



# Sink–float density separation of post-consumer plastics for feedstock recycling

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## Abstract

The paper focuses on current mechanical waste processing technologies and out-of-the-box processes linked to the processing of coal and mineral resources, to ensure high-quality feedstock recycling of polyolefin-rich post-consumer plastic fractions. Moreover, the study aims to provide the basis for the technical and economic feasibility of the chemical recycling route of this plastic fraction. When evaluating common mechanical processes, either dry or wet ones, sink–float separation in a cylindrical centrifugal force separator achieves the best results. It combines the advantages of a simple, robust apparatus of low complexity and high capacity with selective separation through the accelerated settling of particles in the centrifugal field. Furthermore, the disconnection of the separation medium feed from the solid input increases residence times. Based on the above findings, a pilot-scale plant was constructed which consists of a centrifugal force separator and a hydro jig for the pre-separation of heavy waste components. Several test campaigns were conducted to separate polyolefins from various waste fractions. Two-stage processing in the centrifugal force separator rendered almost 90 wt% of polyolefin content in the produced lightweight fraction and of polyolefin recovery. One-stage processing, on the other hand, resulted in reduced polyolefin content in the lightweight fraction.

**Keywords** Plastic recycling · Wet density separation · Processing · Polyolefins

## Introduction

According to the report by “Plastics Europe 2016”, about 4–6 wt% (weight percentage) of the global petroleum production was processed into 322 million tons of polymer products in 2015 [20]. 49 million tons were intended for Europe (28 EU member states plus Norway and Switzerland). Half of the produced polymers are either polyethylene or polypropylene (PE, PP), which are the most common

polyolefins (hereinafter referred to as POs). These POs are mainly used for packaging and usually have a short lifetime, which means they are often used only for a few days. In view of their recyclability, POs are of high interest to a sustainable polymer waste management. In 2014, more than 25 million tons of polymer waste, so-called post-consumer plastics (hereinafter referred to as PCP), ended up in Europe in three waste management paths [20].

1. Landfilling with the main goal of safe disposal, mostly including pre-treatment for mass reduction and inertisation.
2. Energy recovery with the main goal of utilising the energy bound in the polymer structure by converting it into so-called solid recovered fuels to be used in co-combustion plants (e.g. cement kilns).
3. Material recycling with the main goal of reutilising the material by polymer type, including treatment steps for cleaning, sorting, and granulating.

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According to a proposed European Union directive on Circular Economy, in 2015, the Commission published the first version of the Circular Economy Action Plan, which set the ambitious target of treating waste as a resource. This means that resources should be managed sustainably and not be wasted. The key objective of this directive is to transform the linear European economy into a circular economy which includes favouring waste recycling over incineration and landfilling. The goals are: increased recycling targets for municipal waste and packaging waste; imposing strict landfill restrictions; reducing food waste; promoting the re-use approach; and creating minimum standards for producer responsibility. The following objectives of the action plan are relevant to plastic recycling [5]:

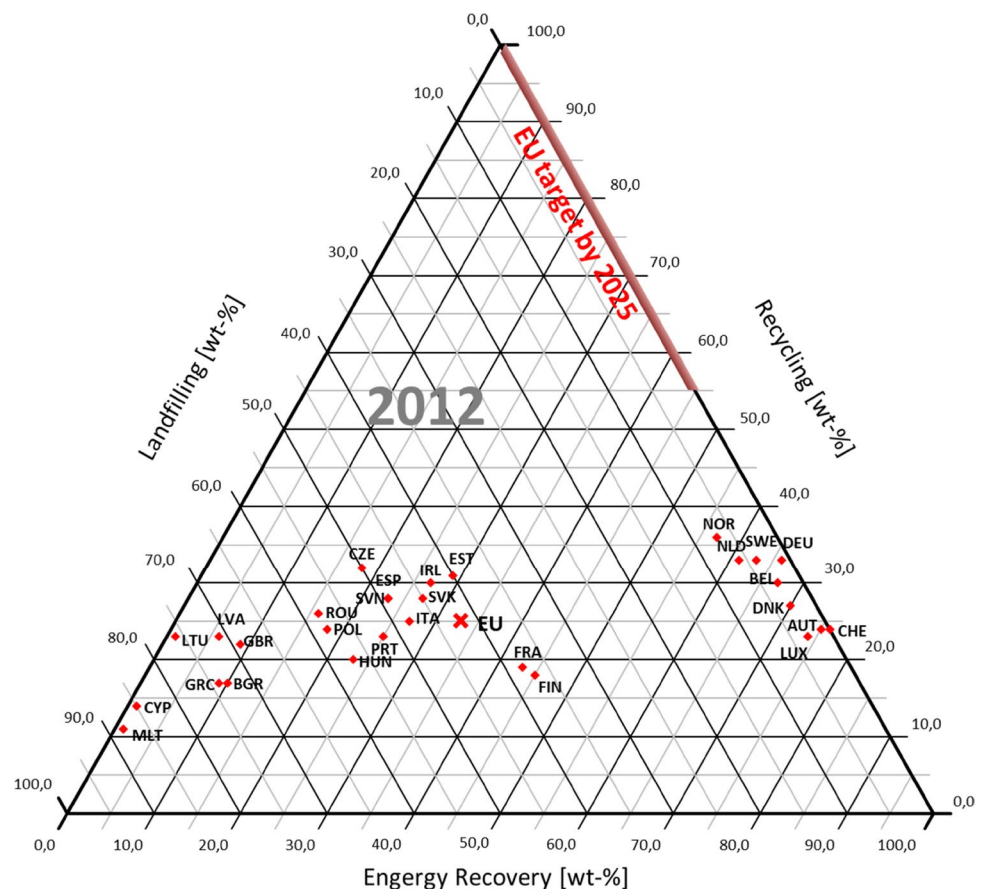
- Reducing the landfill of municipal waste to a maximum of 10 wt% by 2030 and raising the recycling rate up to 65 wt%.
- All packaging waste (glass, plastic, paper and cardboard, metals, wood, etc.) is expected to be recycled by 75 wt% by 2030, with the specific target for plastic packaging being 55 wt%. This is more than double the current recycling performance of 22.5 wt% [5, 6].

