

Mechanical Processing of Post-Consumer Plastics for Feedstock Recycling

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Keywords: *recycling, post-consumer plastics, polyolefins, processing, jig, centrifugal force separator*

1. Abstract

This paper gives an impression of the work conducted in the Research Studio Austria (RSA) “Plastic Reborn” by the Chairs of Mineral Processing, Waste Processing Technology and Waste Management, Process Technology and Industrial Environmental Protection of the Montanuniversitaet Leoben and industrial partners. Its main project objective is to make additional shares of waste polymers, especially polyolefins out of industrial and other solid waste fractions accessible for feedstock recycling by a novel wet mechanical process.

The methods of choice are test series conducted on a self-built pilot processing plant for industrial and other solid waste fractions with different polyolefin contents. Additionally, experiment based calculations and laboratory investigations were carried out.

The results show that a combination of a jig and several centrifugal force separators can separate a light fraction with a polyolefin mass content of over 90 % out of different waste fractions, which is thereby suitable for feedstock recycling. The accruing byproducts, namely the heavy and middle fractions, were found to be suitable for energy recovery.

This new type of wet mechanical process is capable of separating products for feedstock recycling and energy recovery out of mixed waste fractions of different industrial and other solid waste origins. This process can therefore be used as a bridge technology to make additional shares of post-consumer plastics available for feedstock recycling. Consequently, this technology can be a first step to achieving the intended EU goals of 55 mass percent material plastic recycling by the year 2025 [1].

2. Introduction

2.1. Production and consumption of polymers in Europe

According to the report of “Plastics Europe 2016” [2] about 4-6 % of the global petroleum production was processed into 322 Mt of polymer products in 2015. 58 Mt of latter can be related to Europe (In [2] Europe is defined as the 28 member states of the European Union as well as Norway and Switzerland.). Excluding export the European self-demand on polymer products amounted to 49 Mt, which can be classified according to their application or type of polymer as illustrated in Table 1 and Table 2.

Table 1: European polymer demand in 2015 by polymer type [2]

Type	Fraction (%)	Applications
Polyethylene (PE)	29.4	Bags, trays, containers, food packaging, toys, bottles, pipes, houseware
Others (ABS, PMMA, PTFE ...)	19.9	Optical fibers, eyeglasses, touch screens, telecommunication, medical implants
Polypropylene (PP)	19.1	Food packaging, bank notes, microwave proof containers, pipes, automotive parts
Polyvinylchloride (PVC)	10.1	Window frames, pipes, cables, floor and wall coverings, insulation
Polyurethane (PUR)	7.5	Building insulation, pillows and mattresses, insulation foams
Polyethylene terephthalate (PET)	7.1	Bottles for beverages, cleaners and other liquids
Polystyrene (PS)	6.9	Eyeglasses, frames, plastic cups, packaging, building insulation

Table 2: European polymer demand in 2015 by application [2]

Application	Fraction (%)	Period of application
Packaging	39.9	Days to weeks
Others (furniture, sport ...)	22.4	Months to years
Building and construction	19.7	Years to decades
Automotive	8.9	Years
Electrical and electronic	5.8	Years
Agriculture	3.3	Weeks to months

The tables above show that half of the produced polymers are either PE or PP, which can be further summarized as polyolefins (POs). These POs are mainly used in the field of packaging and therefore have a short time of application, mainly of just a few days. Consequently, POs are of high interest regarding a sustainable polymer waste management.

2.2. Treatment of post-consumer plastics in Europe

In Europe 25.8 Mt of polymer waste was disposed in 2014. These so called post-consumer plastics can be treated by three different waste management paths:

1. Landfilling with the main goal of safely disposing off post-consumer plastics, mostly including a preceding treatment step for mass reduction and inertisation.
2. Energy recovery with the main goal of using the energy bound in the polymer structure of the post-consumer plastics, mostly realised by (co-)combustion as so called solid recovered fuels in cement kilns or similar plants.
3. Material recycling with the main goal of reusing the material by polymer type including treatment steps for cleaning, sorting and granulating the post-consumer plastics.

