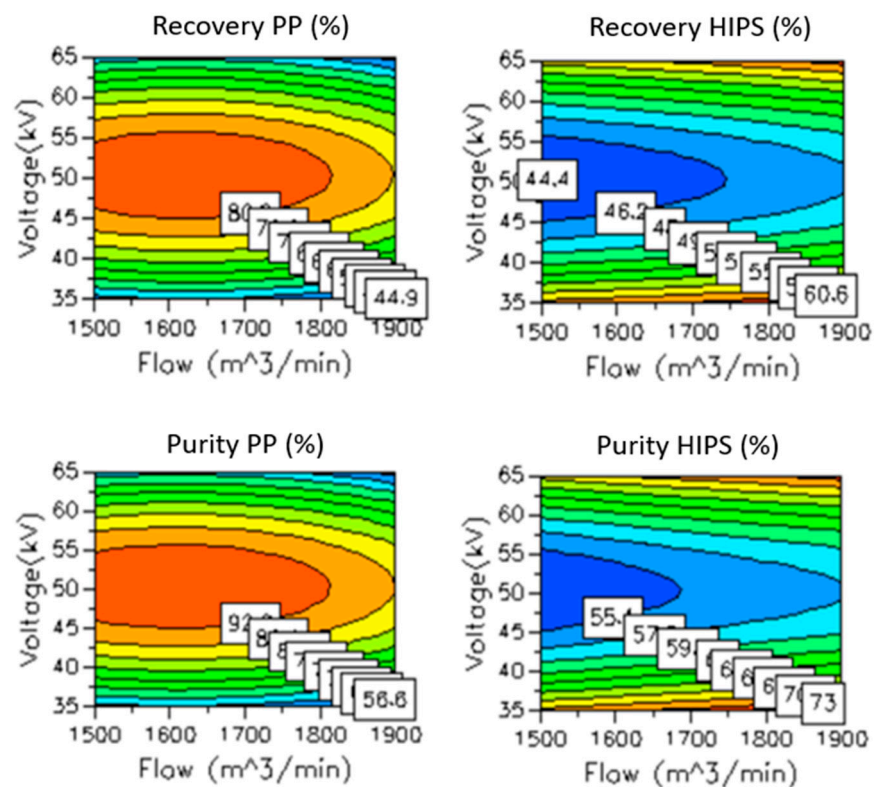


Figure 7. The responses predicted by MODDE 5.0 software as a function of the air flow and the applied high voltage.

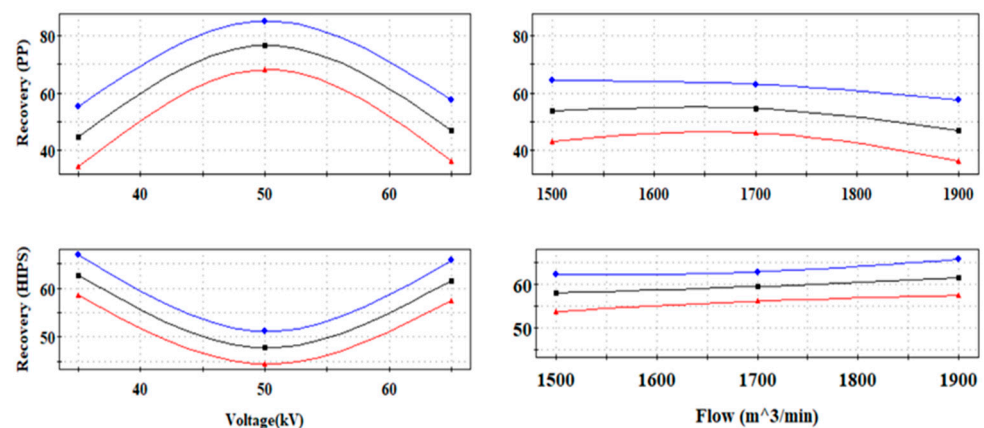


Figure 8. MODDE 5.0—predicted variation in the collected mass values of HIPS and PP. The upper (blue) and the lower (red) curves on each graph indicate the limits of the 95% confidence interval.

4. Discussion

In the triboelectric series, PP tends to be negative relative to HIPS [3]. This indicates that when they are rubbed together, HIPS usually gains a positive charge while PP usually gains a negative charge. Neither the design, nor the operating conditions of the fluidized bed tribocharger were optimized for processing this specific granular mixture. By enhancing the efficiency of the triboelectric charging, it is expected to improve the performances of the electrostatic separation process, too. One solution would be the use of HIPS walls to facilitate the triboelectric charging of PP particles, which represent 88% of the mixture and have fewer chances to collide with the HIPS particles, which represent only 12% of the in-feed. To increase the role of particle–wall collisions in the tribocharging process, the authors have designed a device consisting of a multitude of propeller-type elements,

entrained by an epicyclical train. The device is still under testing and the results will be presented in a forthcoming paper.

