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Doctoral Thesis

Potential, Processing and Recycling Aspects of Plastics from Non-Hazardous, Mixed, Solid Wastes – Solid Recovered Fuel, Mixed Commercial and Municipal Waste

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This doctoral thesis is dedicated

to my deceased grandpa,

Dipl.-Ing. Friedrich Möllnitz

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AFFIDAVIT

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

Date 03.02.2021

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KURZFASSUNG

Potenzial, Verarbeitungs- und Recyclingaspekte von Kunststoffen aus nicht gefährlichen, gemischten, festen Abfällen - Ersatzbrennstoffe, gemischte Gewerbe- und Siedlungsabfälle

Das Recycling von Kunststoffen aus homogenen Abfällen ist bereits Stand der Technik und gewinnt auch für gemischte, feste Abfälle aufgrund des zunehmenden gesetzlichen Drucks an Bedeutung. Es ist bekannt, dass gemischte gewerbliche Abfälle sowie gemischte Siedlungsabfälle relevante Mengen an Kunststoffen enthalten. Diese Abfälle werden üblicherweise in Abfallverbrennungsanlagen behandelt oder zu Ersatzbrennstoffen für die Mitverbrennung verarbeitet. Um zukünftige Recyclingziele zu erreichen, ist die Lenkung von Kunststoffen aus diesen Abfällen von der thermischen Verwertung in ein mechanisches oder chemisches Recycling eine vielversprechende Option. In dieser Dissertation werden daher verschiedene Aspekte einer möglichen Wertschöpfung von Kunststoffen aus gemischten, festen Abfällen entlang ihrer Wertschöpfungskette vom Abfall bis zur Kunststoffverarbeitung betrachtet. Um das Potenzial verschiedener Kunststofftypen aus gemischten Abfallströmen für das Recycling zu bewerten, wurde deren Gehalt in Abhängigkeit ihrer Objektdimension (2D und 3D) in vorzerkleinertem gemischten Gewerbe- und Siedlungsabfall auf Partikelgrößenebene bestimmt. Dabei wurde festgestellt, dass beide Abfälle ein relevantes Kunststoffpotential (>15%) in unterschiedlichen Korngrößenklassen und Dimensionen aufweisen. In Folge dessen wurde in Versuchen zur mechanischen Aufbereitung dieser Abfälle zur Herstellung kunststoffreicher Fraktionen festgestellt, dass eine Vorsiebung mittels Trommelsieb zu einer Effizienzsteigerung der Nachfolgeaggregate (z.B. Trennleistung eines Ballistikseparators) führt. Die Trennleistung einer nachfolgenden, sensorgestützten Sortierung wird jedoch durch die erzeugten kurz-, mittel- und langfristigen Massen- und Volumenstromschwankungen negativ beeinflusst. Weiterführende Untersuchungen haben gezeigt, dass die erzeugten zweidimensionalen, kunststoffreichen Outputfraktionen hohe Polyolefingehalte (>50%) besitzen, welche mit nass-mechanischen Dichtetrennverfahren bei gleichzeitiger Partikelreinigung, zurückgewonnen werden können. Die untersuchte Trocken- mit anschließender Nassaufbereitung scheint somit für eine Rückgewinnung von bestimmten Kunststoffen aus gemischten, festen Abfällen für ein anschließendes Recycling geeignet zu sein. Die generierten Kunststoffströme (gemischt/sortenrein, gewaschen/ungewaschen) wurden hinsichtlich ihrer grundlegenden Verarbeitbarkeit und erreichbaren thermischen, mechanischen und rheologischen Materialeigenschaften untersucht. Dabei wurde festgestellt, dass die Materialien im Pressverfahren verarbeitbar, mittels Compoundierung homogenisierbar sind und akzeptable Materialeigenschaften erreicht werden. Abschließend wird in dieser Doktorarbeit eine Benchmarkstudie zur Analyse der Zusammenhänge zwischen Marktpreisen und Qualitäten von Kunststoffflakes und -rezyklaten angeführt. Die Lenkung von Kunststoffen aus gemischten, feste gewerblichen und kommunalen Abfällen für die thermischen Verwertung in ein Recycling ist somit technisch möglich und würde einen wichtigen Beitrag zur Erreichung von Recyclingzielen, zur Ressourcenschonung sowie zur Treibhausgas- und Abfallreduktion leisten.

ABSTRACT

Potential, Processing and Recycling Aspects of Plastics from Non-Hazardous, Mixed, Solid Wastes – Solid Recovered Fuel, Mixed Commercial and Municipal Waste

The recycling of plastics from homogeneous waste is already state of the art and is also gaining importance for mixed solid waste due to increasing legal pressure. It is known that mixed commercial and mixed municipal waste contain appropriate amounts of plastics. These wastes are usually treated in waste incineration plants or processed into solid recovered fuel for co-incineration. To achieve future recycling targets, diverting plastics from these wastes from thermal recovery to mechanical or chemical recycling is a promising option. Therefore, this doctoral thesis considers different aspects of a possible value creation of plastics from mixed, solid wastes along their value chain from waste to plastics processing. To assess the potential of different types of plastics from mixed waste streams for recycling, their content was determined depending on their object dimension (2D and 3D) in pre-shredded mixed commercial and municipal waste at particle size level. It was found that both wastes have a relevant plastic potential (>15%) in different particle size classes and dimensions. As a result, in trials on the mechanical pre-processing of these wastes to produce plastics-rich fractions, it was found that pre-screening using a drum screen leads to an increase in the efficiency of the downstream units (e.g., separation performance of a ballistic separator). However, the separation performance of a subsequent, sensor-based sorting aggregate is negatively influenced by the short-, medium- and long-term mass and volume flow fluctuations generated. Further investigations have shown that the two-dimensional, plastic-rich output fractions produced have high polyolefin contents (>50%), which can be recovered using wet-mechanical density separation processes with simultaneous particle cleaning. The investigated dry-processing followed by wet-processing appears to be suitable for recovering certain plastics from mixed solid waste for subsequent recycling. The generated plastic streams (mixed/sorted, washed/unwashed) were investigated in terms of their basic processability and achievable thermal, mechanical, and rheological material properties. It was found that the materials are processable by compression moulding, homogenisable by compounding, and acceptable material properties are achieved. Finally, a benchmark study analysing the relationship between market prices and qualities of plastic flakes and recyclates is cited in this thesis. The steering of plastics from mixed, solid commercial and municipal waste for thermal recovery into recycling is technically feasible and would make an important contribution to recycling targets, resource conservation and greenhouse gas, and waste reduction.

PUBLICATIONS AND (CO-)SUPERVISED THESES

In the following, publications and (co-) supervised student theses elaborated in the context of the present doctoral thesis are listed.

Publications in peer-reviewed journals

Möllnitz, S., Feuchter, M., Duretek, I., Schmidt, G., Sarc, R. (2021): *Processability of Different Polymer Fractions Recovered from Mixed Wastes and Determination of Material Properties for Recycling.* Polymers, Special Issue: Polymer Waste Recycling and Management, 13(3), 457, 1-49, https://doi.org/10.3390/polym13030457.

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Möllnitz, S., Khodier, K., Sarc, R. (2019): *Grain Size Dependent Distribution of Different Plastic Types in coarse-shredded Mixed Commercial Waste*. **Oral presentation & written contribution.** 10th International Symposium on Feedstock Recycling of Polymeric Materials (ISFR), May 26th – 29th, 2019 Budapest, Hungary.

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Pomberger, R., Adam, J., Aldrian, A., Kranzinger, L., Lorber, K., Neuhold, S., Nigl, T., Pfandl, K., Sarc, R., Schwarz, T., Sedlazeck, P., Wellacher, M., Curtis, A., Friedrich, K., Küppers, B., **Möllnitz, S.**, Rutrecht, B., Sattler, T.M., Viczek, S.A., Höllen, D., Weißenbach, T. (2018). *Recy & DepoTech 2018: POSTER-Konferenzband zur 14. Recy & DepoTech-Konferenz - Recycling & Abfallverwertung, Abfallwirtschaft & Ressourcenmanagement sowie Deponietechnik & Altlasten, Internationale Abfallwirtschaft & Spezielle Recyclingthemen*. 1 Aufl., Leoben, Austria: AVAW Eigenverlag, 358 S. ISBN: 978-3-200-05858-3.

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1 INTRODUCTION

Plastic materials define the way we live today. They improve the quality of life by making our lives easier, safer, and more enjoyable. Simultaneously, they are essential to accelerate the European transition to a low-carbon circular economy where resources and energy are utilised most effectively.

In 2015, the European Commission published the circular economy package (EU, 2015). With the associated legal framework, new regulations were defined for handling plastics and plastic waste connected with recyclability, biodegradability, and hazardous substances in plastics. Also, the European plastics strategy was adopted at the beginning of 2018. In the European Green Deal (EU, 2019b), which the EU presented in 2019, the European Commission confirms that the plastics strategy (EU, 2018) will be pursued further. Concerning the handling of plastic waste, the following picture of the future for the period until 2030 was drawn (EU, 2018):

- By 2030, all plastic packaging should be reusable or recyclable,
- in 2030, more than half of the plastic waste generated in the EU will be recycled,
- the consumption of single-use plastics should be reduced,
- the deliberate use of microplastics should be restricted,
- the capacity of plastics recycling plants in the EU will be quadrupled (sorting and recycling capacities are expected to be four times higher in 2030 than in 2015) and
- Europe is demonstrating leadership in the development of sorting and recycling technology.

In March 2020, the European Commission's Action Plan (EU, 2020) for the recycling industry was adopted. This follows on from the measures outlined in the European plastics strategy (EU, 2018). To increase the use of recycled plastics and contribute to a more sustainable use of plastics, the commission will propose binding requirements on the recycled content and waste reduction measures for key products such as packaging, construction materials, and vehicles.

At the European level, the future picture is thus set by rising recycling targets (e.g., plastic packaging), increasing recycling capacities for plastic waste, and taking a greater account of eco-design in product manufacture (EU, 2018).

The Circular Economy Package (EU, 2015) stipulates that from 2025 at least 55% of municipal waste must be prepared for re-use or recycling. From 2030 this applies to 60% and from 2035 to 65%. (EU, 2015) Recycling targets for packaging waste are 65% from 2025 and 70% from 2030, with specific targets for paper and cardboard, plastics, glass, metal, and wood (EU, 2015). In addition, the European Commission has issued a directive on single-use plastic products (EU, 2019a). It aims to reduce waste from single-use plastic products and replace them with resource-saving, environmentally friendly alternatives. By 2021, for example, coffee cups (incl. caps), food containers for immediate consumption, as well as cutlery, drinking straws, and stirrers made of plastic are to be replaced (EU, 2019a).

Austria had 2018 a recycling rate for municipal waste of around 52% (BMK, 2020). Approx. 43% were treated thermally and about 5% mechanically-biologically (BMK, 2020). The maximum landfill rate for municipal waste in Europe will be 10% from 2035 (EU,2015). Since 2014, Austria, Germany, Belgium, Denmark, the Netherlands, and Sweden had practically no waste going to landfill, while Cyprus, Croatia, Greece, Latvia, and Malta have disposed of more than three-quarters of their municipal waste in this way. (EU, 2015)

To increase circularity, it is important to analyse the life cycle of plastics, from production to recycling and closing the loop. In 2019, 368 million tonnes (Mt) (+2.5% compared to 2018) of plastic were produced worldwide (PlasticEurope, 2020). About 16% (57.9 Mt) of this was produced in Europe (PlasticEurope, 2020). The six most populated European countries cover 80% of European plastic demand (50.7 Mt) (Germany, Italy, France, Spain, United Kingdom, Poland) and the Benelux (PlasticEurope, 2020). The European plastics demand is distributed among different application areas shown in Figure 1. The sections „Packaging" (39,6%) and „Building and Construction" (20.4%) cover about 60% of the European plastics demand (PlasticEurope, 2020). The bubble size represents the relative amount of each plastic type used in the application areas. It can be seen that in the packaging industry, the plastic types polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) are predominantly used. In the construction sector, large quantities of polyvinyl chloride (PVC), PE, e.g., cable sheathing, pipes, window and door profiles, and PS in expanded form (EPS) as insulation material are used (PlasticEurope, 2020).