As indicated in Figure 1 these three waste management paths are applied in different intenseness among the European countries.

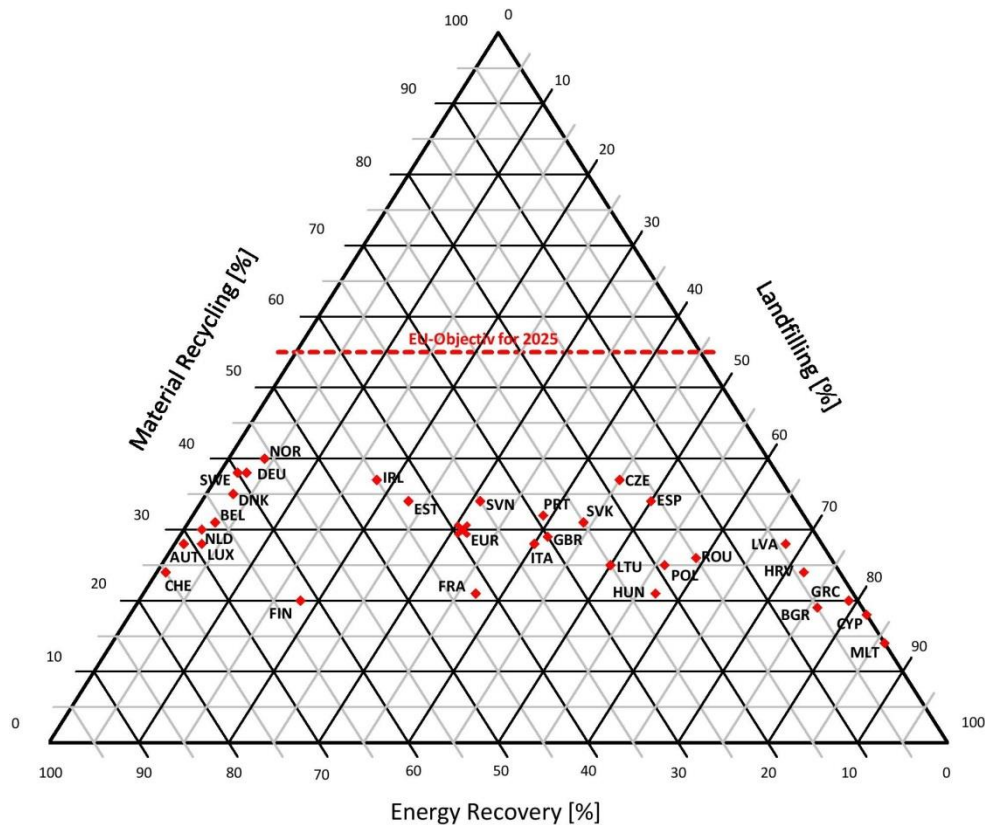


Figure 1: Treatment of post-consumer plastics in Europe in 2014 [3]

This ternary chart is likely used by the Chair of Waste Processing Technology and Waste Management of the Montanuniversitaet Leoben (MUL) for displaying the dynamic of municipal waste management performance of states [4]. Each state is positioned inside the chart according to its intenseness of adaption of the three possible waste management paths for post-consumer plastics in 2014. The European states can now be assigned into three groups:

1. States that focus on a combination of landfilling and energy recovery of post-consumer plastics. Therefore these states are positioned near the lower right edge of the chart. This group includes Malta, Cyprus, Greece, Latvia and Bulgaria.
2. States that focus on a combination of energy recovery and material recycling (most of them have already launched a landfill ban for post-consumer plastics). Therefore these states are located near the mid to lower left edge of the chart. This group includes Norway, Switzerland, Germany, Austria, Denmark, Belgium, Luxembourg, the Netherlands and Sweden.
3. States that are in a transition process and use a specific combination of landfilling, energy recovery and material recycling. Thus they are situated in the middle of the chart. This group covers Finland, Ireland, Poland, Estonia, Portugal, Italy, Great Britain, France, Slovenia, Hungary, Lithuania, Romania, Spain, Slovakia and the Czech Republic.