Therefore, recyclable polyolefins may contribute to increased recycling rates as they cover most of the plastics included in the municipal waste and sorted packaging waste (see supplementary information [16]). As illustrated in the RIL (Recycling, Incineration, and Landfilling) diagram below (Fig. 1), the application of these three waste management paths varies among the European countries. This method was developed by the Chair of Waste Processing Technology and Waste Management of Montanuniversitaet Leoben (MUL) to visualise the dynamics of national municipal waste management performances [21] and is based on [6, 19].

The countries' positions in the diagram mirror their respective intensity of adaptation to the three waste management paths for PCP (reference year 2012). As a result, the European countries may be divided into three groups that indicate the respective changes in recycling policies that are necessary to meet the EU recycling targets by 2025.

1. Countries characterised by the emphasis on landfilling, coupled with a small portion of energy recovery: Malta (MLT), Cyprus (CPR), Greece (GRC), Latvia (LVA), Bulgaria (BGR), and Great Britain (GBR). They are positioned near the lower left edge of the diagram. This

**Fig. 1** Treatment of post-consumer plastics (PCP) in Europe (EU27+2) in 2012; EU target by 2025 for separately collected plastic packaging waste: recycling rate  $\geq 55$  wt% and landfill ban (0 wt%)



group has to cut landfilling dramatically to meet EU targets.

2. Countries being in a transition process and using a specific combination of landfilling, energy recovery, and material recycling: Finland (FIN), Ireland (IRL), Poland (POL), Estonia (EST), Portugal (PRT), Italy (ITA), France (FRA), Slovenia (SVN), Hungary (HUN), Lithuania (LTU), Romania (ROU), Spain (ESP), Slovakia (SVK), and the Czech Republic (CZE). This combination of waste treatment is in the middle of the chart. These countries already have incineration technology which they can probably develop. Further, they still need to enforce the landfill ban on plastics to achieve EU recycling targets.
3. Countries placing greater focus on the combination of energy recovery and material recycling: Norway (NOR), Switzerland (CHE), Germany (DEU), Austria (AUT), Denmark (DNK), Belgium (BEL), Luxembourg (LUX), the Netherlands (NLD), and Sweden (SWE) (most of them have already launched a landfill ban for PCP). They are positioned near the middle to lower right edge of the chart. These countries need to shift their focus from incineration of plastics to recycling.

Without a doubt, Europe's plastic recycling performance generally needs improvement because 40 wt% of Europe's PCP is landfilled, slightly more than 30 wt% are energetically recovered, and barely 30 wt% undergo material recycling. This currently makes material recycling the least favoured option. A major reason for the obvious need to further close the gap in the material cycle of plastics may be found in the lack of other recycling options regarding mechanical recycling. This recycling technology is hampered by the low product quality of already used material, as compared to virgin material. Shortcomings that narrow the scope of application of secondary material include odour and colour as well as reduced mechanical, physical, and chemical properties.

Apart from mechanical recycling, feedstock or chemical recycling is another promising option to boost PCP recycling. It uses thermal cracking or pyrolysis, often connected with a refinery. When established refining and petrochemical technologies are applied, these processes trigger endless recycling of the valuable hydrocarbons and render similar product qualities like virgin material. Tracking the history of the thermo-chemical conversion processes described above (depolymerisation or degradation) [1, 14, 18, 24] clearly shows that the successful implementation and establishment of these technologies strongly depend on a specified feedstock available in specific quality and quantity. Furthermore, it is a well-established fact that POs, representing the major portion of plastics, are used worldwide and are highly suitable for feedstock recycling.

Currently, most mechanical waste preparation techniques involving solid waste fractions containing PCP are based on dry processing technologies, especially when used for energy recovery purposes. Thus, high calorific values representing the principal fuel property are achieved more easily and more efficiently than with wet mechanical processing. Although the sensor-based sorting technology is widely used for PCP separation, it requires complex plant structures. Other dry processes which mainly serve the conditioning of waste streams are conducted in plants of lower complexity. Wet processes employed in coal processing for coal firings are preferred in waste processing if the calorific value of the product stream plays a minor role and if a selective and efficient separation is required, as is the case with material recycling. Other advantages of wet processing refer to the increase in material-specific throughputs per unit, the potential to also separate fine particles, reduction of dust emission (explosion protection), and the simultaneous removal of surface contaminations. The other side of the coin relates to higher efforts and costs in terms of dewatering and wastewater treatment.

Applying the proper mechanical preparation to the waste streams of exploitable PO potential must be regarded as the key to ensure adequate feedstock qualities and quantities as well as to support the technical and economic feasibility of the chemical plastic recycling route. This paper aims to demonstrate whether a high-quality PO fraction (PO-content > 90 wt%) can be separated from diverse PCP containing waste fractions of various initial PO contents (~ 10, ~ 30 and ~ 50 wt%) by density when applying a jig for heavy material (> 2000 kg/m<sup>3</sup>, kilogram per cubic meter) pre-separation and a sink–float process in a centrifugal force separator.