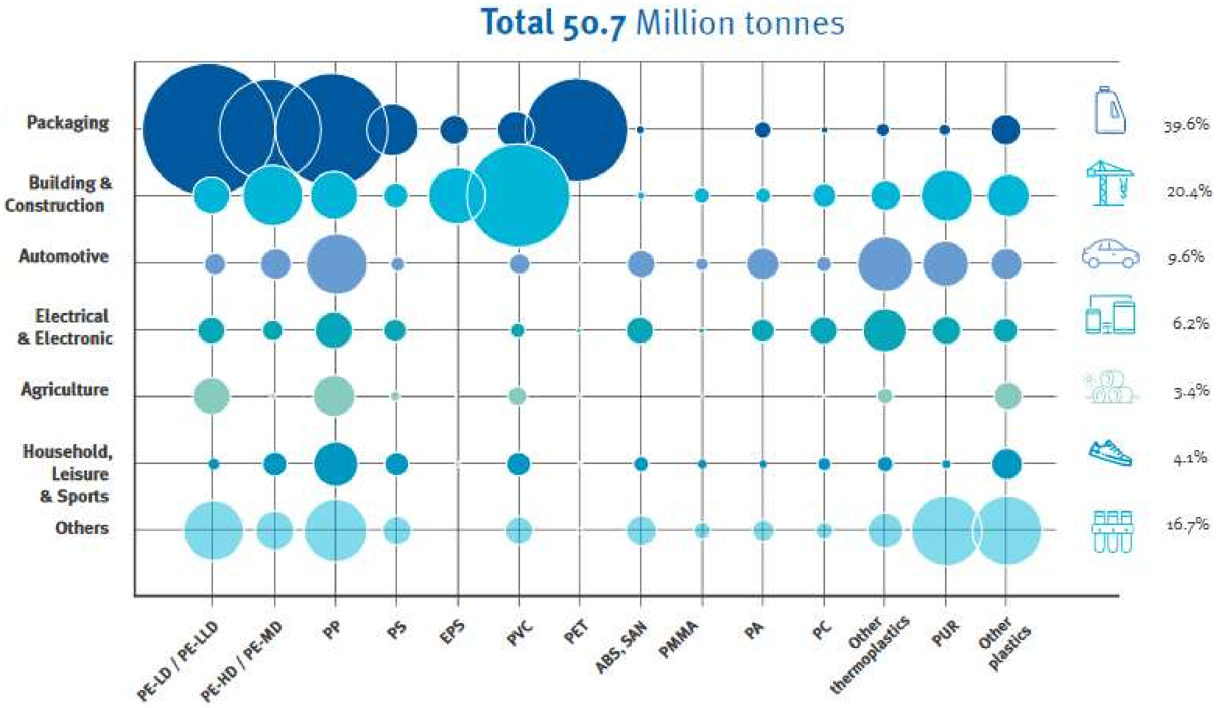

Figure 1: European plastics demand distribution by segments and polymer types in 2019. (PlasticEurope, 2020)

Looking at the European demand for plastic types broad application areas (see Figure 2) in 2019, it can be seen that polyolefins cover almost 50% (PP: 19.4% and PE: 29.8%), followed by PVC (approx. 10%), polyurethane (PUR) and PET with 7.9% each. The share of PS is 6.2%. (PlasticsEurope, 2020)

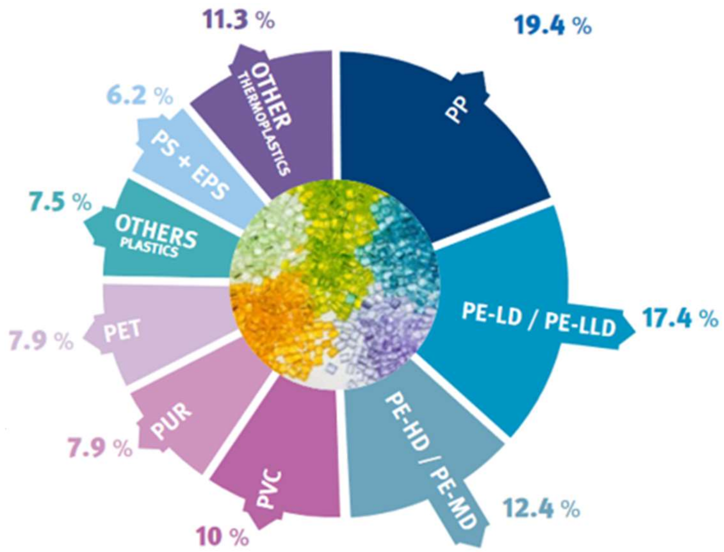

Figure 2: European plastics demand distribution by plastic types in 2019. (PlasticEurope, 2020)

To understand the life cycle of plastic products and their materials, it is essential to know that not all plastic products are the same and have different service lives. Some objects are also the product itself (i.e., a bottle), and some are parts of a product (i.e., parts of electronic devices). Plastic products also have very different lifespans - depending on the area of application. Some products have a lifespan of less than one year (e.g., packaging), others of more than ten years (e.g., plastic parts of a car), and some have a service life of 50 years or more (e.g., pipelines in houses). Therefore, within the individual value chains, different plastic products have different applications from production to waste.

As a consequence, the amount of plastic waste collected does not necessarily correlate with the demand for plastics in the same year. Another reason for the difference is the amount of uncollected plastic waste that is littered, unauthorized dumped, or exported outside the EU. (PlasticEurope, 2020)

In 2019, 29,1 Mt of plastic post-consumer waste were collected in Europe (PlasticEurope, 2020). To close the value cycle, 32.5% was recycled and 42.6% used for energy recovery. Nevertheless, 25% of plastic post-consumer waste was still landfilled (PlasticEurope, 2020). Zero landfilling is needed to achieve the circular economy of plastics. Countries with landfill ban of recyclable and recoverable wastes have, on average, higher recycling rates and significantly more energy recovery of plastic post-consumer waste (see Figure 3) (PlasticEurope, 2020). The next development step for countries with landfill restrictions is the recovery of recyclable materials, especially plastics, from those wastes that are currently energy recovered for recycling.

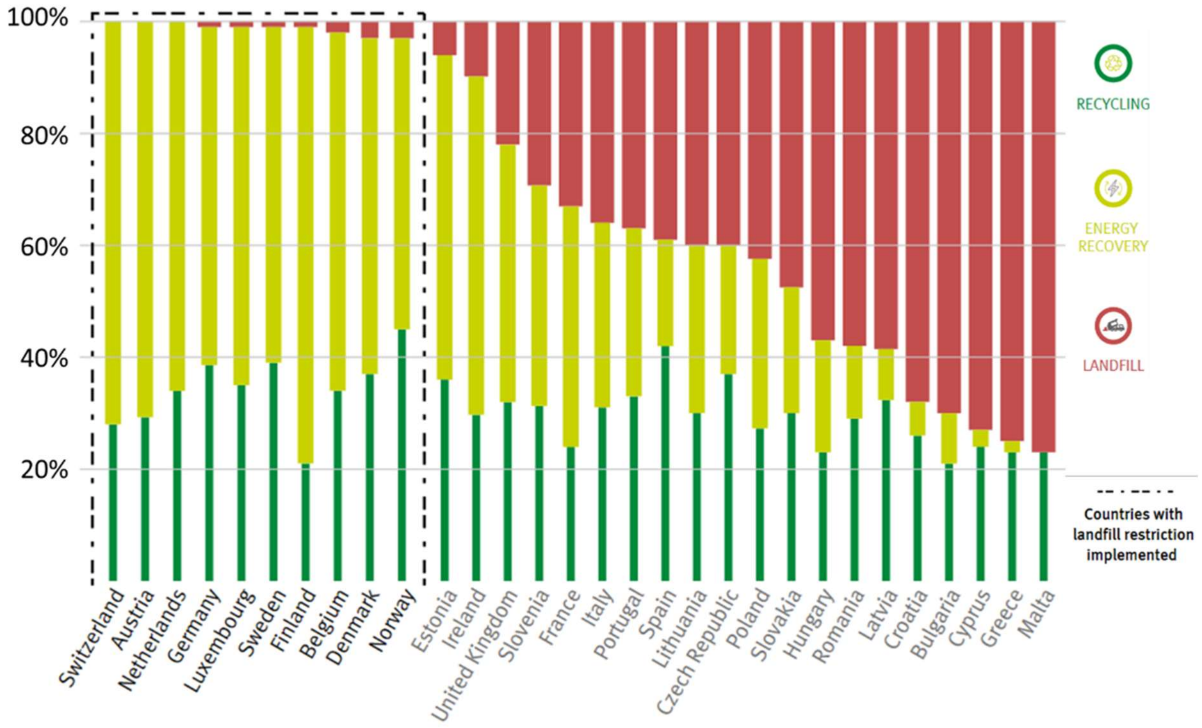

Figure 3: Plastic post-consumer waste rates of recycling, energy recovery, and landfill per European country in 2019. (PlasticEurope, 2020)

In Austria in 2018, the volume of mixed municipal waste from households and similar establishments amounted to approximately 1,458,800 t (BMK, 2020). Besides, around 263,000 t (BMK, 2020) of bulky waste from households and similar establishments was collected. Both together result in approx. 7% of total waste generation in Austria (BMK, 2020). In 2018, 86.1% of these wastes were treated thermally directly, or after processing in the first treatment step, 12.3% were treated biologically, and 22,000 t (1.5%) of valuable materials (mainly metals) were sorted out for recycling (BMK, 2020).

In Europe, 219,563,000 t of municipal waste were generated in 2018 (Eurostat, 2020). Of this, approx. 27% was thermally recovered, 49% recycled, and 24% landfilled (Eurostat, 2020).

1.1 Mechanical treatment of mixed wastes

There exist many different types of waste treatment plants. Depending on the input material and the treatment target, different combinations of aggregates are used in the plants. The primary classification of waste treatment processes and plants into pre- and post-treatment is shown in Figure 4.

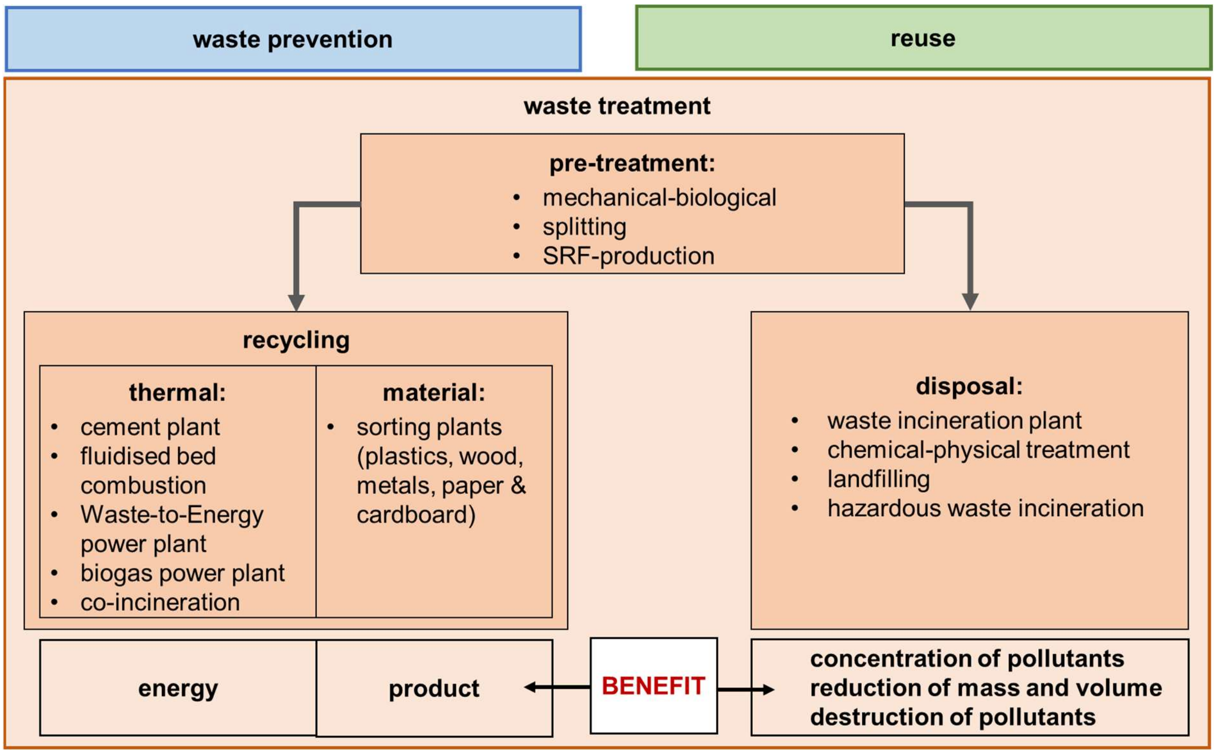

Figure 4: Classification of waste treatment processes (according to Pomberger, 2018).

A mechanical pre-treatment plant aims to sort different waste streams. In the process, valuable materials (e.g., metals, plastics, etc.) and impurities (e.g., PVC, inert, etc.) are to be sorted out, and solid recovered fuels (SRF)[1] from high calorific residue are produced. There are many different waste treatment plants with various purposes and processes. The most frequent mechanical pre-treatment plants for mixed wastes are splitting plants[2], mechanical-biological treatment plants, sorting facilities, and plants for SRF production. Splitting plants are used for pre-treatment of bigger waste streams, which mostly are further processed in other waste treatment plants. In sorting plants, either separately collected wastes (e.g., lightweight packaging waste) or already pre-treated mixed waste (e.g., from a splitting plant) is further sorted into different recyclable fractions, e.g., plastic types. In SRF production plants, both untreated mixed wastes and sorting residues from other waste pre-treatment plants are processed into SRF with various qualities.

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[1] SRF is a term defined according to DIN EN 15359:2012-01 and must fulfil the specified criteria (solid, non-hazardous waste, compliance with quality criteria (calorific value, chlorine and mercury content), use as a substitute for primary energy sources in thermal processes).

[2] Splitting plants are material flow separation plants in which the material flow is separated according to properties, e.g. according to sortability, calorific value, dimensionality etc.