Overall, 40 % of Europe's post-consumer plastics are landfilled, slightly more than 30 % are energetically recovered and a bit less than 30 % are materially recycled. Material recycling is therefore currently the least used option. This is mainly due to the high demands for feedstock purity in order to produce secondary polymer material with an equal quality to virgin material.

2.3. Feedstock recycling of post-consumer plastics

According to a proposed directive of the European Union on circular economy, the share of material recycling of post-consumer plastics shall be increased to 55 % by 2025 [1]. Apart from mechanical recycling a promising option to recycle more post-consumer plastics materially is feedstock or chemical recycling via thermal cracking or pyrolysis e.g. connected to a refinery. Once liquefied by thermo-chemical conversion the obtained hydrocarbon intermediates can be easily treated by diverse processes according to their chemical and physical properties. In best case they are refined to ethylene and propylene ready to close the material cycle via repeated polymerisation. But decades of research and a multiplicity of failure indicate that polymer (hydrocarbon) feedstock recycling in thermo-chemical conversion units needs adequately prepared feedstock of specified

quality. This can be provided by well adapted post-consumer plastic mechanical processing like density separation. Especially POs representing approximately 50 % of the waste polymers can be separated from other polymers utilizing water as a separation medium, because contrary to other polymer types their density is lower than 1 g/cm³.

This was the starting point of the Research Studio Austria (RSA) “Plastic Reborn”. The Chairs for Mineral Processing (MP), Process Technology and Industrial Environmental Protection (PTEP) and Waste Processing Technology and Waste Management (WPWM) at MUL as well as industrial partners try to develop, investigate and optimize such a novel process.

3. The pilot processing plant

3.1. Feed material

The desired feed materials are post-consumer plastic fractions with a high share in POs. Prior to the pilot plant test runs the Chair of WPWM examined different post-consumer waste streams of municipal and industrial origin, to identify the quantitative potential of post-consumer POs in Austria. This comprehensive study [5] depicts a theoretical potential of 310.000 tons of POs per year as well as additional 2.2 Mt of POs which could be recovered once by profound landfill mining. POs containing waste stream are included in the study if they meet the following criteria:

1. The waste stream must be non-hazardous.
2. The waste stream must have a POs content of a least 20 %.
3. The waste stream must provide a mass flow of at least 20.000 t per year in Austria (except material from landfill mining).

As a result, seven waste fractions were chosen and examined regarding their processability in the pilot plant and reachable separation efficiency. The particle size distribution (PSD), the parameter p_{80} – 80th percentile of the PSD (particle size of 80 % cumulative passing) - as well as the PSD and average PO content (\bar{g}_p) were determined. Table 3 shows these parameters for waste fractions with high (A), average (B) and low (C) PO content, which results in separation behavior are presented within this paper. Additionally, pictures of these waste fractions can be seen in Figure 2.

Table 3: Waste fractions and parameters [3]

Waste fraction	p_{80} (mm)	\bar{g}_p (%)
A	7.8	55.8
B	9.8	34.4
C	10.9	11.8



Figure 2: Waste fraction A, B and C (left to right) [3]

3.2. Function principle

To test and proof the developed mechanical processing concept based on density separation, a small scale pilot plant was designed, built and taken into operation by the Chairs of MP and PTEP. As indicated in the simplified flow chart (compare Figure 3) the pilot plant consists of two separation stages. The feed material which has to be shredded to a particle size lower than 20 mm should be wetted before entering the first separation stage in order to avoid influences on the particles' behavior by hydrophobicity.