Higher purities and recovery rates (sometimes beyond 95%) are constantly reported in the literature [8–11]. Nevertheless, in practically all cases, the experiments were performed with balanced binary mixtures (50% polymer A + 50% polymer B), for which tribocharging is facilitated by the fact that the A and B particles have equal chances to collide with particles of different nature. When the mixture was composed of several plastics, two, three, or four successive tribo-electrostatic separations were needed to obtain good quality products. The experiment described in the paper was conducted with a strongly unbalanced mixture of 88% PP + 12% HIPS, for which standard tribo-electrostatic separation techniques would not be effective as the minority of the HIPS particles achieve very high levels of charge, would collide with the electrode of opposite polarity, and be deviated to the wrong collecting compartment. The downward-oriented air flow between the co-axial cylindrical electrode impedes such collisions and entrains the charged particles to the appropriate collectors.

The results obtained from this study reveal that the two parameters analyzed, namely the applied high voltage U and the air flow F , have a significant influence on the efficiency of electrostatic separation. The coefficients of U^2 are higher than those of U in mathematical models (6)–(9). This explains, for instance, the parabolic aspect of the curves in Figure 7, which express the variation in the recovery as a function of the applied voltage U . Conversely, the quasi-linear aspect of the curves expressing the recovery as a function of the air flow F reflects the fact that the coefficients of F^2 are higher than those of F in (6) and (7). The coefficients of UF in the mathematical models are relatively low but point out the existence of an interaction between the applied voltage U and the air flow F on the recovery and purity and of the obtained products. Thus, as expected, the effects of the voltage U are stronger at low values of air flow F , and the effects of flow rate F are stronger for the low values of the applied voltage U .

By using the response surface modeling methodology, the optimum operation point was reached with a voltage of 50 kV and a flow rate of 1700 m³/min. These values were obtained for a mixture characterized by a well-defined granule size range (2 mm to 5 mm) and a quite particular composition (88% PP and 12% HIPS). The optimum values will be different for granular mixtures having different compositions and granulometric characteristics.

5. Conclusions

The results presented in this paper demonstrate that the use of tribo-electrostatic separation techniques represents a sustainable approach to resource recovery. The high recovery and purity rates of the plastics collected at the outlet of the separator foster the management of the waste-derived raw materials. The more waste plastics are recovered, the less their environmental impact is and the more sustainable the production and consumption practices become.

The specific conclusions of the experimental study conducted on a waste plastic mixture composed of 88% PP and 12% HIPS can be formulated as follows:

- (1) The design of the new tribo-electrostatic separator enables better control of particle trajectories in the electric field generated between the two vertical co-axial cylindrical electrodes. By adjusting the air flow and the electric field intensity in the active zone of the separator, it is possible to reduce the number of particles that inappropriately impact the electrodes, and hence improve the quality of the recovered products.
- (2) The response surface methodology employed for the design of the experimental study enabled the optimization of the operation of a newly patented electrostatic separator, which is expected to be an efficient tool for the processing of waste granular plastic mixtures in the recycling industry.
- (3) For PP, the optimum results (purity: 97.3%; recovery: 83.2%) were obtained for an applied voltage of 50 kV and an air flow rate of 1700 m³/min. The performance indexes

for HIPS were less satisfactory (less the 75% for both the purity and the recovery), but these results were obtained without any attempt being made to maximize the efficiency of the triboelectric charging. Therefore, it can be considered that they open promising prospects for using tribo-electrostatic separation for efficient recycling of granular waste plastic.

Further research should be conducted to optimize the operation of the fluidized bed device and evaluate other potential triboelectric chargers (vibratory-type, rotating-cylinder-type, cyclone-type). Several technical solutions are under investigation to facilitate the direct transfer of the granular mixture from the outlet of the triboelectric charger to the input of the air-assisted electrostatic separator. The robustness of the air-assisted tribo-electrostatic separation needs to also be investigated, to evaluate—on the one hand—the sensibility of the outcome of the process for possible fluctuations of the control variables (applied high voltage and air flow), and—on the other hand—the influence of un-controlled “noise factors”, such as the variability of the composition of the in-feed waste plastic mixtures, or changes in the environmental conditions (temperature and relative humidity of ambient air).

Author Contributions: Conceptualization, L.D., T.Z. and S.N.; methodology, K.M., L.D. and M.M.; validation, L.D. and S.N.; investigation, F.M.; resources, T.Z.; data curation, F.M. and K.M; writing—original draft preparation, F.M.; writing—review and editing, L.D. and T.Z.; supervision, K.M. and M.M.; project administration, S.N., L.D. and T.Z.; funding acquisition, S.N., M.M. and T.Z. All authors have read and agreed to the published version of the manuscript.