The Austrian waste pre-treatment plant of the company Hackl in Wulkaprodersorf (see Figure 6), which was in operation in 2020, is suitable for describing the state of the art of these plants. In this plant (see Figure 4), two different types of waste (lightweight packaging and mixed commercial waste) are treated in three different plant modules. The first module is the "splitting module," in which the waste is split and preconditioned using different screening and sorting stages. The separated, plastic-rich waste stream is then further processed in the “sorting module”. For the enrichment and separation of the plastic types (PE, PP, PET, PVC, and PS) and wood, the three technologies, sensor-based, robotic, and manual sorting, are used in combination. The residual streams of the two modules, “splitting” and “sorting,” are finally processed in the "SRF-module" to primary and secondary SRF. (Waltenberger et al., 2020)

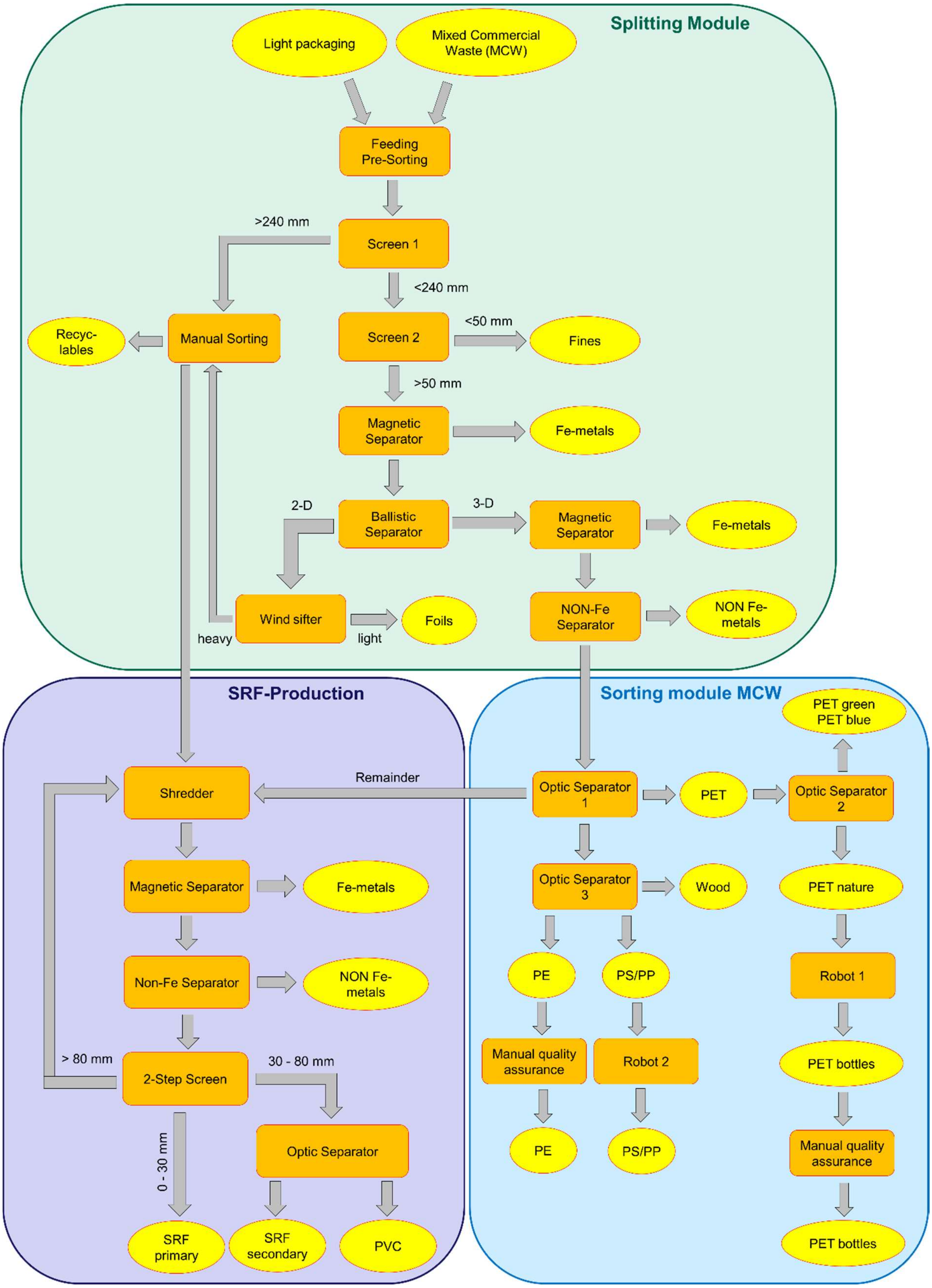


Figure 5: Process flowsheet of an Austrian waste pre-treatment plant (according to Waltenberger et al., 2020).

1.2 State of the art of a plastic recycling facility

The PET recycling process is particularly suitable for presenting the state of the art in plastic recycling facilities (PRF), as almost all available technologies are used here due to the high-quality requirements for the recyclates. (Forrest, 2016) Figure 6 shows the necessary material treatment process of the PET recycling process described below.

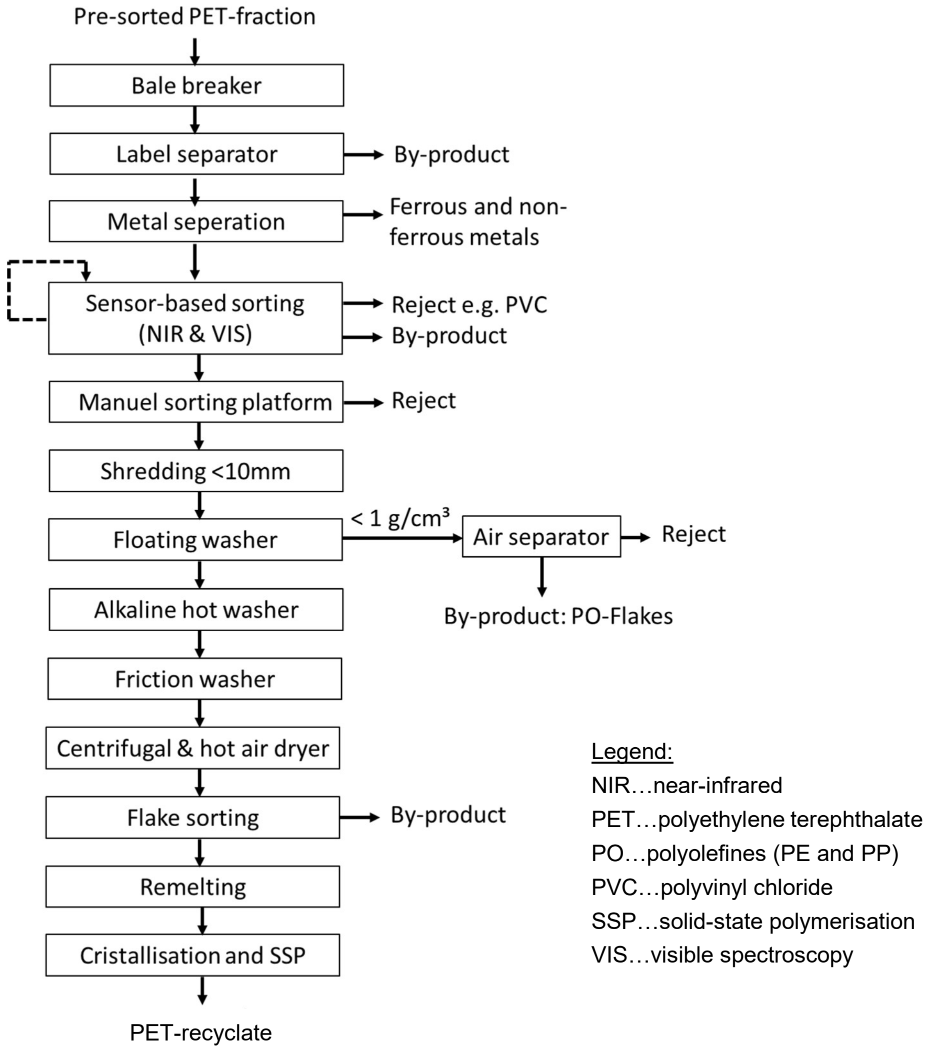


Figure 6: Simplified flow chart of the recycling of PET packaging. (Forrest, 2017; Letcher, 2020; Raju, 2016)

The qualities of the sorted PET bottles and mixed PET fraction provided by the sorting or other waste treatment plants are taken over as bale goods from the material recycling facility. Processing begins with opening the bale and separating the binding wire. This is followed by pre-sorting to separate incompatible components (e.g., labels, metals, PVC, other plastics, etc.). The separated materials are often sold as by-products. It is usually carried out using a combination of single- and multi-stage, sensor-based material and colour sorting with a downstream manual control station. After pre-sorting, the material is shredded to a particle size of <10 mm to disintegrate the material components and as a requirement for the subsequent separating and transport processes. The subsequent washing process is usually carried out in two or more stages, whereby at least the second stage is operated as an alkaline hot wash. The separation of polyolefinic plastic particles (e.g., from closures and labels) is usually carried out by gravimetric sorting in sink-float tanks at a separation density of 1 g/cm³. The process principle of density separation can be implemented in different types of aggregates (sorting centrifuge (Andritz, 2020) or centrifugal force separator (Bauer et al., 2019). In PET recycling, the floating material is not a reject but a saleable by-product. The PET flakes are discharged in the sink material of the density separation stage. The alkaline washing makes it necessary to rinse the PET flakes to remove the caustic soda from the surface before the drying process. This is usually followed by a multi-stage sorting of the PET flakes to minimise contaminants in the end product. The problem is that relevant incompatibilities with adhesive residues or additives only become apparent during the remelting process. Many other plastics are not thermally stable at the usual remelting temperatures of PET (approx. 260°C) and form decomposition products. The subsequent remelting process is carried out using extrusion with melt filtration. SSP (solid-state polymerisation), with which the degree of polymerisation and crystallisation of PET can be adjusted to virgin material level, is often used in PET recycling. Finally, various refining processes and granulate treatment (e.g., screening) can take place. (Forrest, 2017; Letcher, 2020; Raju, 2016)

1.3 Solutions for plastic wastes

There are several options for plastic waste recycling: primary recycling (ReUse), mechanical or material recycling, chemical recycling, and energy recovery (Figure 7).

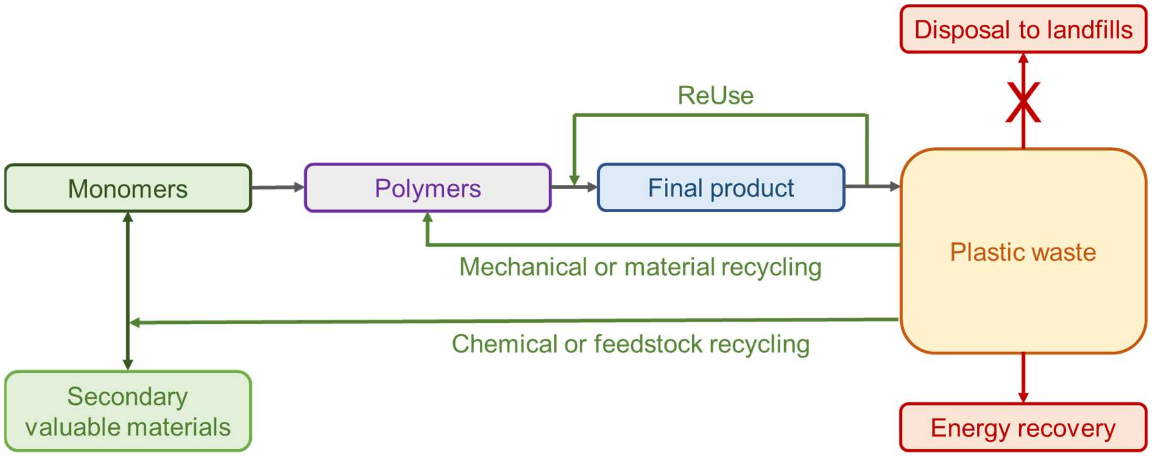


Figure 7: Methods of waste plastic treatment (according to Zhang et al., 2021).

- **ReUse** involves using the same product without essential changes in a new use cycle (e.g., refillable packaging after cleaning) (Zhang et al., 2021).

- **Mechanical or material recycling** of waste plastics: This is the most common method for the recycling of plastic waste (Ignatyev et al., 2014; Letcher, 2020; Soto et al., 2018; Zhang et al., 2021). In mechanical recycling, the chemical structure (macromolecules) remains unchanged, and only mechanical/physical treatment is utilized to process so-called recyclates. Mechanical recycling is mainly used if large quantities of a single type of low contaminated material are available. Quality criteria for recyclates for the final plastic processing companies are not standardised but defined individually by the recycling and processing companies. Criteria include, e.g., exceptionally pure colour and low content of contaminations (EU, 2006; Friedrich et al., 2019; Vilaplana & Karlsson, 2008). Of particular importance for mechanical recycling are contaminants (e.g., heavy metals) in the input material. Depending on the product, these are only permitted in minimal quantities (Friedrich et al., 2019). For this reason, the removal of impurities and pollutants must be carried out as far as possible in pre-treatment (Soto et al., 2018; Zhang et al., 2021).

- **Chemical or feedstock recycling** (Bauer et al., 2013; Ignatyev et al., 2014; Letcher, 2020; Soto et al., 2018; Zhang et al., 2021): This type of recycling has a high potential for heterogeneous and contaminated plastic waste material if more intensive separation and processing in case of mechanical recycling is neither economically nor technically feasible. In chemical recycling, the polymer chains are split (e.g., through the use of heat), whereby monomers or petrochemical raw materials such as oils and gases are obtained, e.g., in a conventional crude oil refinery (Bauer et al., 2013; Letcher, 2020). These can be used to produce new plastics or for other petrochemical purposes. Other important processes are pyrolysis, hydrogenation, gasification, and the use as substitute reducing agents in the blast furnace process (Letcher, 2020).

- **Thermal recovery** (Lombardi et al., 2015; Moya et al., 2017; Zhang et al., 2021): The thermal recovery of plastics has the basic idea of using the energy content of plastics. Heavily contaminated, polluted, or mixed plastic waste serves as a substitute for primary fuels such as coal, oil, and gas. The energy content differs depending on the type of plastic, and values of up to 40,000 KJ/kg (Lombardi et al., 2015) can be achieved. In certain plants designed for thermal recovery, electricity, district heating, or even steam can be generated. A disadvantage of the thermal recovery method is the release of various pollutants, e.g., acid gases during plastics' combustion containing halogens.