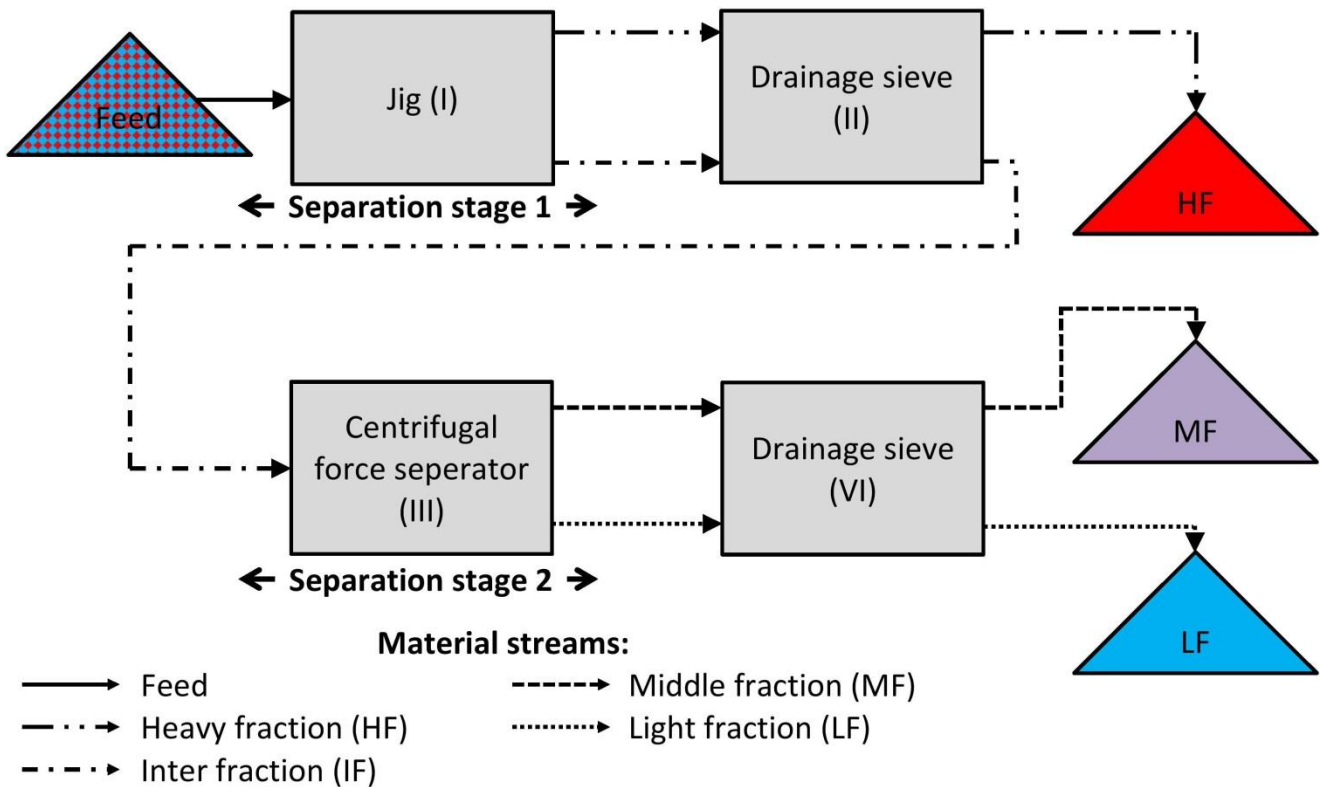


Figure 3: Flow chart of the pilot processing plant [3]

Separation stage one is composed of a jig (I) with the aim to sort out abrasive impurities like glass, stones and metals (inerts) in order to protect the following appliances. The jig consists of an upper and movable lower tray in which former is equipped with a screen lining to collect the fed particles and latter executes an alternating up and down movement driven by an eccentric gear to generate a periodical upstream when filled with water. Consequently the induced upstream scatters the particles in the bed and start layering according to their initial drop acceleration, which is mainly a function of particle size, shape and density. In the case of considered post-consumer polymer fractions particle density is the dominant factor because of the polymers huge density difference to other impurities. In the so built layers of different density, the polymers concentrate in the upper and the impurities in the lower ones. Using a barrage the polymers are transferred into the inter fraction (IF) and the impurities into the heavy fraction (HF). Both, the HF and the IF, are discharged onto a drainage sieve (II) for dewatering. The HF is abstracted, the IF is transferred to the second separation stage and the water is recirculated to the jig.