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References

1. Kahhat, R.; Kim, J.; Xu, M.; Allenby, B.; Williams, E.; Zhang, P. Exploring e-waste management systems in the United States. *Resour. Conserv. Recycl.* **2008**, *52*, 955–964. [[CrossRef](#)]
2. Scarascia-Mugnozza, G.; Sica, C.; Russo, G. Plastic materials in European agriculture: Actual use and perspectives. *J. Agric. Eng.* **2011**, *42*, 15–28. [[CrossRef](#)]
3. Ongondo, F.O.; Williams, I.D.; Cherrett, T.J. How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Manag.* **2011**, *31*, 714–730. [[CrossRef](#)] [[PubMed](#)]
4. Bressanelli, G.; Saccani, N.; Pigosso, D.C.; Perona, M. Circular Economy in the WEEE industry: A systematic literature review and a research agenda, *Sustain. Prod. Consum.* **2020**, *23*, 174–188. [[CrossRef](#)]
5. Sin, L.T.; Tuen, B.S. (Eds.) Recycling and circular economy of plastics. In *Plastics and Sustainability*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 175–203.
6. Vermeşan, H.; Tiuc, A.E.; Purcar, M. Advanced recovery techniques for waste materials from IT and telecommunication equipment printed circuit boards. *Sustainability* **2019**, *12*, 74. [[CrossRef](#)]
7. Tilmatine, A.; Medles, K.; Bendimerad, S.E.; Boukholda, F.; Dascalescu, L. Electrostatic separators of particles: Application to plastic/metal, metal/metal and plastic/plastic mixtures. *Waste Manag.* **2009**, *29*, 228–232. [[CrossRef](#)]
8. Dascalescu, L.; Zeghloul, T.; Iuga, A. Electrostatic separation of metals and plastics from waste electrical and electronic equipment. In *WEEE Recycling: Research, Development, and Policies*; Chagnes, A., Cote, G., Ekberg, C., Nilsson, M., Retegan, T., Eds.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 75–106. [[CrossRef](#)]
9. Wu, G.; Li, J.; Xu, Z. Triboelectrostatic separation for granular plastic waste recycling: A review. *Waste Manag.* **2013**, *33*, 585–597. [[CrossRef](#)]
10. Silveira, A.V.M.; Cella, M.; Tanabe, E.H.; Bertuol, D.A. Application of tribo-electrostatic separation in the recycling of plastic wastes. *Process Saf. Environ. Prot.* **2018**, *114*, 219–228. [[CrossRef](#)]
11. Achouri, I.-E.; Boukholda, M.-F.; Medles, M.; Richard, G.; Zeghloul, T.; Dascalescu, L. Electrostatic separation of tribocharged granular mixtures of two or more plastics originating from WEEE. *IEEE Trans. Ind. Appl.* **2022**, *58*, 7701–7708. [[CrossRef](#)]
12. Zelmat, M.; Rizouga, M.; Tilmatine, A.; Medles, K.; Miloudi, M.; Dascalescu, L. Experimental comparative study of different tribocharging devices for triboelectric separation of insulating particles. *IEEE Trans. Ind. Appl.* **2013**, *49*, 1113–1118. [[CrossRef](#)]
13. Calin, L.; Caliap, L.; Neamtu, V.; Morar, R.; Iuga, A.; Samuila, A. Tribocharging of granular plastic mixtures in view of electrostatic separation. *IEEE Trans. Ind. Appl.* **2008**, *44*, 1045–1051. [[CrossRef](#)]