### Dry versus wet mechanical waste treatment—a comparison

In a comprehensive comparison, Bauer [3] has outlined the respective benefits and drawbacks of wet and dry mechanical processing technologies for plastic separation. Emphasis is put on the separation of POs from the residual material stream, making it as efficient and complete as possible. Sensor-based sorting technology using near-infrared light (NIR SBS) proves to be the dry processing technology most frequently employed for PCP separation.

On the other hand, wet density separation processes including sink–float separation [22] and separation by layering (hydro jigs, [11, 12, 15, 28]) are promising options for PO separation. Separation by layering provides efficient pre-separation of heavy waste components, such as glass, stones, and metals. Therefore, the following considerations focus on three wet density separation processes

depending on sink–float separation: one uses gravity and the others use centrifugal force.

### Theoretical background of wet density separation

Figure 1 illustrates the density ranges of common types of materials in municipal waste. Obviously, POs have a lower density than most of the other wastes and the separation medium, water, assumed at about  $1000 \text{ kg/m}^3$ . Only various biogenic materials and wood reach densities lower than that of PO. Therefore, employing the sink–float separation technique seems to be most efficient to separate PO from PCP waste fractions. To curb contamination of the PO fraction, very inhomogeneous waste fractions should undergo pre-separation, for instance, by including a screening step, which allows discharge of impurities like biogenic materials and wood.

### Comparing the benefits and drawbacks of various sink–float separators

Sink–float separators may either use gravity or centrifugal force. Centrifugal force devices may display cylindrical–conical or cylindrical designs. The cylindrical–conical configuration is characteristic of the conventional cyclones, also known as gas cyclones, which are used to sort PCP in various mechanical processing plants. They are related to the cylindrical separator, whose axis is inclined from the horizontal; however, they are applied only in the field of coal and mineral processing, e.g. large coal dense medium separators (LARCOCODEMS) [4]. The cylindrical separator differs from the conventional cyclone through one or more openings which are mounted perpendicularly to the cylindrical separation chamber. These openings facilitate the tangential discharge of the separation medium or, in case of special designs, also its multiple feeds. In cyclones, on the other hand, the separation medium is centrally discharged via the vortex finder and the apex [25] (see Fig. 2).

Moreover, in a cylindrical centrifugal force separator (hereinafter referred to as CFS) [2, 7, 9, 10, 29], the input material stream is directly fed into the vortex without passing the supplying pump, the measurement, and control equipment. This advantage helps prevent plugging and abrasion. The separation medium and the solid particles move in a countercurrent flow. In addition, we assume that, compared to the conventional cyclone, the modified geometry also causes a change in the flow pattern of the separation medium, particularly regarding the three velocity components—radial, tangential, and axial. Furthermore, it is easy to influence particle residence time through constructional and operational changes. Thus, a beneficial (high) ratio to the settling time is generated and efficient separation may be expected.

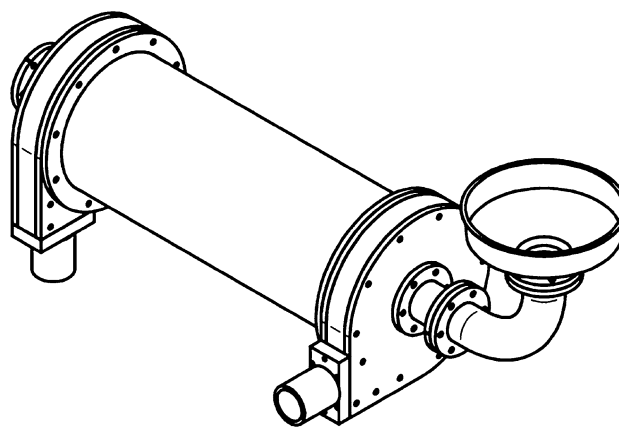


Fig. 2 Cylindrical centrifugal force separator (CFS)