  Furthermore, the incinerated quantities have to be replaced by new plastic. Thermal plants can be waste to energy or power plants, cement rotary kilns, or waste incineration plants. In waste incineration plants, the exceptionally high calorific value of plastics has a partially negative impact on plant throughput. In power plants, plastics are usually used together with regular fuels. It is essential to meet the respective plant's quality requirements, which provide specifications for the fuel composition.

- **Landfilling (Lebreton & Andrady, 2019)**: Landfilling plastics is not a reasonable solution for resource conservation and landfill volume savings. However, the extent to which plastic waste (untreated) may be landfilled depends on the legal framework in the individual member states. There exists no EU-wide landfill ban. Plastic mixtures are difficult to recycle, which is why landfilling is still the main disposal route for plastic waste in many European countries (see Figure 3). In total, in ten EU countries (Switzerland, Austria, Netherlands, Germany, Luxembourg, Sweden, Finland, Belgium, Denmark, and Norway), plastic waste disposal is forbidden. Waste with a TOC (total organic carbon) of more than 5% - and thus plastic waste - may not be deposited untreated in landfills.

In 2019, close to 5 Mt of plastic recyclates were produced in European recycling facilities (PlasticEurope, 2020). This corresponds to approx. 17% of the total post-consumer plastic waste collected or ~53% of the amount recycled. This means that about 47% of recyclable plastic is exported (PlasticEurope, 2020). Approximately 80% (PlasticEurope, 2020) of the 5 Mt of plastic recyclates were used to produce new plastic products. The rest was exported outside Europe. Recyclates can be used in new plastic products in different ways.

On the one hand, certain areas of a product can be replaced by 100% recycled material (e.g., the middle layer of a product made of recyclate and the contact surfaces made of virgin material). Another way to save expensive virgin plastic is to replace a certain percentage of the matrix with recycled material. In this case, the entire polymer material of an object consists of a certain percentage of recycled material at every point (Letcher, 2020). Another variant is the processing of polymer products with 100% recycled content. Therefore, the product variety is not limited, and the plastic recyclates are therefore used in products in the following market sectors: The largest share of plastic recyclates (46%) is currently used in the "Building & Construction" sector. About 24% is reprocessed into packaging applications (e.g., PETtoPET recycling). Approximately 13% of the recyclates produced are used for agricultural products (e.g., agricultural films). In the automotive (3%), electronics (2%), and houseware, leisure, and sports (1%) sectors, comparatively few recyclates are used to replace virgin material. About 11% are needed in other market sectors. (PlasticEurope, 2020)

2 MATERIALS

The materials used for the investigations in the present doctoral thesis were mixed commercial solid waste (MCW), mixed municipal solid waste (MMW) both from Austria (Upper Styria and Graz), and SRF made out of MCW and MMW. These three waste streams are briefly described below.

2.1 Mixed commercial solid waste

On a federal level, there is no specific legislation on commercial waste in Austria. The term "commercial waste" is not defined, neither in federal nor in provincial legislation. In the Austrian waste catalogue, ÖNORM S 2100 (ÖNORM S 2100 based on Waste Catalogue Ordinance) commercial waste is assigned to waste group 91 "Solid municipal waste, including similar commercial waste". A definition of MCW is given, for example, in Germany that has stipulated the Commercial Waste Regulation (BMU, 2017). There, MCW is a non-municipal residual waste not collected separately, such as office wastes, industrial wastes, etc. Typical MCW is characterised by relatively low moisture content, high calorific value, low organic content, and high content of recyclables (Weißenbach, 2019).

Owing to its energetically usable calorific value higher than that of MMW, it is used to produce SRF (Pomberger, 2007; Sarc and Lorber, 2013; Sarc et al., 2014). The composition of MCW varies widely and depends on the industry in which it is generated (Weißenbach, 2019). Little is known about the detailed composition and volume of MCW in Austria. (Weißenbach, 2019)

2.2 Mixed municipal solid waste

According to § 2, number 4, point 2 of the waste management act 2002 (AWG, 2002), unprocessed mixed municipal waste is *"waste from private households and other waste which, because of its nature or composition, is similar to waste from private households; the classification shall take into account the European Waste List as defined in Article 7 of Directive 2008/98/EC on waste. Mixed municipal waste within the meaning of the European Waste List shall continue to be regarded as mixed municipal waste even if it has undergone a treatment process which has not significantly altered its properties."*

In contrast to MCW, MMW has a higher moisture content, lower calorific value, higher organic content, and relatively lower recyclable content. The composition of MMW depends on various factors, including the available waste collection system, the socioeconomic structure of the population, or the situation of urban or rural households. The most essential components of MMW are organic fractions, plastics, paper, and cardboard.

2.3 Solid recovered fuels

According to Viczek et al. (2020), solid recovered fuels (SRF) represent a subgroup of refuse derived fuel (RDF): "*While RDF can be prepared of various non-hazardous and hazardous, liquid and solid waste materials (e.g., sewage sludge, waste wood, used solvents), the term SRF only refers to solid fuels made from non-hazardous mixed or sorted solid wastes, are furthermore quality assured, i.e., meet the criteria defined by EN 15359, and utilized for energy recovery.*"

SRF can be differentiated into two qualities (Viczek, 2020):

- *"SRF for secondary firing (SRF "secondary"): SRF with a lower heating value between 12 and 18 MJ/kg$_{OS}$ (corresponding to class NCV 3 or 4 in EN 15359) suitable for the use in secondary firing (calciner, kiln inlet, or hot disc combustion chamber, etc.) in the kiln system of cement manufacturing plants. Grain sizes can range up to 80 mm when used in a calciner or at the kiln inlet and up to 300 mm for a hot disc combustion chamber.*

- *SRF for primary firing (SRF "primary"): SRF with a lower heating value between 18 and 25 MJ/kg$_{OS}$ (corresponding to class NCV 1, 2, or 3 in EN 15359), and grain sizes below 30 (35) mm suitable for the use as a main burner fuel in the rotary kiln of cement manufacturing plants."*

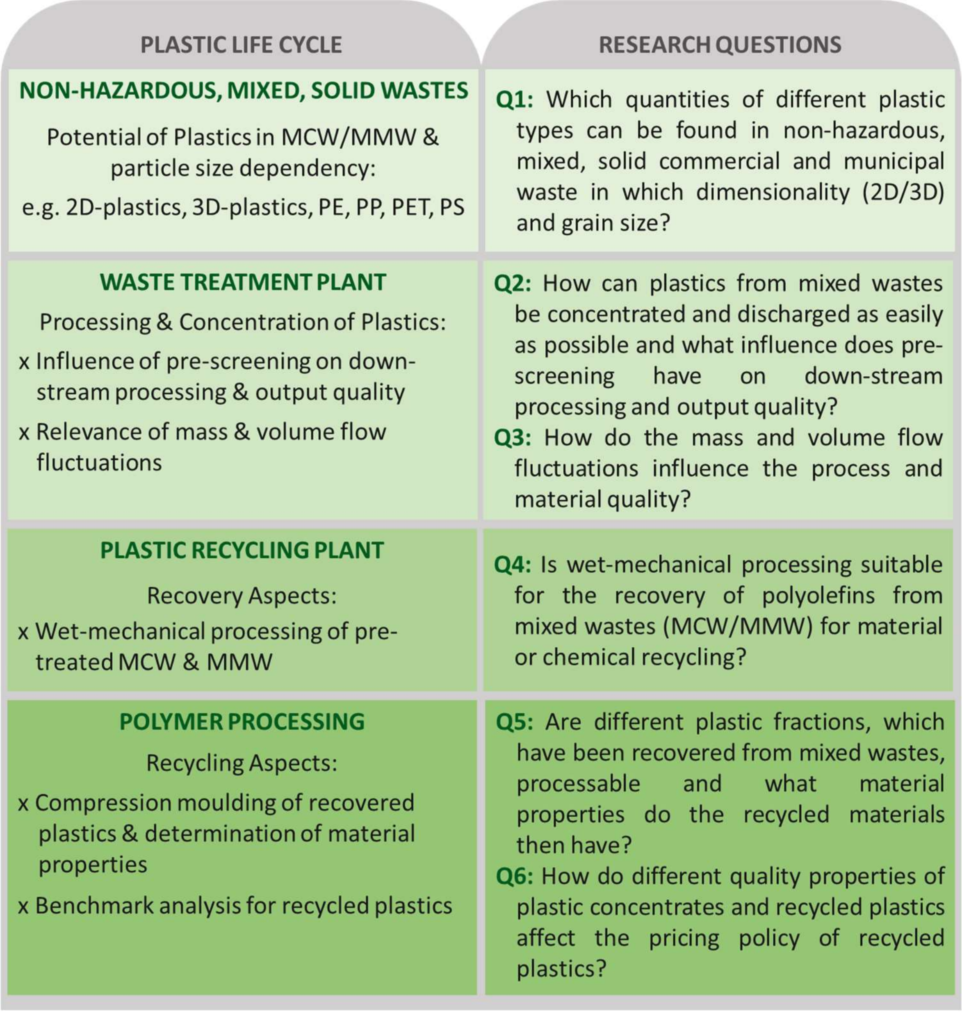
3 CONCEPT OF THE PHD THESIS AND SCIENTIFIC METHODOLOGY

In the following chapters, the research gap, i.e., degree of novelty of the work, the research framework, and the structure and methodology of this doctoral thesis are presented.

3.1 Degree of novelty of the work

The novelty of this thesis corresponds to the research gaps identified along the stakeholder chain from mixed solid non-hazardous waste to plastic recyclates and defined by precise research questions. The research questions were formulated within the project “ReWaste4.0” but also as a result of the emerged problems during the research project. The research was planned and carried out based on the research questions posed. These research questions are in accordance with the research chapters/papers included in the present doctoral thesis.

The following subchapters present the scope of each paper and its specific research question. The research questions were assigned according to the life cycle of end-of-life plastics and aligned along the stakeholder chain (see Figure 8).



PLASTIC LIFE CYCLE	RESEARCH QUESTIONS
NON-HAZARDOUS, MIXED, SOLID WASTES Potential of Plastics in MCW/MMW & particle size dependency: e.g. 2D-plastics, 3D-plastics, PE, PP, PET, PS	**Q1:** Which quantities of different plastic types can be found in non-hazardous, mixed, solid commercial and municipal waste in which dimensionality (2D/3D) and grain size?
WASTE TREATMENT PLANT Processing & Concentration of Plastics: x Influence of pre-screening on down-stream processing & output quality x Relevance of mass & volume flow fluctuations	**Q2:** How can plastics from mixed wastes be concentrated and discharged as easily as possible and what influence does pre-screening have on down-stream processing and output quality? **Q3:** How do the mass and volume flow fluctuations influence the process and material quality?
PLASTIC RECYCLING PLANT Recovery Aspects: x Wet-mechanical processing of pre-treated MCW & MMW	**Q4:** Is wet-mechanical processing suitable for the recovery of polyolefins from mixed wastes (MCW/MMW) for material or chemical recycling?
POLYMER PROCESSING Recycling Aspects: x Compression moulding of recovered plastics & determination of material properties x Benchmark analysis for recycled plastics	**Q5:** Are different plastic fractions, which have been recovered from mixed wastes, processable and what material properties do the recycled materials then have? **Q6:** How do different quality properties of plastic concentrates and recycled plastics affect the pricing policy of recycled plastics?

Figure 8: Division of research topics along the plastics life cycle and related research questions. Note: Q is used for the research question in the thesis.

The knowledge of the two different disciplines of plastics technology and waste management is combined in this dissertation in order to come to a small step closer to the common goal of "closing the plastics cycle". Extensive knowledge of both disciplines is necessary to recover used plastics from mixed, contaminated, solid wastes, process them efficiently, and turn them into characterised materials with application options. According to the current state of the art, mixed solid wastes (e.g., MCW and MMW) are predominantly (except for PET recovery and PVC removal) processed into substitute fuel in a wide variety of spitting, mechanical-biological, or SRF plants and used in energy recovery plants.

In the following, the six research questions are posed, and the procedure for their scientific answer is briefly presented.

Research question 1:

Which quantities of different plastic types can be found in non-hazardous, mixed, solid commercial, and municipal waste in which dimensionality (2D/3D) and grain size?

In large-scale test series, about 21 tonnes of MCW and about 70 tonnes of MMW in untreated form were shredded and primary sampled. The samples were then mass reduced and screened in nine grain size classes (screen cuts: 5, 10, 20, 40, 60, 80, 100, 200, and 400 mm). Grain sizes smaller than 20 mm were discarded. Fractions coarser than 20 mm were manually sorted into nine material fractions, generating a ‘plastics-2D’ and a ‘plastics-3D’ fraction, among others. To determine the content of plastic types of the two sorted plastic fractions from MCW and MMW, they were further sorted manually into six plastic types (PE, PP, PVC, PUR, PET, and PS) using a near-infrared sensor and a Fourier transform infrared spectrometer. PE was further sorted into HDPE and LDPE with a distinction between nature and coloured objects for both types. For PS, a distinction was made between expanded (EPS) and compact objects made of PS.

Research question 2:

How can plastics from mixed wastes be concentrated and discharged as easily as possible, and what influence does pre-screening have on down-stream processing and output quality?