The exact composition of the second separation stage was part of several test series, which will be discussed in chapter 4.2. In general it consists of one to three centrifugal force separators (CFS) (III). A CFS as it can be seen in Figure 4 basically consists of an inclined cylinder with 4 tube-guided streams in and out of the separator. The feed material is separated by sink-/float-separation in a centrifugal field thus having a higher throughput than a sink-/float tank only using gravity. These centrifugal forces are induced by the separation medium, which is pumped into the separator tangentially at the lower end and thus builds up a medium vortex with an air core and then leaves tangentially at the upper end. The IF which either enters the separator axial from the upper central tube directly into the air core or is dispersed within the separation medium at the lower end is split into a middle fraction (MF) consisting of plastics with a higher and a light fraction (LF) consisting of plastics with a lower density than the separation medium. The MF and LF are transferred onto another drainage sieve (IV) for dewatering and process water recovery afterwards. The recovered process water is recirculated to the CFS.

This pilot processing plant is thereby capable of splitting post-consumer plastics into a HF consisting of impurities like stones, glass and metals, a MF consisting of polymers with a density higher than 1 g/cm³ and a LF consisting of polymers with a density lower than 1 g/cm³ using water as separation medium. It can process up to 200 kg/h using about 25 m³/h of water which is circulated within the plant.

3.3. The centrifugal force separator

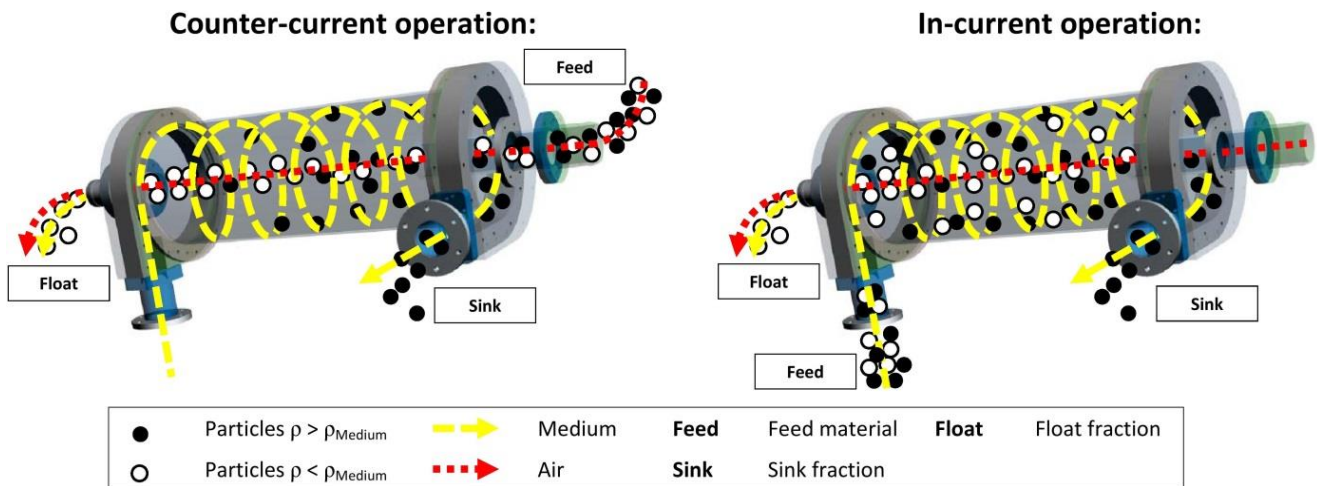


Figure 4: The CFS in counter- (left) and in-current (right) operation

In Figure 4 both examined operation options of the CFS are depicted. On the left the counter-current operation is shown whereby the feed material enters through the upper central tube directly into the air core. Particles with a higher density than the separation medium sink to the separator shell accelerated by the centrifugal forces and leave through the upper tangential tube with the bulk of the separation medium as sink fraction. Particles with a density lower than the separation medium stay in the air core and leave the separator by gravity through the lower central tube as float fraction. This operation favors a high quality sink fraction because in order for a particle to be transferred into this fraction it has to pass through the medium vortex. The advantage of this CFS set-up is that no material has to be transported through the pumps and therefore doesn't reduce their durability.