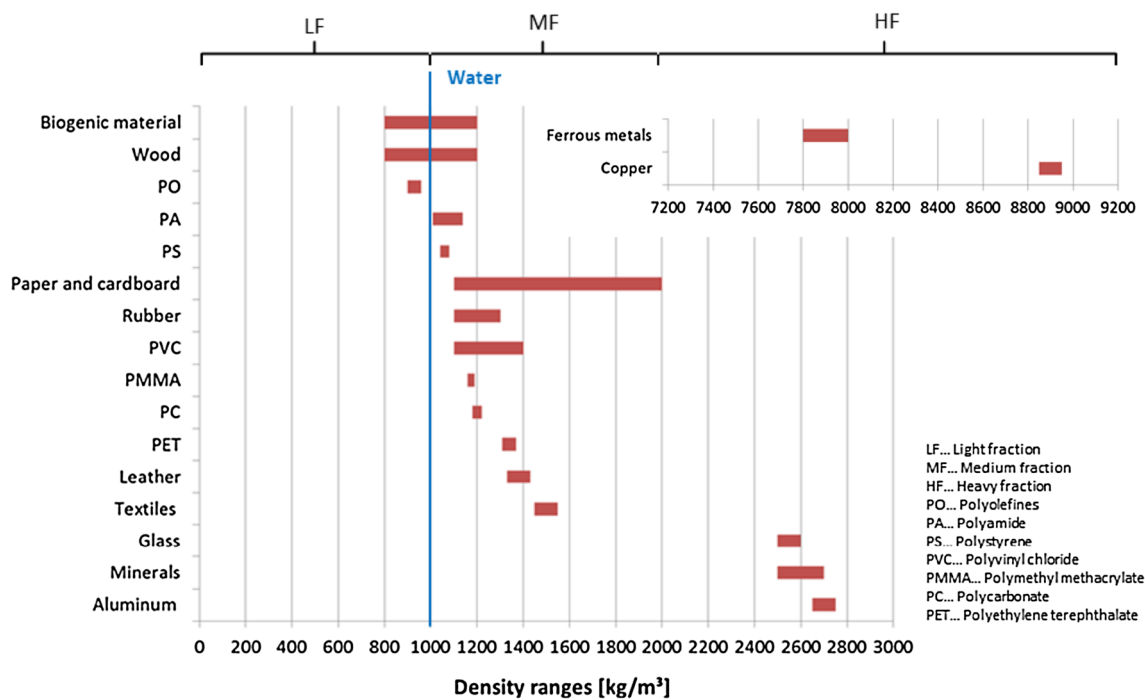
Table 1 compares the various technologies of PCP sink–float separation currently applied and gives an overview of their specific benefits and drawbacks. Comprehensive descriptions of the function principles, design, and schemes have been provided by Schubert [25] as well as by Kranert and Cord-Landwehr [13].

### Jig and centrifugal force separator: the pilot scale plant, “Plastic Reborn”

Based on the comparison and evaluation of various mechanical processing technologies and apparatuses, a pilot-scale plant was built at Montanuniversitaet Leoben. It was designed to separate POs from diverse waste fractions containing PCP to enhance feedstock recycling. This test facility is the key element of Research Studio Austria, “Plastic Reborn”, which has been funded by the Austrian Research Promotion Agency and several industrial partners. The concept of the pilot-scale plant, with an average throughput capacity of  $65 \text{ kg/h}$  dry material (max.  $125 \text{ kg/h}$ , kilograms per hour), is based on wet density separation and serves to meet several purposes: processing of waste fractions already mechanically treated, such as mixed plastics of rather homogeneous character, resulting from packaging waste sorting; processing of more heterogeneous material streams originating from municipal waste and similar industrial wastes, rejects from paper mills, or even selected fractions from landfill mining; and as the ultimate goal, producing three output streams that include heavy fraction (HF), medium fraction (MF), and light fraction (LF) (boundaries according to the density: see upper axis of Fig. 3). The HF mainly contains heavy inorganic components such as glass, sand, stones, and metals. After optional metal separation, this fraction is landfilled. Potential utilisation of this recycled material in the construction industry is under investigation. The MF will primarily comprise residual [heavy, density

**Table 1** Comparison of the benefits and drawbacks of sink–float separators, concerning efficient post-consumer plastic separation

Sink–float separators	Benefits	Drawbacks
Gravity separator	+ Simple process	Large space requirement Adhering air bubbles affecting the separation process Feed and discharge elements affecting the separation process Use of gravity alone—strong impact of particle size and shape Low flow velocities causing low material throughputs with increased size ratio
	+ No rotating parts	
	+ Low investment costs	
Sorting cyclone	+ Simple and compact process	Wide local fluctuations of the centrifugal force field Increased forces generated by increased flow velocities, yet causing low residence times and affecting separation process
	+ No rotating parts	
	+ Increased forces due to centrifugal force field	
Sorting centrifuge	+ Increased material throughputs per unit	Complex process and apparatus Rotating parts subjected to high forces Increased maintenance expenditures High investment and operating costs Sensitivity towards input material quality and mass flow
	+ Low investment and operating costs	
	+ Very high forces in the centrifugal force field	
	+ Negligible impact of particle size and shape	
	+ Parallel dewatering facilitated by the design Small space requirement	
	+ Surface purification resulting from increased shear forces between particles and liquid ring	



**Fig. 3** Density ranges of common waste types



between the inner air core and the outer water vortex. The results of the separation process may be improved by reprocessing the LF in a second stage.

### Experimental description of the test runs conducted in the pilot-scale plant

Separation efficiency is evaluated by calculating the PO content (or purity) of the output stream LF and the PO recovery to the LF derived from mass balancing. Along with the total mass recovery, they are defined in relation to dry mass, as expressed in the following formulas (1–3):

$$\begin{aligned} \text{Content of material : } c_{i,j} &= \frac{m_{i,j}}{m_{j,\text{tot}}}, \\ \text{Material recovery : } r_{i,j} &= \frac{m_{i,j}}{m_{i,F}}, \\ \text{Mass recovery : } r_{m,j} &= \frac{m_{j,\text{tot}}}{m_{F,\text{tot}}}, \end{aligned} \quad (1-3)$$

where  $c_{i,j}$  is the content of material  $i$  (purity) (kg/kg in wt%),  $m_{i,j}$  the mass of material  $i$  in stream  $j$  (kg),  $m_{j,\text{tot}}$  the total mass of stream  $j$  (kg),  $r_{i,j}$  the recovery of material  $i$  (kg/kg in wt%),  $m_{i,F}$  the mass of material  $i$  in the feed (kg),  $r_{m,j}$  mass recovery (kg/kg in wt%),  $m_{F,\text{tot}}$  total mass of the feed (kg).