Large-scale experiments were conducted to investigate how plastics could be enriched and discharged from MCW and MMW. For the investigations, about 40 tonnes of MCW and about 75 tonnes of MMW were shredded in a dry mechanical treatment line to a maximum particle size of 300 mm to ensure a particle size ratio of 1/3-1/4 to the screen cuts of the downstream aggregates. First, the processing line was configured without a drum screen (80 mm) for both wastes (MCW and MMW). The drum screen was then placed between the shredder and the ballistic separator to investigate the influence of the pre-screening on the output fractions of the processing line. The ballistic separator divided the material flow into a 2D-, 3D- and a fine fraction (<80 mm). During each test, samples of all output fractions were continuously taken from the falling stream according to ÖNORM S 2123-3. At the end of each test run, all output streams were documented and weighed. The respective total mass balances were created from these data in combination with the mass flow data from the digital material flow monitoring system (placed after drum screen). Decoupled from the process line, a sensor-based sorting machine (NIR-sorter) was set up for further processing of the samples of the 3D-fraction. With manual, continuous material feed and slow throughput rates to prevent particles from overlapping, the plastics in the samples (LDPE, HDPE, PP, PET, PUR, PS, and PVC) were separated from non-plastics and carbon blackened plastics via positive sorting. After separation with the SBS into a target (3D-plastics - eject) and a residual fraction (reject), both output streams were sorted manually. Also, 2D-objects that were incorrectly discharged into the 3D-fraction were sorted out manually. To determine the composition of the respective 2D-fraction, the 2D-samples were manually sorted into nine material fractions (composites, metal, paper & cardboard, textile, wood, inert, fines (<80 mm), and plastics-2D and -3D). All samples of both fine fractions (screen & ballistic separator) were subjected to an additional screening analysis with five screen cuts (10, 20, 40, 60, and 80 mm).

Research question 3:

How do the mass and volume flow fluctuations influence the process and material quality?

Three different test series to material processing and online monitoring were carried out to investigate the relevance of mass and volume fluctuations. In test series A), the on-site material flow monitoring was carried out in a waste treatment plant with mixed commercial waste (MCW) as input material by utilizing a hyperspectral imaging (HSI) near-infrared (NIR) camera above a conveyor belt in the 3D-material processing line. In test series B), volumetric and mass flow fluctuations were recorded in a pilot-scale processing line for MCW, using a digital material flow monitoring system (consists of laser triangulation, HSI NIR sensor, VIS camera, and a belt scale). The test series C) investigated how manually generated material flow fluctuations affect the sorting performance (purity and yield) of an industrial-scale sensor-based sorting machine. The material for the test series C) was sorting residue from an Austrian lightweight packaging waste sorting plant (reject fraction) endowed with a pure PET- fraction (32.3 mass-%) as eject fraction. For analysis of the two output flows, eject and reject the amount of PET and rest in the eject and reject fraction was mass-specifically determined by manual sorting. For the assessment of fluctuations occurring in test series A), B), and C), a distinction between short-, mid-, and long-term fluctuations was made.

Research question 4:

Is wet-mechanical processing suitable for the recovery of polyolefins from mixed wastes (MCW/MMW) for material or chemical recycling?

Samples of the 2D-fractions obtained from the experiments presented in Paper 2, *"Influence of pre-screening on down-stream processing for the production of plastic enriched fractions for recycling from mixed commercial and municipal waste,"* were used as input material for wet-mechanical separation experiments with the pilot plant called centrifugal force separator

(CFS). For the polyolefin separation tests, about 110 kg_{OS} of MCW_2D and MMW_2D were shredded to smaller than 20 mm and mashed with water before feeding in the CFS. The feed material to be separated is fed directly into the water vortex at the upper end of the inclined separator. Those particles, which are specifically heavier than the separating medium, are discharged as a heavy fraction (HF). The specifically lighter particles LF (mostly polyolefins - PO) are discharged as a light fraction. Both material flows are discharged separately via a dewatering screen. To achieve a further concentration of the POs of the light fractions, they were fed into the CFS once again, simulating a cascade connection of two CFS plants. The input materials and generated material outputs (LF I/II and HF I/II) were continuously sampled, and a mixed sample was created in each case. The process water was collected and decoupled from the treatment line, fed to a static drum filter to separate the liquid and solid phases. Also, process water samples were taken, and samples of the generated sediment after static filtration. The water content and the float and sink fraction (manual sink/float analysis) were determined for all material samples.

Furthermore, the calorific value (LHV and UHV) was determined. Also, the chlorine, heavy metals, and metalloids (Sb, As, Pb, Cd, Cr, Co, Ni, Hg) and ash contents of the feed materials and the target fractions (LF II) were determined, and quantitative elemental analysis (CHNOS) was performed. The samples of process water were also subjected to a detailed chemical analysis. In addition to general parameters such as filterable, settleable substances, pH value, and density, inorganic and organic parameters were determined. The sediment composite sample was also subjected to a detailed chemical analysis. The dry residue, the calorific value (LHV and UHV), the heavy metals, and metalloids were determined.

Research question 5:

Are different plastic fractions, which have been recovered from mixed wastes, processable, and what material properties do the recycled materials then have?

For the extensive processability tests, about 200 kg of standard solid recovered fuels (SRF) before post-shredding, a wet-mechanically pre-treated PO-fraction from a plastics sorting plant, and a PO-fraction from an SRF plant (wind sifter light fraction) were used. All materials were prepared differently in a mechanical pre-treatment (e.g., washed/unwashed) and finally shredded to a particle size smaller than 4 mm for the subsequent plastics processing. The shredded plastic materials were then divided in two, with one stream per material being compression moulded directly into plates and the other homogenised in an extruder before compression moulding. Test specimens were made from the produced plates required for extensive mechanical, thermal, and rheological material characterisation. For the examined plastic materials, the following properties were investigated: thermal (crystallization and melting temperature and the respective enthalpies), mechanical properties (tensile test and (notched) impact strength), characterisation of the flow behaviour (MFR), bulk density (flakes after shredding and granulates after extrusion) and ash content.

Research question 6:

How do different quality properties of plastic concentrates and recycled plastics affect the pricing policy of recycled plastics?

To determine the quality benchmark for plastic recyclates, a market analysis of secondary plastic granulates was carried out. For this, the plastic types HDPE, LDPE, PP, PET, and PS are investigated as they represent about 60% of the demand for the plastic packaging waste processing industry in Austria. To analyse the correlation between price and quality, different stakeholders (plastic waste processing companies, plastic waste recycling companies, final plastic product manufacturing companies, working clusters, associations, research institutes, etc.) along the value chain from plastic waste to “new” plastic products in Austria were interviewed (in person, by telephone, and by mail) with an assessment guide. In addition to the interviews with stakeholders in Austria, the plastic recyclers and the plastics processing industry in Germany was approached with short and targeted e-mail questions. All feedbacks were finally evaluated on a stakeholder-specific basis. The market data from the exchange for plastic raw materials "Recybase" were evaluated from May 2014 to August 2019 for the examined plastic types for the analysis of price developments of plastic recyclates and virgin material.

3.2 Scope of Investigations

This doctoral thesis investigates the potential, processing, and recycling aspects of plastics from non-hazardous, mixed, solid wastes along the plastics cycle. The plastic life cycle can be divided into **four stakeholder areas** (subject areas) in a simplified way (see Figure 9): *"Non-hazardous, mixed, solid wastes"* with plastic recovery potential, *"waste treatment plant"* (pre-processing, concentration, and recovery of plastics), *"plastic recycling plant"* (processing of the plastic concentrates to recyclate) and the area *"polymer processing"* (production of plastic products from recycled material and determination of material properties). These four stakeholder areas along the plastic life cycle follow one another, interact thematically and influence each other. Within and across these four areas, this doctoral thesis investigates the following **three research areas** which build on each other (see Figure 9): "*Potential of Plastics*", *"Processing and Concentration of Plastics,"* and *"Recovery and Recycling Aspects"*. In these three research areas, scientific peer-reviewed publications on selected research topics were written to answer the research questions addressed in this doctoral thesis.

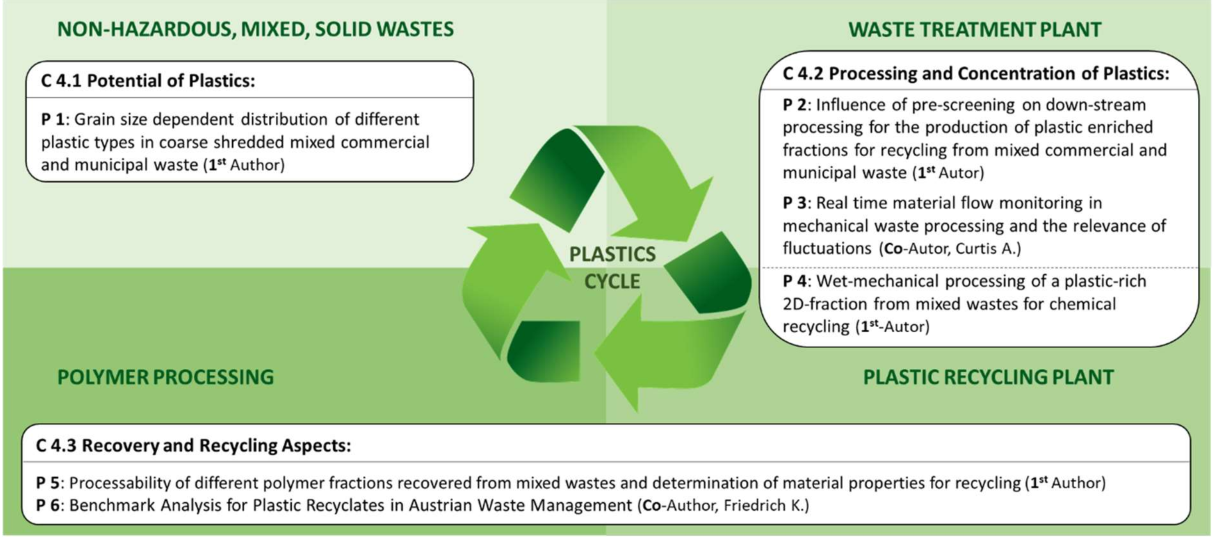


Figure 9: Concept of this doctoral thesis, divided into three research areas (black boxes). Note: C is used for chapters and P for publications in the thesis.

4 PRACTICAL-SCIENTIFIC WORK AND EXPERIMENTAL RESULTS

This chapter presents the practical-scientific work and its results in the form of six peer-reviewed and published publications.

4.1 Potential of Plastics

Knowledge of the plastic content and the plastic types contained in the wastes examined (MCW and MMW) is necessary as a basis for further research work. Only if sufficient plastics are contained, it is economically and technically relevant to recover and recycle them, in addition to the legal requirements. An additional benefit of recovering plastics from SRF, splitting plants, etc., in the first treatment step or before, is creating free treatment capacities in these and downstream treatment plants. These are urgently needed in view of the increasing volume of waste and the fact that many plants are already working at their limit. The collection of this knowledge base, especially for mixed commercial waste, is presented in detail in the following publication 1.

4.1.1 Publication 1

Grain size dependent distribution of different plastic types in coarse shredded mixed commercial and municipal waste

Möllnitz, S., Khodier, K., Pomberger, R., Sarc, R.

Waste Management 103 (2020), 388-398, https://doi.org/10.1016/j.wasman.2019.12.037

Author Contributions:

MS: Conceptualisation, Methodology, Formal Analysis, Investigation, Data curation, Writing – original draft, Writing - Review and Editing, Visualisation, Project administration.

KK: Conceptualisation, Methodology, Investigation, Data curation, Writing – original draft (section 2.2.1), Writing - Review and Editing, Project administration.

PR: Resources, Supervision, Funding acquisition.

SR: Methodology, Resources, Writing – review and editing, Supervision, Funding acquisition.

Due to confidentiality agreements with project partners, not all original data were included in the paper or its appendix. These can be found in Appendix A of the present thesis.

Waste Management 103 (2020) 388–398

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Grain size dependent distribution of different plastic types in coarse shredded mixed commercial and municipal waste

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ABSTRACT

The Waste Framework Directive regulates the recycling of waste in Europe. The definition of waste is specified in different guidelines and regulations. Mixed Commercial Waste is waste from industry which is not collected separately. Currently there is little known about its composition. Mixed Municipal Waste, on the other hand, is household waste that cannot be attributed to any separately collected waste fraction (AdSLR, 2012). Both wastes are currently treated focussing on the generation of refuse-derived fuel rather than on the separation of recyclables (mainly performed for metals).

The purpose of this paper is to characterise the amounts of various plastic types contained in different grain sizes of two-dimensional and three-dimensional plastics sorting fractions of both waste types. Nine types of plastics were identified as potential recycling materials for which recycling processes as well as a market are available. Both wastes were shredded, sampled and sieved into nine grain size classes (GSC). Fractions coarser than 20 mm were sorted, generating a 'plastics-2D' and a 'plastics-3D' fraction among others. The two plastics fractions were further characterised as plastic types using a near-infrared sensor and a Fourier-transform infrared spectrometer. The results reveal a potential for plastic recycling through mechanical and feedstock recycling options for the examined wastes. Certain types of plastics, of certain dimensionality, tend to come in certain grain sizes, which is essential for mechanical enrichment and discharge.

1. Introduction

The European Directive on waste (2008/98/EC) (Waste Framework Directive – WFD) establishes definitions and stipulates the basic concept for the development of sustainable waste management in the EU. The following waste hierarchy should be applied to sustainability in waste management (i. e. proper waste treatment and production of secondary raw materials and energy resources) according to the directive (EU, 2018): *'Prevention, Preparing for re-use, Recycling, Other recovery, e. g. energy recovery; and Disposal.'* When applying the waste hierarchy, member states shall encourage those options that produce the best overall environmental outcome, taking the principles of environmental protection as well as technical feasibility and economic viability into account. Article 11 of the directive defines re-use and recycling measures and goals. Regarding Austria, waste management is currently undergoing a transformation: It is developing from a thermal to a recycling economy (Pomberger et al., 2017).