On the right the counter-current operation is depicted. The feed material is dispersed in the separation medium and enters the separator at the lower tangential tube. Particles with a density lower than the separation medium float up to the air core and leave the separator via the lower central tube as float fraction by gravity. Particles with a higher density than the separation medium sink to the separator shell and exit through to the upper tangential tube together with the bulk of the separation medium as sink fraction. This operation favors a high quality float fraction because this time a particle has to float up via the medium vortex in order to be discharged to the float fraction.

4. Results and discussion

4.1. Test run set-up

The first test series with post-consumer plastics were performed using the three waste fractions A, B and C (see Table 3) as feed material. Separation stage 2 was set-up using one CFS in counter-current operation. The aim of this test series was to separate a LF with a share in PO of at least 90 % in order to have a product of sufficient quality to be used for feedstock recycling. Additionally the quantity and quality of the MF and HF was determined in order to identify whether a usage as substitute fuels (e.g. in cement kilns) is possible or a disposal is necessary. Finally, also the process water should be analyzed, because water treatment is always a crucial part regarding wet processes.

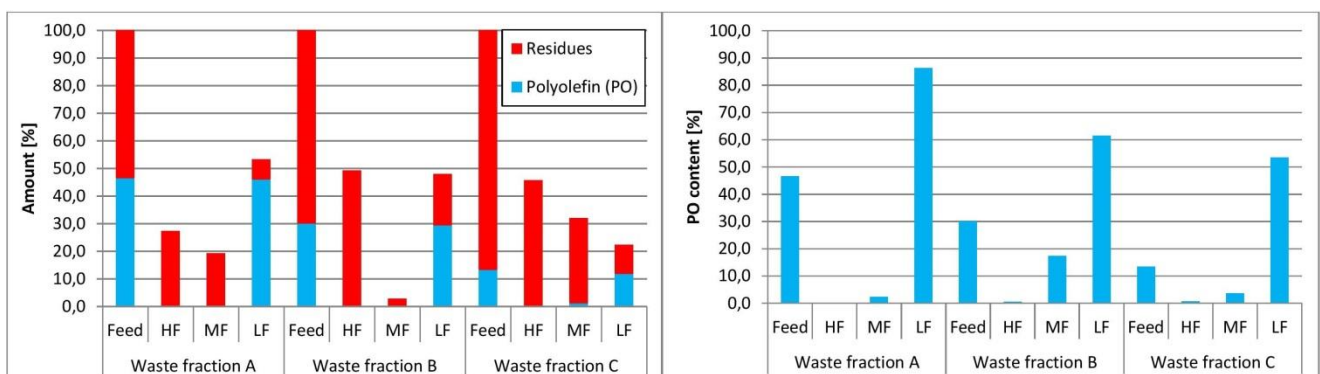


Figure 5: Results of the first test series PO amount (left) and contents (right) of the feed and the three products: Light (LF), middle (MF) and heavy fraction (HF)

As can be seen in Figure 5 nearly all of the POs of the feed material (Feed) could be transferred to the light fraction (LF) with no losses to the heavy (HF) and minor losses to the middle fraction (MF). The recovery can be evaluated as excellent with an average of 95 % for all three waste fractions. But none of the three LF could reach the aim of a PO content of at least 90 %.

4.2. Light fraction (LF)

Despite of the pleasant results for PO recovery the LF is not yet a marketable product. In order to achieve the wanted share the pilot plant had to be modified. Regarding the fact that the LF was contaminated with non-PO polymers as well as lighter impurities and not with heavy impurities like metals, glass or stones, a modification of separation stage one would have little to no effect. So separation stage two was targeted for modification.