The PO content of the input and output fractions was determined by simple sink–float analysis in the laboratory. It was assumed that all floating particles represent PO if not identified otherwise by visual inspection. Moreover, a proper guideline for good laboratory practice was developed to achieve reliable results. The three test campaigns covered the following scopes:

1. analysing the effects of significant operation parameters on the separation process in the CFS, based on the PO content in the LF when processing a PP/PET (polyethylene terephthalate) mixture;
2. determining the separation efficiency to be obtained in the pilot-scale plant “Plastic Reborn” when density separation is applied to representative waste fractions containing PCP under optimised operation conditions;

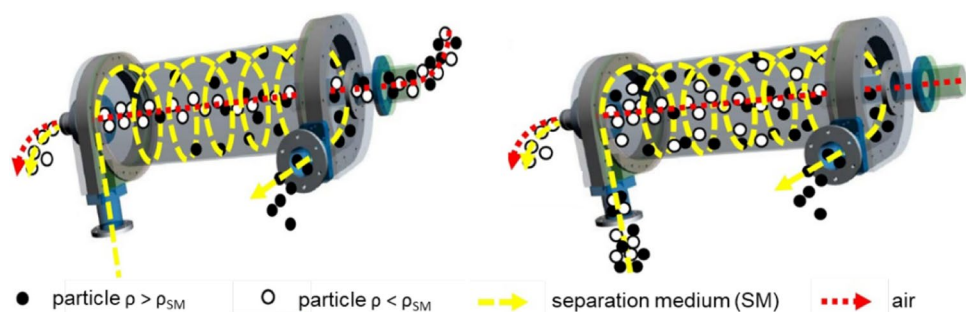
3. testing the potential enhancement of separation efficiency by using two-stage processing and exploring the various relationships between the two CFS stages under identical operation conditions.

*Ad 1.* The main parameters affecting the separation process in the CFS are length, inclination, and volume flow rate of the separation medium. Both length and inclination are relevant criteria for the particle residence time in the separator. Moreover, the inclination impacts the LF. The volume flow rate corresponds to the strength of the velocity field in the CFS and determines the magnitude of the tangential velocity as well as the acting centrifugal forces. During the first test campaign, the three parameters mentioned above were tested on both a high (+) and a low (–) level. Sufficient information for a statistical test evaluation was gathered by conducting eight test runs, which was required for a  $2^k$  factorial test for  $k=3$  determinants. Moreover, to meet reproducibility standards, each test run was repeated three times with an identical parameter setup, but with a randomised sequence to avoid systematic errors. The three parameters were modified for the individual test runs, using variations for length ( $L$ ) between  $L+$  and  $L- = 0.6 L+$ , for inclination ( $\alpha$ ) between  $\alpha+$  and  $\alpha- = 0.5 \alpha+$ , and for the volume flow rate (VF) between  $\text{VF}+$  and  $\text{VF}- = 0.8 \text{VF}+$ . The PO content of the LF served as the test variable. The processed input material consisted of a 2:3 synthetic mixture of coloured PO flakes (actually PP flakes,  $\rho \sim 900 \text{ kg/m}^3$ ) and coloured PET flakes ( $\rho \sim 1300 \text{ kg/m}^3$ ).

*Ad 2.* Within the second test campaign, diverse waste fractions containing PCP of various initial PO contents were processed in the pilot-scale plant. Separation efficiency was expressed in PO content of the LF and PO recovery to the LF was analysed. Moreover, fractions were grouped into three categories with a PO content of  $\sim 10$ ,  $\sim 30$ , and  $\sim 50 \text{ wt\%}$ , each including at least two fractions.

*Ad 3.* To prove a potential increase in separation efficiency when applying two-stage processing, the LF of the first separation step was reprocessed. In addition, we studied the effects of countercurrent (standard) and cocurrent operation modes, available for the CFS (see Fig. 5) based

**Fig. 5** Cylindrical centrifugal force separator (CFS) in standard countercurrent operation (left) and in cocurrent operation (right)



**Table 2** Results of a  $2^k$  factorial test displaying the impact of three operation parameters, length, inclination, and volumetric flow rate of the separation medium, on the separation process in the CFS

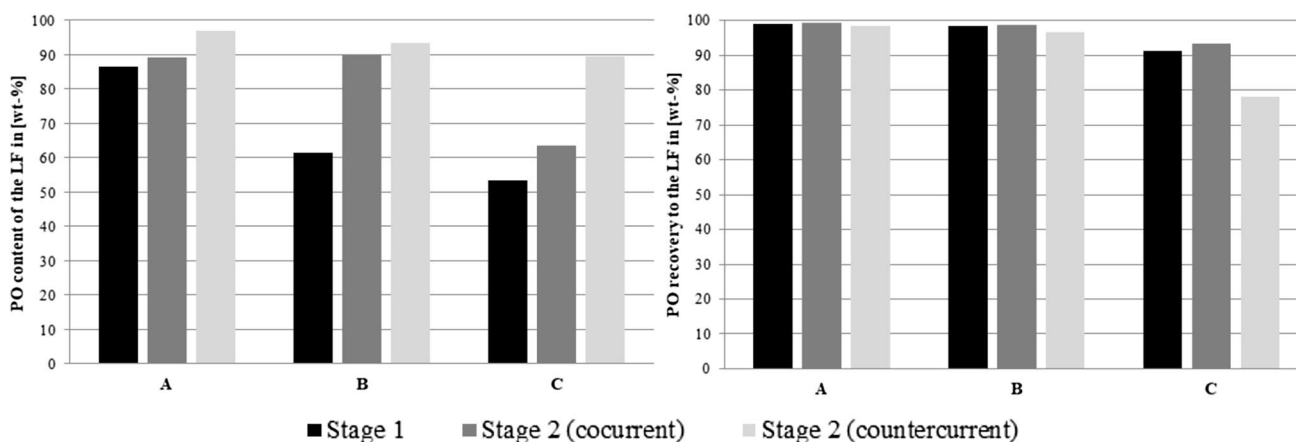
Applied parameter	PO content (wt%)			Parameter	Average effect	Sig-nificance ( $\sigma=0.01$ )
	1	2	3			
$L-/a-/VF-$	98.8	98.4	98.0	$L$	11.9	Yes
$L-/a-/VF+$	99.5	97.9	98.4	$a$	-8.8	Yes
$L-/a+/VF-$	96.8	96.1	96.3	$VF$	9.0	Yes
$L+/a+/VF+$	99.0	98.5	99.0	$L/a$	5.3	Yes
$L+/a-/VF+$	98.0	97.8	97.5	$L/VF$	1.3	No
$L-/a-/VF-$	99.5	99.5	99.5	$a/VF$	4.7	No
$L+/a+/VF-$	97.8	98.0	98.5	$L/a/VF$	-1.1	No
$L+/a+/VF+$	99.5	99.5	99.5			