While the recycling of glass, paper or metals has developed faster, plastics recycling is lagging behind. For municipal waste, recycling rates of 55% need to be achieved by 2025 (EU, 2018). There is currently no attempt made by the EU to introduce recycling rates for Mixed Commercial Waste (MCW). Separate collection of at least paper, plastic, metal and glass from households and eventually other origins - as far as these waste streams resemble household waste – came into force in 2015, taking technical, environmental and economical aspects into account. By 2020, the preparation for re-use and the recycling of aforementioned waste fractions will finally be increased to at least 50%. (EU, 2018) The European Commission has established rules and calculation methods for verifying compliance with the targets (regarding Article 11 - WFD) and the performance of member states (EU, 2011). They include the definition of different wastes, e. g. Mixed Municipal Waste (MMW), that is relevant for this paper. A definition of MCW is given only in Germany that has stipulated the Commercial Waste Regulation

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(GewAbfV, 2017). MCW is non-municipal residual waste not collected separately, such as office wastes, industrial wastes, etc. Typical MCW is characterised by a rather low content of moisture, high calorific value, low organic content and high content of recyclables. Owing to its energetically usable calorific value that is higher than that of MMW, it is used to produce Solid Recovered Fuel (SRF) (Pomberger, 2007; Sarc and Lorber, 2013; Sarc et al., 2014). The composition of MCW varies widely and depends on the industry in which it is generated. For individual regions, the emergence of MCW has been estimated to account for 30–70% of the amount of MMW (AdSLR, 2010; Pomberger and Gungl, 2010).

Little is known about the detailed composition and volume of MCW in Austria. Wellacher and Pomberger (2017) give an averaged composition of three types of MCW available on Austrian market, following three sorting campaigns of MCW and determination of their mean composition. Plastics were summarised into an SRF fraction (73.8%). Only PET (1%) was sorted separately. Other recyclable material fractions that were separately sorted were wood (8%), paper (6.8%), metals (6.4%), and inert (4%). (Wellacher and Pomberger, 2017)

MMW is waste that cannot be attributed to any of the separately collected waste fractions because it is contaminated or mixed. In contrast to MCW, MMW has a higher content of moisture, lower calorific value, higher organic content and quite lower recyclable content. The composition of MMW depends on various factors including the available waste collection system, the socio-economic structure of the population or the situation of urban or rural households. The most important components of MMW are organic fractions, plastics, paper, and cardboard. For example, the results of a sorting analysis of MMW for Styria, Austria is shown in BMLFUW (2018).

MMW is treated in splitting plants, mechanical-biological plants and thermal plants (note: in Austria landfilling of untreated MMW is legally forbidden). The separation of recyclable material is still subordinate to the prioritised generation of SRF. The total mass of MMW in Austria was 1.437.600 tonnes in 2017, with a slight subsequent decline (BMLFUW, 2018). In the EU 28, approx. 2.5 billion tonnes of waste are produced per year (Eurostat, 2016). Municipal waste accounts for only about 10% (approx. 248 million tonnes in 2017) of the total waste generated (Eurostat, 2017). Municipal waste management is very important, however, because of - among other factors - its complex characteristics deriving from composition and biological activity, etc. Currently, most plastics present in MCW and MMW end up in thermal recovery and are irrevocably lost for recycling. Even more is requested by the industry for usage in new feedstock recycling technologies (e. g. as a substitute reducing species in the blast furnace or to recover molecular intermediates for synthetic crude oil production) (Kranzinger et al., 2018). Future recycling rates can only be met by upgrading relevant plastics from 'Other recovery, e. g. energy recovery' to 'recycling'. For example, polypropylene and polyethylene are recyclable and demanded as secondary raw materials. Different properties and material types of the two-dimensional (e. g. foils) and three-dimensional plastic parts (e. g. rigid tubes) observed during the shredding process suggest that shredded materials occur in different grain size classes.

The purpose of this paper is to determine which materials are mainly included in the two-dimensional and three-dimensional plastic fractions of both investigated wastes. The distribution of two- and three-dimensional plastic parts, and the plastic types they contain, among different grain size fractions of shredded wastes are also investigated. This information is particularly valuable because specific plastic types are expected to accumulate in specific grain size classes, which is of interest for subsequent recovery processes. Based on data gained, the potentials of plastics and plastic types over different grain sizes are analysed and screening is assessed in its function as an aggregate for potential accumulation and recovery options in commercial and municipal solid waste.

2. Materials and methods

2.1. Materials

For the purposes of this paper, about 21 tonnes of MCW from the area of the city of Graz, Austria (Figure I, left, of the supplementary material) and 70 tonnes of MMW (Figure II, left, of the supplementary material) from Allerheiligen (Mürztal, Austria) were shredded in experimental runs taking about an hour each in October 2018. Both wastes originated from direct collection and were not treated before shredding.

The investigation presented in this paper is focussed on the grain size dependent distribution of plastic types, hence the source of waste investigated is irrelevant for further analyses, in contrast to its quality.

2.2. Methods

Fig. 1 shows the experimental pathway from feeding input material to the shredder (shredding and primary sampling) via mass check including mass reduction and screening up to the analysed material fractions (achieved by manual sorting). The theoretical background of the design of sampling and screening with sorting analysis following is described by Khodier et al. (2019). In Fig. 2, the subsequent analysis of plastic types of different grain sizes is shown. The entire investigation period was five weeks for MCW and seven weeks for MMW, performed from October to December 2018.

2.2.1. Shredding and primary sampling

Shredding reduces the grain size, enabling representative sampling. It also discloses the material for sorting steps. A Terminator 5000 SD shredder with F-type cutting unit made by the Austrian company Komptech was applied, operating at maximum shaft rotation speed (31 rpm) and minimum gap width. The waste was fed using a wheel loader. Each experiment took 66 min. The sampling time interval for performing increments was determined based on the mass flow of the first three minutes, estimated using laser triangulation volume flow measurement, and on the results of a calibration experiment measuring bulk densities. The main experiment was initiated after six minutes. During the subsequent 60 min, 20 increments of a target mass of 12 kg each were performed in intervals of 3 min, aiming at a total sample mass of 240 kg. The sampling time $\boldsymbol{t_{inc}}$ (s) for taking an increment was calculated using Eq. (1), as described by Khodier et al. (2019), from the increment mass $\boldsymbol{m_{inc}}$ (kg), the volume flow $\dot{\boldsymbol{V}}$ (m^3/s) and the bulk density $\boldsymbol{\rho_{bulk}}$ (kg/m^3). Bulk densities determined in the calibration experiments were 161.8 kg/m^3 for MCW and 344.0 kg/m^3 for MMW.

$$t_{inc[s]} = 0.5 \cdot \left\lceil 2 \cdot \frac{m_{inc[kg]}}{\dot{V}_{[m^3/s]} \cdot \rho_{bulk[kg/m^3]}} \right\rceil \tag{1}$$

The sampling procedure was manual, with two people holding an open container. The container dimensions are 117 × 37 × 30 (length × width × depth in cm).

2.2.2. Mass check including mass reduction and screening

For the primary sample as well as for each fine fraction of the screening steps, the feasibility of reducing its $m_{partkg]}$mass was assessed compliant with Khodier et al. (2019): in case the fraction fulfilled the inequality given in Equation (2) for a f_{red} mass

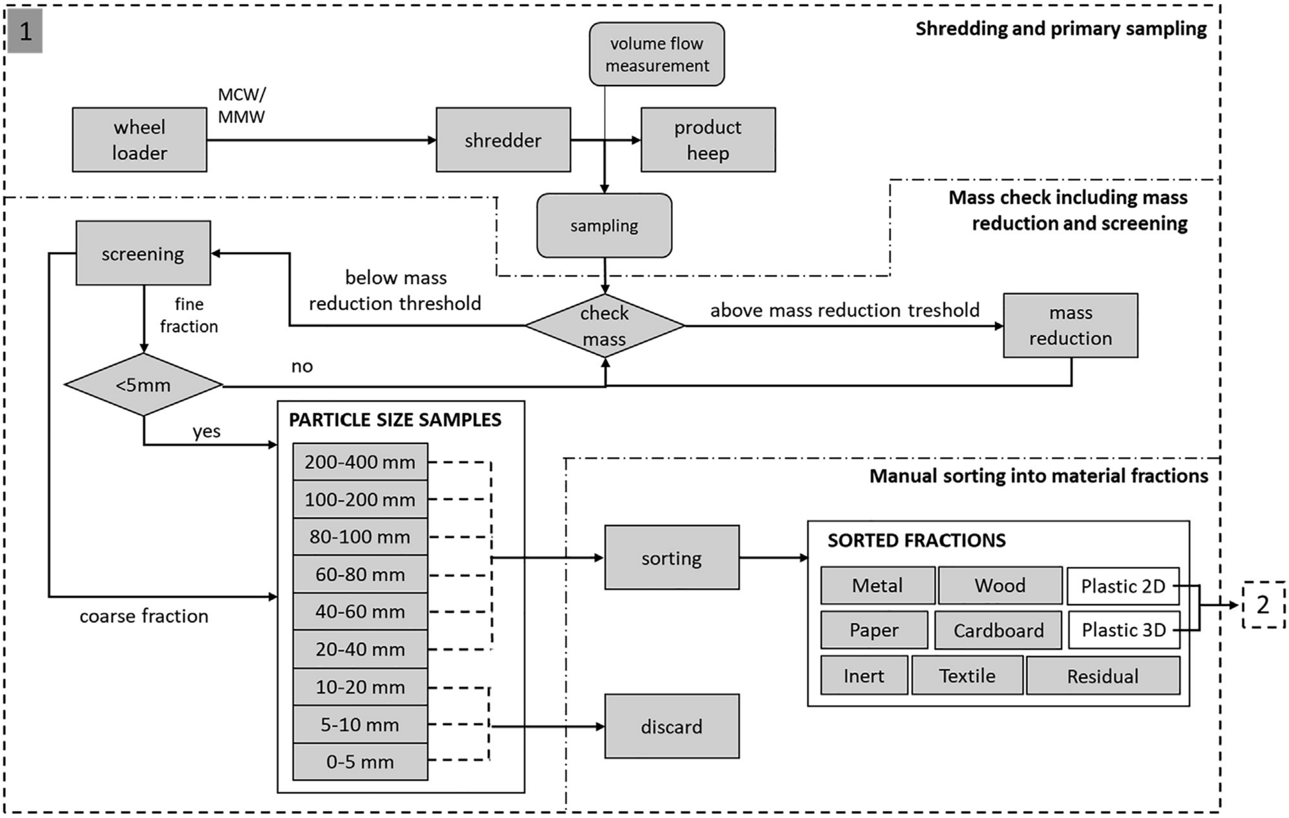

Fig. 1. Flowchart for the methodology of mechanical treatment and field investigations of MCW and MMW in Allerheiligen from input material to manually sorted material fractions (1). The plastic-2D and plastic-3D fractions were sensor-based sorted in plastic types (2).

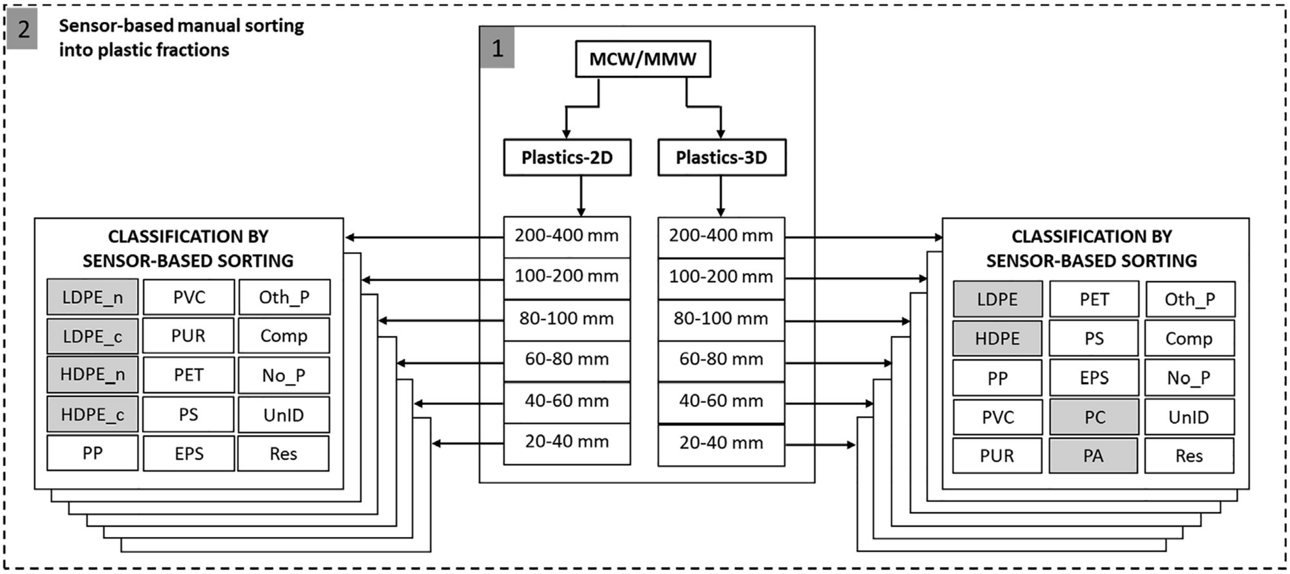

Fig. 2. Flowchart of material sorted in field investigations (1) to sensor-based sorted plastic types in the laboratory (2).

reduction factor of 0.5, 0.6 or 0.7. Mass reduction was applied using the smallest valid f_{red} value of the three.

$$m_{part[kg]} \geq \frac{0.66 \cdot d_{max[mm]}}{f_{red[-]}} \tag{2}$$

Mass reduction and screening were performed compliant with Khodier et al. (2019). An equilateral octagonal prism-shaped batch drum screen was involved (side length: 454 mm, depth: 1,000 mm) featuring 30 mm high carriages between the edges of the prism for improved material transport. Operating at a rotation speed of 5 rpm, the device screened for all screen cuts of at least 40 mm during 3 min and for smaller screen cuts during 4.5 min. The screen plates have circular holes corresponding to the GSC shown in Fig. 1. Batches of 75 L were processed for screen cuts of at least 20 mm and batches of 37.5 L for smaller screen cuts.