As a first assessment on this modification, the parallel processing of the MF and LF by additional CFS was taken into consideration. The options were thereby in-current, counter-current or no treatment of the LF and MF by a CFS respectively which resulted in eight possible additional treatment combinations. Because currently only one CFS is available a test series in continuous operation could not be conducted. So the MF and LF of the three waste fractions were separately treated with one CFS in batch operation. After the test runs the separated sink and float fraction of each run were dried and weighted. With this numerical basis mass balances for all eight treatment combinations could be calculated.

The results of these calculations are displayed in Table 4 and Table 5 in grids. Each grid shows the results for treating the middle (MF; horizontally) and light fraction (LF; vertically) of one of the three waste by one of the three treatment options: “No treatment” (NT), “In-Current” (IC) and “Counter-Current” (CC). The values given in the first row and column of each grid are the values of PO content in the LF and PO recovery to the LF as determined by the first test run (compare with Figure 5). In all other parts of the grids plus and minus symbols determine whether the experimental based calculations show no (o), a minor (+ / -) or significant (+ + / - -) tendency to increase or decrease of the PO content or recovery by the denoted treatment combination.

Content of polyolefin in the light fraction in mass percent for different treatments combinations of the light (LF) and middle fraction (MF)														
Waste fraction	Treatment of MF			Waste fraction	Treatment of MF			Waste fraction	Treatment of MF					
	A	NT	IC		CC	B	NT		IC	CC	C	NT	IC	CC
Treatment of LF	NT	86,4	-	-	Treatment of LF	NT	61,4	o	o	Treatment of LF	NT	53,5	-	-
	IC	+	+	+		IC	++	++	++		IC	+	+	++
	CC	+	+	+		CC	++	++	++		CC	++	++	+

Treatment options: No treatment (NT), In-current operation (IC), Counter-current-operation (CC)

Tendencies: None (o), minor increase/decrease (+/-), significant increase/decrease (+ +/- -)

Table 4: Polyolefin content in the LF for different treatments combinations

Recovery of polyolefin to the light fraction in mass percent for different treatments combinations of the light (LF) and middle fraction (MF)														
Waste fraction	Treatment of MF			Waste fraction	Treatment of MF			Waste fraction	Treatment of MF					
	A	NT	IC		CC	B	NT		IC	CC	C	NT	IC	CC
Treatment of LF	NT	99,0	o	o	Treatment of LF	NT	98,4	o	o	Treatment of LF	NT	91,2	o	+
	IC	o	--	o		IC	o	-	o		IC	+	--	-
	CC	o	o	o		CC	o	o	o		CC	-	-	+

Treatment options: No treatment (NT), In-current operation (IC), Counter-current-operation (CC)

Tendencies: None (o), minor increase/decrease (+/-), significant increase/decrease (+ +/- -)

Table 5: Polyolefin recovery to the LF for different treatments combinations

Comparing Table 4 and Table 5 three findings can be achieved:

1. Choosing no treatment for the LF results in a minor decrease to no effect on the PO content of the LF regardless of which treatment option is used for the MF. (Compare first rows of Table 4) This is believed to be due to more impurities than PO being separated from the MF and added to the LF. The effects on the PO recovery to the LF are mostly insignificant. (Compare first rows of Table 5)
2. Contrary choosing no treatment for the MF results in a minor to significant increase of the PO content of the LF regardless of which treatment option is used for the LF. (Compare first columns of Table 4) Also for these options the effects on the PO recovery to the LF are mostly insignificant. (Compare first columns of Table 5)
3. Choosing to treat both fractions with either of the two treatment options (in or counter-current operation) results in a minor to significant increase of the PO content of the LF. (Compare second to third row/column of Table 4) The effects on the PO recovery to the LF are mostly insignificant except for the option of treating both fractions by incurrent-operation which results in a significant decrease. (Compare second row/column of Table 5)

Taking these findings and the fact, that a significant increase in PO content of the LF especially of waste fraction B and C is the crucial factor into consideration, the favorable option is a combination of counter and incurrent-operation treatment of both fractions. (Compare second row/third column and third row/second column respectively of Table 4 and Table 5) Both options significantly increase the PO content of the LF - especially for waste fraction B and C – whilst not or only minor decreasing the PO recovery to the LF. In order to substantiate this working hypothesis test series using these configurations shall be conducted in the near future.