$L$ , length;  $a$ , inclination;  $VF$ , volume flow, -, low; +, high; 1, ... 3, artificial PP/PET mixtures

**Table 3** Separation efficiency achieved by processing representative waste fractions containing PCP under the process concept of “Plastic Reborn”

PO content of the feed (wt%)	Description	Feed		HF		MF		LF		
		$r_m$	$c_{PO}$	$r_m$	$c_{PO}$	$r_m$	$c_{PO}$	$r_m$	$c_{PO}$	$r_{PO}$
		(wt%)		(wt%)		(wt%)		(wt%)		
-50	Aa	100.0	46.4	27.4	0.2	19.3	2.4	53.3	86.4	98.9
	Ab	100.0	48.3	22.2	0.9	31.9	15.2	45.9	94.2	89.6
-30	Ba	100.0	31.4	30.9	0.5	33.8	2.8	35.3	85.8	96.5
	Bb	100.0	20.2	49.2	0.5	2.8	17.4	47.9	61.4	97.6
-10	Ca	100.0	13.4	45.7	0.7	32.0	3.6	22.3	53.5	89.0
	Cb	100.0	10.8	47.2	0.4	31.0	0.5	21.8	47.7	96.7

$r_m$  Mass recovery,  $c_{PO}$  content of polyolefins,  $r_{PO}$  recovery of polyolefins,  $Aa, \dots Cb$  waste fractions with different PO contents



**Fig. 6** Results of two-stage processing to increase separation efficiency, content of polyolefins (left), and recovery of polyolefins (left)

on [26]. The resulting separation efficiency was evaluated as described above. The detailed results of the three mentioned test campaigns are outlined in the following chapter (see Tables 2, 3; Fig. 6).

### Results and discussion

Table 2 presents the results of the first test campaign, which aimed to reveal the effects of the three operation parameters, length, inclination, and volume flow rate of the separation medium, on the separation process in the



CFS. The efficiency of the separation was measured by the PO content in the LF when separating PP from a 2:3 PP/PET mixture.

The findings reveal that all 24 test runs resulted in very high PO contents of >96 wt%. Yet, statistical test analysis applying a  $2^k$  factorial design indicated several differences. Accordingly, the separator, length, has the most significant impact on the separation process; it should be as long as possible because the value of the average effect is positive (see Table 2). On the other hand, inclination and volume flow rate affect the separation efficiency in a similar way, provided inclination is low and the volume flow rate is high. In conclusion, we may state that the effects of each of the three parameters are significant on the 0.01 level; considering their combinations, only that of the relationship between length and inclination is of higher relevance.

The favourable impact of both high length and low inclination on the separation process in the CFS is based on the increased particle residence time in the separation chamber. Thus, particles with a lower settling velocity have more time to adapt, which raises the probability of being discharged to that fraction matching their density. High volume flow rates increase tangential velocities which enhance centrifugal forces. As a result, particles will settle rapidly, thus reducing the settling time.

Table 3 demonstrates the PO contents of the LF and the PO recovery to the LF which were achieved by processing representative waste fractions containing PCP under the process concept of “Plastic Reborn”. For the sake of completeness, the mass recovery and the PO content of the MF and HF were included.

The results in Table 3 show that the PO recovery to the LF exceeds 90 wt% for almost all the waste fractions processed, which implies that losses of PO to the residual fractions, particularly to the MF, are low. The PO content of the LF comes close to the rate of 90 wt%, particularly required for the PO-rich waste fractions, but decreases when the initial PO content of the waste fractions under consideration is low. In these cases, the level ranges between 45 and 60 wt%, which is not satisfactory. This effect may be explained by the fact that the CFS produces a purer MF when being operated in the countercurrent mode [8]. Due to the case that the particles are centrally fed via the separator cover directly into the water vortex, close to the interface between the vortex and the inner air core, we observed that certain particles are quickly discharged. They leave the separation chamber at the bottom via the LF outlet without being subjected to the density selection of the acting forces, because they do not enter the water vortex, responsible for separation. The reason for this deficit may be seen in the interplay between hydrodynamics and the surface conditions of some particles, such as adhered air bubbles, hydrophobic character, or elongated shape. However, this problem can be solved by

increasing the separator length, which enhances the probability that these particles are absorbed by the vortex and undergo normal separation.