2.2.3. Manual sorting into material fractions

After screening, all fractions >20 mm were sorted into plastics-2D, plastics-3D, six other material fractions (as shown in Fig. 1) and a residual fraction. Sample photos of all sorted fractions are shown in Figure III of the supplementary material. Fractions containing all two-dimensional plastic objects (e. g. films) are called plastic-2D. Fractions assigned to all three-dimensional plastic objects (e. g. bottles) are referred to as plastics-3D. The feature deciding on object assignment to plastics-2D or plastics-3D was film-like behaviour on the screen, which was not experimentally checked but visually assessed during manual sorting. The sorted GSC of plastics-2D and 3D from both investigated wastes were packed in air-tight buckets and taken to the laboratory for further investigation. As mentioned before, fractions <20 mm were not analysed due to their disproportional time and cost effort, hence these fractions were discarded and no plastics-2D and plastics-3D obtained for further investigation.

2.2.4. Manual separation of plastic types using near-infrared technology

All GSC of the plastics-2D and -3D samples of both investigated wastes were sorted into ten plastic fractions and one unidentified fraction (UnID for short) using sensor-based sorting technology. The polymer types of highest industrial demand were sorted sensor-based while other sorting fractions such as composites (Comp), no plastics (No_P) and residue (Res) were visually assigned by the experimenters. All sorting fractions are shown in Fig. 2. Sorting analyses were performed by hand.

2D LDPE and HDPE plastic types were further subdivided into nature (clear/milky without colour) and coloured. This distinction helps trade both fractions separately to the recycling industry due to their exploitation options. For objects made of PS, the plastics-2D and plastics-3D fractions were additionally distinguished into foamed (EPS) and unfoamed (PS). Beside the sorting structure of plastics-3D, the technical plastics PA and PC were introduced as sorting fractions. These are the most common plastics, as available sorting fractions show, and quite rarely used in film production; they can, therefore, be neglected for plastics-2D. Previously mentioned deviations from the sorting structure of plastics-2D and plastics-3D are shown in Table I of the supplementary material and highlighted in grey in Fig. 2. Exemplary sample images of sorted plastic-2D and plastic-3D fractions are shown in Figure IV and Figure V of the supplementary material.

For sensor-based sorting, a specially made sorting stand was used, equipped with a near-infrared (NIR) sensor (EVK-Helios-G2-NIR1). The sensor-based sorting station complies with the applying industry standard. The analysis of bulk material will be discussed in the following to present the method of operation. Such an analysis is divided into the following two steps:

1. Teaching various material types contained in bulk material and subsequent creation of a sorting recipe (TeachIn) and
2. Actual execution of the separation based on the sorting recipe (Gundupalli et al., 2017; Serranti et al., 2012).

2.2.4.1. Creation of a sorting recipe. Creating a sorting recipe (an overview is given in Figure VI of the supplementary material) requires specific spectra of the different material types. Individual representative sample objects must be removed from the bulk material before the recipe is created. These sample objects are imaged using the NIR-sensor in the wavelength range of approx. 990 nm to 1,700 nm. Images contain an NIR-spectrum assigned to each object pixel. NIR-spectra specific for material are achieved by selecting and averaging spectra of several pixels. The result is a reference spectrum, helping assign unknown objects to the material classes included in the recipe. Exemplary reference spectra of the sorted plastic types are shown in Figure VII of the supplementary material. Correct assignment of an object's recorded spectrum to a material type was enabled by comparison with reference material spectra stored in the database and assigned to the corresponding material type. The assignment above was checked by a Fourier-transform infrared (FTIR) spectrometer (Cary 630 FTIR spectrometer made by Agilent Technologies, ATR unit with diamond crystal). Additionally, objects defying pre-allocation were identified. FTIR measurement apples the mid-infrared range from 2.5 μm to 14.3 μm. The generated spectrum is fitted to data records stored in the database, performing assignment to a material type. At the sensor-based sorting stand, only those wavelength ranges of the spectra are applied as a distinctive feature for the learned material type that display significant intensity differences. Nine relevant types of plastics (LDPE, HDPE, PP, PVC, PUR, PET, PS, PC and PA) were identified and their reference spectra included in a recipe.

Individual pixels of objects in the detection area were classified and provided with spectra so that imagery of the invisible NIR-spectrum could be displayed. Classified pixels were used to assign each object to one of the learned material types. For this purpose, the classified object pixels of each material class are added up. Each object is assigned to the class of material that dominates among classified objects pixels. This prevents faults from individual misidentified pixels entering the sorting decision.

2.2.4.2. Practical approach for plastic type separation. Plastic types were separated after creating the sorting recipe according to 2.2.4.1. Original materials (plastics-2D and plastics-3D fractions of all grain sizes) were used for sorting without previous drying or further processing steps. Seven plastic types of plastics-2D and nine of plastics-3D were sorted using NIR-technology (see Section 2.2.4). Each object was individually fed to the NIR sensor by hand. Material was assigned based on the created sorting recipe and visualised on-screen. Any detected object was thus assigned to the corresponding fraction. Plastics not matching any type taught were assigned to the 'Oth_P' fraction. Composite objects were assigned to the 'Comp' fraction and all non-plastic objects were assigned to 'No_P'. Carbon-black coloured plastic objects, which could not be detected because of their high absorbance in the NIR range and plastic objects defying identification (owing to, say, a high degree of surface contamination like food residues) were assigned to the 'UnID' fraction. Any fine residue remaining after sorting and everything having particle size larger than 20 mm, was assigned to the 'Res' fraction. To validate the separation results, a random sample survey of the fractions was carried out using an FTIR (see Section 2.2.4.1.).

3. Results and discussions

For the examined wastes (MCW and MMW), the following aspects are included: total composition of the investigated wastes, grain size dependent plastic content, the composition of the plastics-2D and plastics-3D fractions, grain size dependent distribution of sorting fractions, distribution of GSC in the sorting fractions.

All stated values are wt.– $\%_{OS}$ (OS: original substance), given in full percent only for clarity purposes.

3.1. Total composition and plastic content of investigated wastes

The diagrams on the right of Figures I and II of the supplementary material show the total sample composition of waste examined using sorting analysis (see Fig. 1). The content of plastics-2D in the examined wastes was observed to be similar (MCW: 9%, MMW: 8%). The content of plastics-3D in MCW is twice as high, amounting to 14%. In other words, the total plastic content in investigated MMW (15%) is about one third lower than that in MCW (23%). This is consistent with a first interpretation of MCW having a higher potential for plastics recovery. Due to the higher plastics-3D content, MCW is an interesting option for plastic recycling processes.

The content of the fine fraction <20 mm is about one third of the total mass of the respective shredded wastes. Even if the fine fraction is not considered, the ratios therefore remain similar for both wastes. Fractions <20 mm were not sorted because of the disproportionate effort required. Other sorting fractions (e. g. metal, wood, inert, etc.) were present in both waste types in similar amounts as well.

3.2. Comparison of grain size dependent plastic contents in investigated wastes

Results for the grain size dependent distribution of plastics-2D and plastics-3D in the observed wastes are shown in Fig. 3.

For MCW (Fig. 3, left), the content of plastics-2D increases with grain size. At 46%, the largest relative content was identified in the GSC 200-400 mm. In contrast, the plastics-3D content decreases with increasing GSC from 29.1% (20–40 mm) to 11.7% (200–400 mm). This is consistent with the high content of large packaging films that the shredding technology used cannot properly process. On the one hand, grain sizes of >100 mm are most suitable for discharging plastics-2D. On the other hand, grain sizes <100 mm are recommended for discharging the plastics-3D fraction.

Likewise, content increasing from 5.9% (20–40 mm) to 22.6% (200–400 mm) is observed for plastics-2D in MMW (Fig. 3, right). Up to a grain size of 100 mm, a slight increase of the plastics-3D is also noted. In the 200–400 mm GSC, a plastics-3D content of <1% was observed. This is consistent with the low volume of 3D plastic products sized >200 mm present in MMW. Analysis of MMW, as well as of MCW, shows that plastics-2D was most common in the largest GSC. The highest content of plastics-3D was found in the 80–100 mm GSC. These two GSC thus have the highest potential for a yield of the two fractions.

3.3. Composition of investigated plastic fractions in both wastes

The following section deals with the results for material composition in the plastics-2D and plastics-3D fractions of investigated wastes. Fig. 4 shows the results of the sorting analysis summed over all grain sizes for the plastics-2D and plastics-3D fractions of MCW and MMW.

A comparison of plastics-2D and plastics-3D in MCW (Fig. 4A and B) shows that the content of LDPE in plastics-2D is 4.6 times higher than the content in plastics-3D. This is also observed for HDPE, where the content is 14.5 times higher for plastics-2D than it is for plastics-3D. For both types of plastic, this is consistent with the high film content in plastics-2D since both materials are frequently used in film production. A higher content of HDPE in plastics-3D would have been expected, though, because many solid, hollow and profile components are made of HDPE. For PP, the opposite is observed. The content of PP film is much lower (8.3%) in plastics-2D than it is in plastics-3D (18.7%). This is consistent with bulky solid profile components increasingly found in plastics-3D, such as pipes. PET and PS are mainly used for making multilayer films (e. g. chip bags), here constituting a separate fraction. A low content of these materials (<1%) is therefore detected in plastics-2D. In plastics-3D, both plastics are more common (PET: 17.9%, PS + EPS: 10.9%). Remarkable is the high PVC content of about 7% in plastics-3D, whereas in plastics-2D, only 0.2% is observed. This is again consistent with quite few PVC films used for packaging, whereas profile objects such as pipes or window frames are more frequently found in plastics-3D in MCW. The high UnID content in plastics-3D (20.1%), five times higher than it was in plastics-2D, is as remarkable. It is consistent with the high amount of black massive objects present in the plastics-3D fraction.

Comparing plastics-2D and plastics-3D of MMW (Fig. 4C and 4D) provides the same findings for LDPE, HDPE, PET, PS + EPS, PVC as it does for MCW. While the LDPE content in MCW plastics-2D is much higher than its HDPE content, it is lower in MMW. This may be consistent with the presence of shopping bags, often made of HDPE and used in place of commercial waste bags. The amount of uncoloured films in both wastes is higher for LDPE and HDPE. For PP, the content in plastics-3D is observed to be about 2.6 higher than in plastics-2D and, accordingly, slightly higher than in MCW. This is not surprising because a high amount of non-packaging household objects is made of PP (e. g. bottles, buckets, boxes, etc.), ending up in MMW. The UnID fraction is similar for MMW in both dimensional fractions. Comparing the plastics-2D fractions of both wastes reveals a content of UnID in MMW that is is 3.4 times higher than in MCW. This is consistent with the presence of black coloured films (due to their high absorbance, carbon-black filled plastics cannot be identified in the NIR range) and with the higher degree of contamination (e. g. food residues) on the object surface preventing correct detection. Interesting is the higher amount of the Comp fraction in plastics-2D and 3D of MMW in comparison to MCW. The content of other sorting fractions like PUR, PC, PA, Oth_P, No_P and Res totalled <10% for both wastes. PVC, PUR and EPS were not detected in plastics-2D examined in these studies. This is not surprising since none of them are commonly used for producing films that would end up in MMW. Interesting is that the PVC content is 1.6 times higher

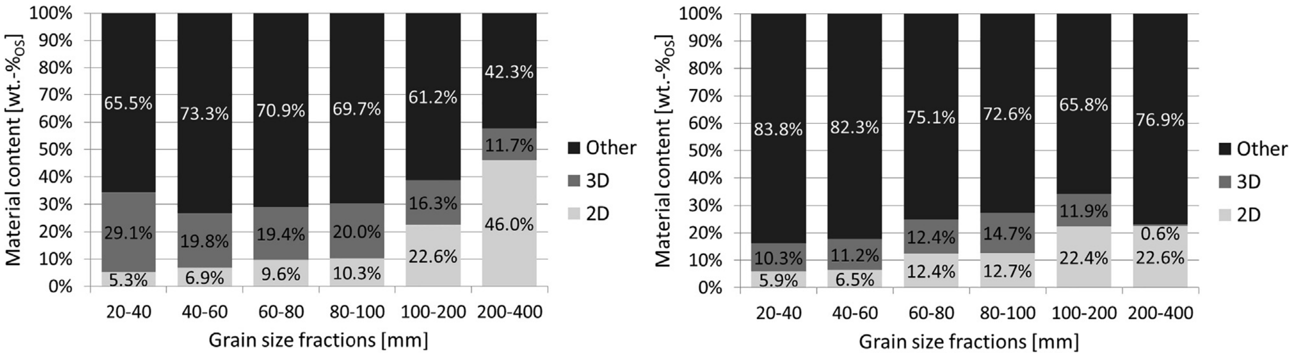

Fig. 3. Content of plastics-2D and plastics-3D in MCW (left) and MMW (right) in different grain sizes.