4.3. Middle and heavy fraction

The MF and HF might only be byproducts of this process, but for a potential future plant their further usage will also be of crucial importance. Obviously they won't be suitable for feedstock or material recycling, so the next option according to the waste hierarchy pyramid is energy recovery. Table 6 shows their suitability to this option, by giving the exceedance of pollutant limits for antimony (Sb), arsenic (As), lead (Pb), cadmium (Cd), chrome (Cr) and quicksilver (Hg) according to the Austrian Waste Incineration Directive (AVV - Abfallverbrennungsverordnung) for the middle (MF) and heavy fraction (HF) of the three considered waste fractions. It can be seen that under Austrian input regulation limits for solid recovered fuels only slight exceedance regarding Sb and Hg-limits of some fractions are made.

Waste fraction		Exceedance of pollutant limit according to Austrian AVV						Energy recovery	
		Sb	As	Pb	Cd	Cr	Hg	wet	dry
A	MF	-	-	-	-	-	-	FBI	ICC
	HF	-	-	-	-	-	-	FBI	ICC
B	MF	-	-	-	x	-	-	ICC	ICC
	HF	-	-	-	-	-	-	ICC	ICC
C	MF	-	-	-	x	-	-	FBI	ICC
	HF	-	-	-	x	-	x	ICC	ICC

Fluidized bed incineration (FBI), Industrial co-combustion (ICC)

Table 6: Possible usage of middle (MF) and heavy fraction (HF) in thermal recycling [4]

Table 6 also depicts the limits of the calorific value in order to be allowed to use a fraction as substitute fuel in a specific form of incineration according to the AVV. If the abstracted MF and HF are used without any further drying they could all at least be used in a fluidized bed incineration (FBI) some even reach the quality requirement for industrial co-combustion (ICC) for instance in cement kilns. If the fractions are further dried up to 65% for the MF and 90% for the HF, they would all be suitable for a usage as solid recovered fuels in a co-combustion plant.

4.3.1. Process water

For every wet process waste water treatment is a key aspect. This has already been taken into account when designing and planning the pilot processing plant as well as when defining the test run program to be accompanied by representative sampling and particular chemical analysis. The results of the laboratory investigations on the process water extracted from the first large scale test series (see 4.1) show that no crucial pollutant limits were exceeded. Hence, the water could be disposed via the public sewage system.

Another problem regarding process water is the accumulation of fine material. This can lead to the formation of turbidity in the process water. Latter moreover leads to a higher density of the separation medium in the CFS (density offset) and causes non-polyolefinic polymers to be discharged to the LF. To avoid this misclassification, the feed material could be processed in the jig more intensively, to remove more impurities

and especially fine particles in separation stage one. Accumulating in the process water of separation stage one, which is rather unsusceptible in changes of the separation, fine particles would be prohibited to derange the process water of separation stage two.

5. *Conclusions and outlook*

The results show, that treating post-consumer plastic fractions by wet mechanical processing using a jig and multiple centrifugal force separators enable the separation of a light fraction with a polyolefin content of at least 90 % while suffering material losses of only 5 %. The processed middle and heavy fraction have the potential to be used for energy recovery.

Therefore this process can be used as a bridge technology to make additional shares of post-consumer plastics, especially polyolefins, available for feedstock recycling and to be a first step towards the proposed EU's goal of 55 % material plastic recycling by the year 2025.

To give an outlook, test series of longer duration and with large quantities of feed material to determine whether or not certain pollutant will accumulate in the process water will be conducted. Additionally, test runs to the substantiation of the best treatment combination for middle and light fraction as well as achieving a sharper cut between impurities and plastics within separation stage one shall be carried out.

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