Two-stage or multiple-stage processing provides yet another option to prolong the particle residence time and, thus, boost separation efficiency. This concept is generally used in mechanical processing plants equipped with conventional cyclones. Figure 6 illustrates the results of the related test campaigns.

To highlight the differences in the operation modes of the CFS, the second stage was conducted under both countercurrent and cocurrent operation modes. The LF produced in the first run underwent reprocessing. Generally speaking, the first stage should be operated in the standard countercurrent mode because of the above-mentioned positive effects on particle separation.

Considering all the processed LF and the two operation options in two-stage processing, we may conclude that the intended increase in PO concentration was successful. Losses in PO recovery, especially if the second stage is operated in the cocurrent mode, may be related to the above-mentioned contrary effect. The functional design of the CFS is highly suitable to produce very pure LF when it is operated in the cocurrent mode.

## Conclusion

Comparing diverse dry and wet mechanical processing technologies has revealed that the separators used in wet float–sink separation are highly suitable for PO recovery resulting from waste fractions containing PCP. Due to their density, these separators facilitate the efficient PO separation because most of the remaining waste components are characterised by higher densities than PO and consequently sink to the bottom. The cylindrical centrifugal force separator (CFS) inclined from the horizontal axis stands out from similar facilities even though its close “relatives”, conical–cylindrical sorting cyclones or gas cyclones are better known. The CFS introduced in this paper has evolved from coal processing. It convinces through a great number of qualities: simple, robust, and low-complex design, accelerated particle settling caused by the applied strong centrifugal force field, high material throughputs per unit, and, last but not least, an increased “economy of scale”. Moreover, compared to common sorting cyclones, enhanced particle residence times are achieved, implying a rise in separation efficiency. The most relevant advantage must be seen in the disconnection of the solid particle feed from the separation medium. It was one of the main objectives of the CFS pilot-scale plant designed at Montanuniversitaet Leoben to study the PO separation from waste fractions containing PCP. The pilot plant also comprises a hydro jig that pre-separates heavy waste components

such as glass, sand, stones, or metals by using a density layering process.

Diverse test runs have shown that it is possible to separate a polyolefin-rich LF (PO flake) when processing various representative waste fractions containing PCP. These waste fractions were divided into three groups according to their initial PO content of ~ 10, ~ 30, and ~ 50 wt%. All waste streams under investigation nearly exceeded the 90 wt% level of PO content of the produced LF and PO recovery to the LF. These highly satisfactory results were achieved by two-stage processing of the LF by using different combinations of the operation modes in the first and second stage (countercurrent–cocurrent and countercurrent–countercurrent). It needs to be noted that the first separation stage operated in countercurrent operation mode only yielded a reduced concentration of LF (50–65 wt%) for an initially low PO content. On the other hand, PO recovery exceeded the 90 wt% level for most of the input fractions even in one-stage processing. Based on the tests, the following parameters proved to be decisive for the sink–flow separation process: length and inclination of the separator, which both affect the particle residence time, as well as the volume flow rate of the separation medium that impacts settling velocity and settling time.