14. Calin, L.; Catinean, A.; Bilici, M.; Dascalescu, L.; Samuila, A. Electrostatic separation of HIPS/ABS and HIPS/ABS-PC plastic mixtures from IT equipment using fluidized bed tribocharging. *Part. Sci. Technol.* **2021**, *40*, 113–122. [[CrossRef](#)]
15. Dodbiba, G.; Shibayama, A.; Miyazaki, T.; Fujita, T. Electrostatic separation of the shredded plastic mixtures using a tribo-cyclone. *Magn. Electr. Sep.* **2002**, *11*, 63–92. [[CrossRef](#)]
16. Zelmat, M.; Tilmatine, A.; Rizouga, M.; Gouri, R.; Medles, K.; Dascalescu, L. Experimental analysis of a cyclone tribocharging device for free-fall triboelectric separation of plastic particles. *IEEE Trans. Dielectr. Electr. Insul.* **2013**, *20*, 1584–1589. [[CrossRef](#)]
17. Higashiyama, Y.; Ujiie, Y.; Asano, K. Triboelectrification of plastic particles on a vibrating feeder laminated with a plastic film. *J. Electrostat.* **1997**, *42*, 63–68. [[CrossRef](#)]
18. Blajan, M.; Beleca, R.; Iuga, A.; Dascalescu, L. Triboelectrification of granular plastic wastes in vibrated zigzag-shaped square pipes in view of electrostatic separation. *IEEE Trans. Ind. Appl.* **2010**, *46*, 1558–1563. [[CrossRef](#)]
19. Buda, G.; Bilici, M.; Samuila, A.; Dascalescu, L. Experimental study of the tribocharging process of plastic granular materials on a vibratory feeder device. *IEEE Trans. Dielectr. Electr. Insul.* **2013**, *20*, 1489–1496. [[CrossRef](#)]
20. Inculet, I.I.; Castle, G.S.P.; Brown, J.D. Electrostatic separation of plastics for recycling. *Part. Sci. Technol.* **1998**, *16*, 91–100. [[CrossRef](#)]
21. Achouri, I.E.; Zeghloul, T.; Richard, G.; Medles, K.; Dascalescu, L.; Senouci, K. Endurance test for evaluating the performances of a novel rotating-cylinder-type triboelectric charging device. *IEEE Trans. Ind. Appl.* **2020**, *56*, 7005–7011. [[CrossRef](#)]
22. Matsushita, Y.; Mori, N.; Sometani, T. Electrostatic separation of plastics by friction mixer with rotary blades. *Electr. Eng. Jpn.* **1999**, *127*, 33–40. [[CrossRef](#)]
23. Miloudi, M.; Medles, K.; Tilmatine, A.; Brahami, M.; Dascalescu, L. Modeling and optimization of a propeller-type tribocharger for granular materials. *J. Electrostat.* **2011**, *69*, 631–637. [[CrossRef](#)]
24. Dötterl, M.; Wachsmuth, U.; Waldman, L.; Flachberger, H.; Mirkowska, M.; Brands, L.; Meier, P.M.; Stahl, I. Electrostatic separation. In *Ullmann's Encyclopedia of Industrial Chemistry*; Wiley: New York, NY, USA, 2016. [[CrossRef](#)]
25. Tilmatine, A.; Medles, K.; Younes, M.; Bendaoud, A.; Dascalescu, L. Roll-type versus free-fall electrostatic separation of tribocharged plastic particles. *IEEE Trans. Ind. Appl.* **2010**, *46*, 1564–1569. [[CrossRef](#)]
26. Calin, L.; Mihalciou, A.; Das, S.; Neamtu, V.; Dragan, C.; Dascalescu, L.; Iuga, A. Controlling particle trajectory in free-fall electrostatic separators. *IEEE Trans. Ind. Appl.* **2008**, *44*, 1038–1044. [[CrossRef](#)]
27. Zhu, L.; He, J.; Chen, H.; Huang, S.; Tang, W.; Yang, B. Distribution of field intensity and separation behavior of charged particles in the cascade electrostatic field. *Powder Technol.* **2024**, *431*, 11906. [[CrossRef](#)]
28. Touhami, S.; Aksa, W.; Maammar, M.; Zeghloul, T.; Medles, K.; Dascalescu, L. Numerical simulation of the behavior of insulating particles in a free fall tribo-electrostatic separator with four vertical cylindrical electrodes. *J. Electrostat.* **2019**, *97*, 8–14. [[CrossRef](#)]
29. Reriballah, H.; Aksa, W.; Touhami, S.; Medles, K.; Zeghloul, T.; Dascalescu, L. Experimental analysis of the operation of a free-fall separator equipped with four rotating cylinders. In Proceedings of the 2019 IEEE Industry Applications Society Annual Meeting, IAS 2019, Baltimore, MD, USA, 29 September–3 October 2019; Institute of Electrical and Electronics Engineers Inc.: New York, NY, USA, 2019. [[CrossRef](#)]
30. Kimi, I.E.; Miloudi, M.; Touhami, S.; Fekir, D.E.; Tilmatine, A. Experimental investigation of a modified free-fall tribo-electrostatic separator with rotating electrodes. *Part. Sci. Technol.* **2021**, *40*, 243–251. [[CrossRef](#)]
31. Dascalescu, L.; Zeghloul, T.; Medles, K. Method and Device for the Electrostatic Separation of Granular Materials. Patent WO2019/171011 A1, 12 September 2019.
32. Bradley, J.; Montgomery, D.C. *Design of Experiments. A Modern Approach*; Wiley: Hoboken, NJ, USA, 2021; ISBN 978-1-119-74601-0.
33. Umetrics, A.B. *MODDE 5.0. User Guide and Tutorial*; Umetrics: Umea, Sweden, 1999.

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