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## References

1. Aguado J, Serrano DP, Escola JM (2008) Fuels from waste plastics recycling by thermal and catalytic processes: a review. *Renew Sustain Energy Rev* 47:7982–7992. <https://doi.org/10.1021/ie800393w>
2. Álvarez MM, Sierra HM, Sánchez Lasheras F, Cos Juez FJ (2017) A parametric model of the LARCODEMS heavymedia separator by means of multivariate adaptive regression splines. *Minerals* 10(7):729. <https://doi.org/10.3390/ma10070729>
3. Bauer M (2014) Mechanical processing of post-consumer plastics for chemical recycling. Dissertation, Montanuniversität Leoben, Austria
4. Cammack P (1987) Der LARCODEMS—ein neuer Schwerttrübscheider für Rohkohle der Körnung 100 bis 0.5 mm (LARCODEMS—a new swarf crusher for raw coal of grain sizes from 100 to 0.5 mm). *Aufbereitungstechnik* 8:427–434
5. EC (European Commission) (ed) (2015) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: towards a circular economy: an EU action plan for the Circular Economy. European Commission, Brussels
6. EP (European Parliament) (ed) (2018) Briefing EU legislation in Progress—circular economy package. Four legislative proposals on waste, March 2018. European Parliament, Brussels
7. Ferrara G, Bevilacqua P, Lorenzi L, Zanin M (2000) The influence of particle shape on the dynamic dense medium separation of plastics. *Int J Miner Process* 59(3):225–235. [https://doi.org/10.1016/S0301-7516\(99\)00078-2](https://doi.org/10.1016/S0301-7516(99)00078-2)
8. Gent M, Mendez M, Torano J, Isidro D, Torno S (2009) Cylinder cyclone (LARCODEMS) density media separation of plastic wastes. *Waste Manag* 29:1819–1827. <https://doi.org/10.1016/j.wasman.2008.12.026>
9. Gent MR, Menendez M, Torano J, Torno S (2011) Optimization of the recovery of plastics for recycling by density media separation cyclones. *Resour Conserv Recycl* 55(4):472–482. <https://doi.org/10.1016/j.resconrec.2010.12.010>
10. Gent MR, Menendez M, Torano J, Torno S (2011) DMS cyclone separation processes for optimization of plastic wastes recycling and their implications. *Waste Manag Res* 29(6):644–655. <https://doi.org/10.1177/0734242X10385178>
11. Hori K, Tsunekawa M, Hiroyoshi N, Ito M (2009) Optimum water pulsation of jig separation for crushed plastic particles. *Int J Miner Process* 92(3–4):103–108. <https://doi.org/10.1016/j.minpro.2009.01.001>
12. Ito M, Tsunekawa M, Ishida E, Kawai K, Takahashi T, Abe N, Hiroyoshi N (2010) Reverse jig separation of shredded floating plastics—separation of polypropylene and high density polyethylene. *Int J Miner Process* 97(1–4):96–99. <https://doi.org/10.1016/j.minpro.2010.08.007>
13. Kranert M, Cord-Landwehr K (2010) Einführung in die Abfallwirtschaft (Introduction to waste management). Vieweg+Teubner Verlag, Wiesbaden
14. Kumar S, Panda AK, Singh RK (2011) A review on tertiary recycling of high-density polyethylene to fuel. *Resour Conserv Recycl* 55:893–910. <https://doi.org/10.1016/j.resconrec.2011.05.005>
15. Kuwayama Y, Ito M, Hiroyoshi N, Tsunekawa M (2011) Jig separation of crushed automobile shredded residue and its evaluation by float and sink analysis. *J Mater Cycles Waste Manag* 13(3):240–246. <https://doi.org/10.1007/s10163-011-0008-y>
16. Kranzinger L, Pomberger R, Schwabl D, Flachberger H, Bauer M, Lehner M, Hofer W (2018) Output-oriented analysis of the wet mechanical processing of polyolefin-rich waste for feedstock recycling. *Waste Manag Res*. <https://doi.org/10.1177/0734242X18764294>
17. McCulloch J, Hölter H (1998) Verfahren und Vorrichtung zum Trennen von Mineralien (Method and device for separating minerals). Patent DE19847229A1. Anmeldedatum: 14.10.1998
18. Panda AK, Singh RK, Mishra DK (2010) Thermolysis of waste plastics to liquid fuel. A suitable method for plastic waste management and manufacture of value added products—a world prospective. *Renew Sustain Energy Rev* 14:233–248. <https://doi.org/10.1016/j.rser.2009.07.005>
19. PlasticsEurope (ed) (2014) Plastics—the facts 2014. An analysis of European plastics production, demand and waste data. Brussels, Belgium: Plastics Europe. <http://www.plasticseurope.org/Document/plastics-the-facts-2014.aspx>. Accessed 12 Nov 2016
20. PlasticsEurope (ed) (2016) Plastics—the facts 2016. An analysis of European plastics production, demand and waste data. Brussels, Belgium: Plastics Europe. <http://www.plasticseurope.org/Document/plastics---the-facts-2016-15787.aspx>. Accessed 12 Nov 2016
21. Pomberger R, Sarc R, Lorber K (2017) Dynamic visualisation of municipal waste management performance in the EU using Ternary diagram method. *Waste Manag* 61:558–557. <https://doi.org/10.1016/j.wasman.2017.01.018>

22. Pongstabodee S, Kunachitpimol N, Damronglerd S (2008) Combination of three-stage sink–float method and selective flotation technique for separation of mixed post-consumer plastic waste. *Waste Manag* 28(3):475–483. <https://doi.org/10.1016/j.wasma.2007.03.005>
23. Sarc R, Lorber KE, Pomberger R (2014) Design, quality and quality assurance of solid recovered fuels (SRF) for the substitution of fossil feedstock in the cement industry. *Waste Manag Res* 32:565–585. <https://doi.org/10.1177/0734242X14536462>
24. Scheirs J, Kaminsky W (2006) Feedstock recycling and pyrolysis of waste plastics. Converting waste plastics into diesel and other fuels. Wiley, Chichester
25. Schubert H (1996) *Aufbereitung fester Stoffe (Treatment of solids), Volume II: Sortierprozesse*. Deutscher Verlag für Grundstoffindustrie, Stuttgart
26. Schwabl D, Flachberger H, Kranzinger L, Bauer M, Hofer W (2017) Innovatives Verfahren zur Anreicherung von Polyolefin-Konzentraten aus industriellen Reststoffströmen zum Zwecke einer stofflichen Verwertung (An innovative process for the enrichment of polyolefin concentrates from industrial residual material streams for material recycling). In: Thomé-Kozmiensky KJ, Goldmann D (eds) *Proceedings of the 10th “Recycling und Rohstoffe” Conference*, TK-Verlag, Berlin, pp 199–218
27. Siebtechnik GmbH (ed) (2018) Pulsator Jig. Typ SK (Product folder). <https://www.siebtechnik.com/wp-content/uploads/2017/04/wb206e-SK.pdf>. Accessed 27 Mar 2018
28. Tsunekawa M, Tsunekawa M, Kobayashi R, Hori K, Okada H, Abe N, Hiroyoshi N, Ito M (2012) Newly developed discharge device for jig separation of plastics to recover higher grade bottom layer product. *Int J Miner Process* 114–117:27–29. <https://doi.org/10.1016/j.minpro.2012.09.003>
29. Venkoba Rao B, Kapur PC, Konnur R (2003) Modeling the size-density partition surface of dense-medium separators. *Int J Miner Process* 72(1–4):443–453. [https://doi.org/10.1016/S0301-7516\(03\)00118-2](https://doi.org/10.1016/S0301-7516(03)00118-2)