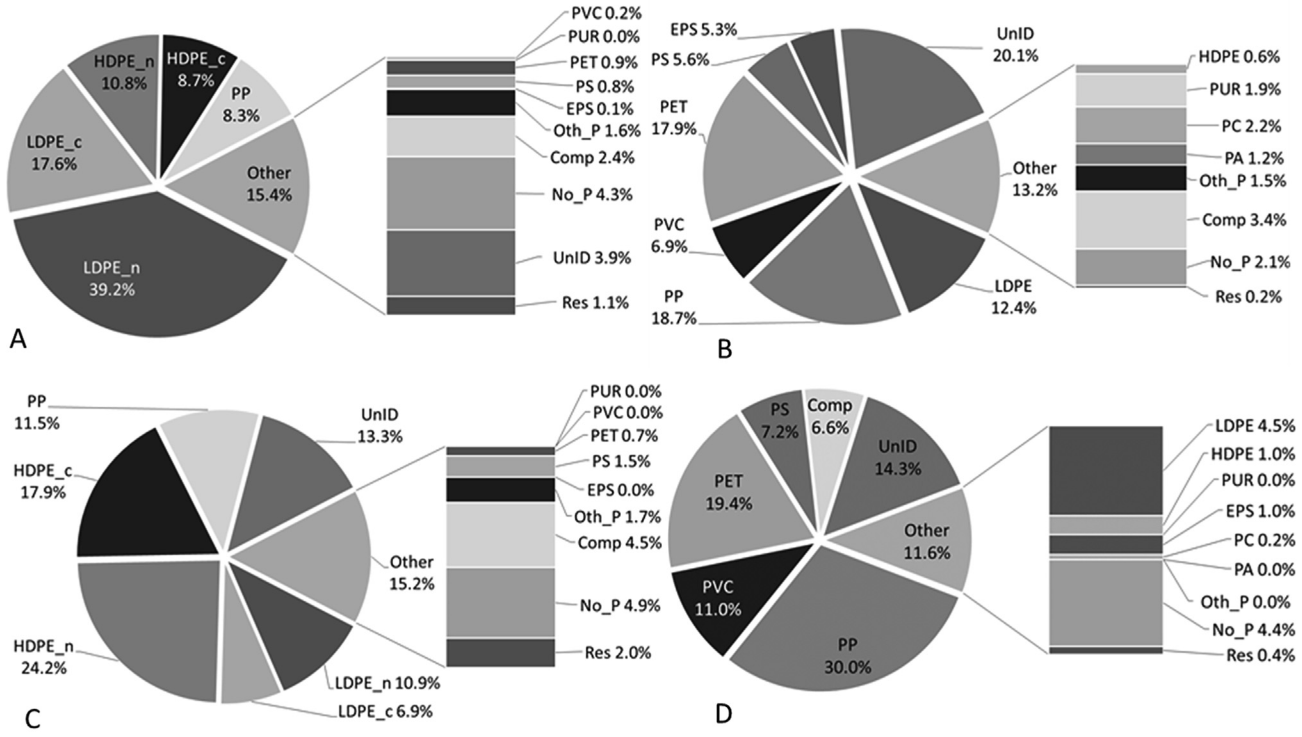

Fig. 4. Total composition of the plastics-2D (A) and plastics-3D (B) in MCW. Total composition of the plastics-2D (C) and plastics-3D (D) in MMW.

in MMW than in MCW. For discharging PVC, often considered as an impurity, the focus should therefore be directed on the 3D fraction. For both investigated wastes it was observed that PP, PS, PVC and PET are more present in plastics-3D whereas HDPE and LDPE are more likely to occur in the plastics-2D fraction. Significant amounts of PC, PA and PUR plastics were only observed in the plastics-3D fraction of the MCW. This was also expected because these plastics are among the engineering plastics, mainly used in 3D-components for technical applications.

3.4. Grain size dependence of sorted fractions in investigated wastes

The cumulative grain size distributions, determined using screening, are shown for all sorting fractions of plastics-2D and plastics-3D of MCW and MMW in Fig. 5.

Comparison shows that materials of plastics-2D are spread across a much broader grain size range. This means that they produce wider scattering over the individual materials than plastics-3D. This is consistent, among other things, with the predominant film fraction of the plastics-2D fraction displaying much larger grain sizes in the initial material before shredding than any objects in the plastics-3D fraction would because their initial sample had a higher fines content. In addition, selective crushing has a different effect on hard, brittle 3D objects than on ductile films. Films are often partially shredded only and able to pass the shredder without any significant reduction in grain size. Note that no concrete trends can be deduced from the screen underflow curves since the individual sorting fractions occurred in the individual GSC in very different relative amounts.

Fig. 6 shows the content of sorted materials over the examined GSC for the plastics-2D (A and B) and plastics-3D fractions (C and D) of MCW. Charts A and C show the total mass distribution over the investigated GSC. For charts B and D, data of the charts A and C were normalised to 100% to give a more detailed insight into the relative amounts of sorted materials in the GSC.

For the plastics-2D fraction, Fig. 6A shows that 38% of the sorted mass accounts for the 100–200 mm GSC. 18.2% are observed in the 200–400 mm and 14.9% in the 60–80 mm fraction. The remaining 28.9% are distributed in similar amounts across the remaining GSC. Obviously, 67.4% of the sorted mass of the plastics-2D fraction have a grain size >80 mm. For the plastics-3D fraction (Fig. 6C), the 40–60 mm GSC accounts for the largest relative content of material: 29.2%. About 20% are contained in 60–80 mm and in 100–200 mm GSC. Only slightly less than 5% of the material is attributable to 20–40 mm and 80–100 mm GSC. 200-400 mm GSC contains only 3% of the sorted mass. Thus, only 36.5% of the sorted mass has a grain size >80 mm. In summary, the comparison of both fractions of MCW shows the opposite behaviour. The majority of the 2D-fraction features large grain sizes while there are small grain sizes in the 3D-fraction. This is consistent with those large packaging films, that can only be shredded to a limited extent with the shredding technology applied.

Examining the distribution of sorted fractions of plastics-2D (Fig. 6B) over GSC discloses that the relative contents of LDPE_n, LDPE_c, HDPE_n and HDPE_c increase with grain sizes up to 80 mm. Remarkably, PP, PS and PET behave the opposite way, i. e. their content decreases with increasing grain size up to 100 mm. PVC and PUR were found in similar amounts in the 20–40 mm and 60–80 mm GSC. Not surprisingly, the No_P fraction is more present in the small 20–80 mm GSC. This is consistent with increasing fatigue of the sorting staff as the sorting depth advanced to smaller grain sizes, raising the misplacement quota. The UnID and Res fractions are similarly distributed over the GSC, with a maximum located in the 20–40 mm GSC. For plastics-3D (Fig. 6D), 49.1% of the 200–400 mm GSC consists of LDPE. 2.6% of HDPE were detected but only in the 60–80 mm GSC. PP is represented in all GSC at relative amounts of 16% to 21%. PVC accounts for 18.7% of the 100–200 mm GSC and is present in other GSC in much smaller quantities (<6%). At 7.3%, PUR is most visible in the 100–200 mm GSC. The relative con-

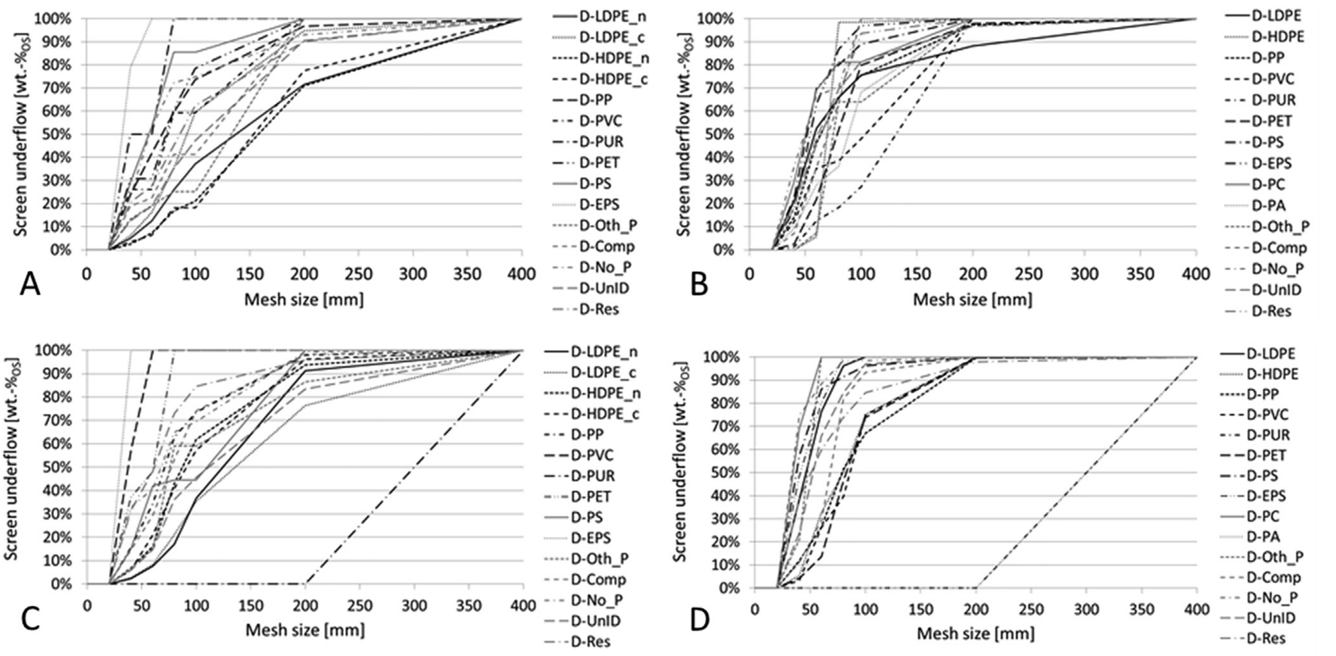

Fig. 5. Cumulative grain size distribution over investigated mesh sizes for all sorting fractions of plastics-2D (A) and plastics-3D (B) in MCW. Cumulative grain size distribution over investigated mesh sizes for all sorting fractions of plastics-2D (C) and plastics-3D (D) in MMW.

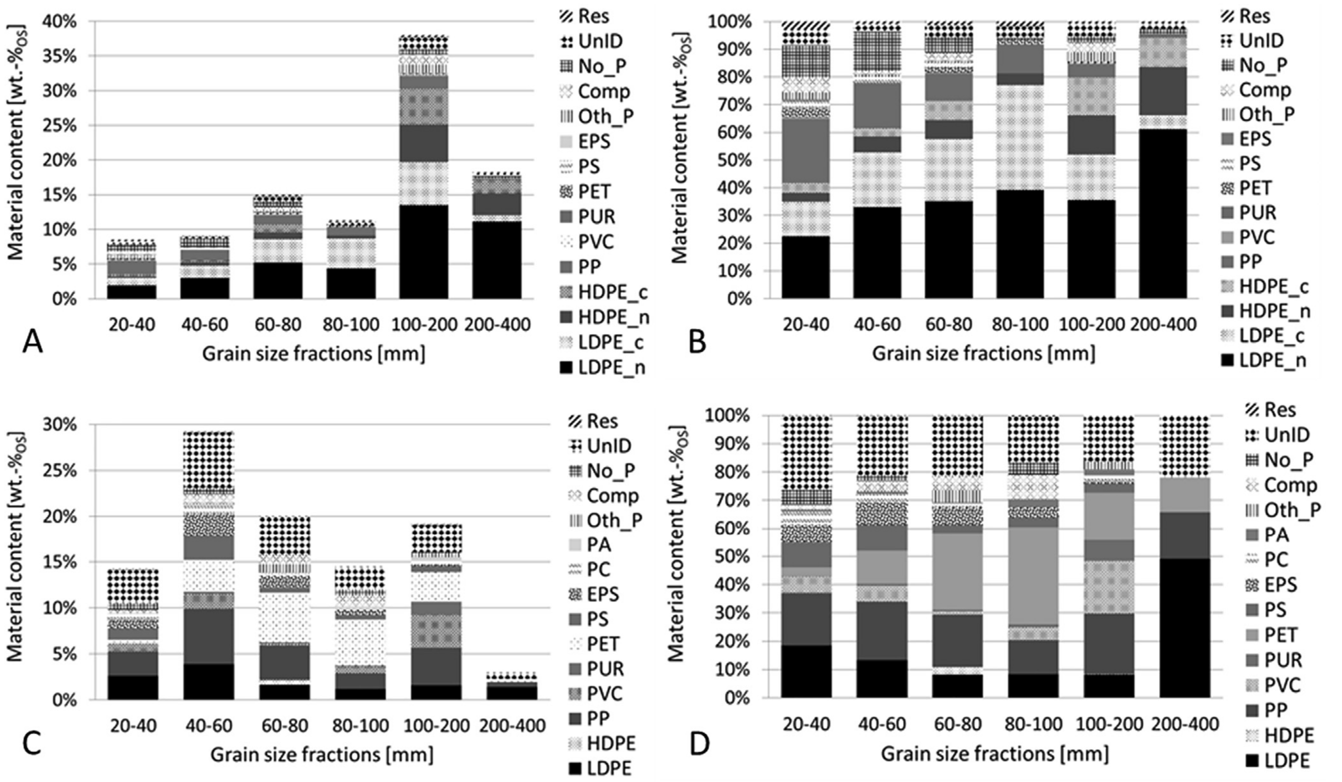

Fig. 6. Plastic type distribution of plastics-2D in investigated GSC in MCW (A); normalised to 100% (B). Plastic type distribution of plastics-3D in investigated GSC in MCW (C); normalised to 100% (D).

tent of PET is highest in the 80–100 mm GSC. PS and EPS are mainly found in relative contents of 6–9% in the 20–40 mm and 40–60 mm GSC.

Fig. 7 shows the relative content of sorted materials on the examined GSC for plastics-2D (A and B) and plastics-3D (C and D) of MMW in the same way as in Fig. 6.

For the plastics-2D fraction of MMW (Fig. 7A), a very similar mass distribution over grain size classes can be observed. The 200–400 mm GSC is an exception, yielding the smallest mass fraction of 7.7% for MMW. This may be consistent with the smaller grain size of MMW and a lower relative content of large films than that present in MCW. The mass distribution across the GSC of

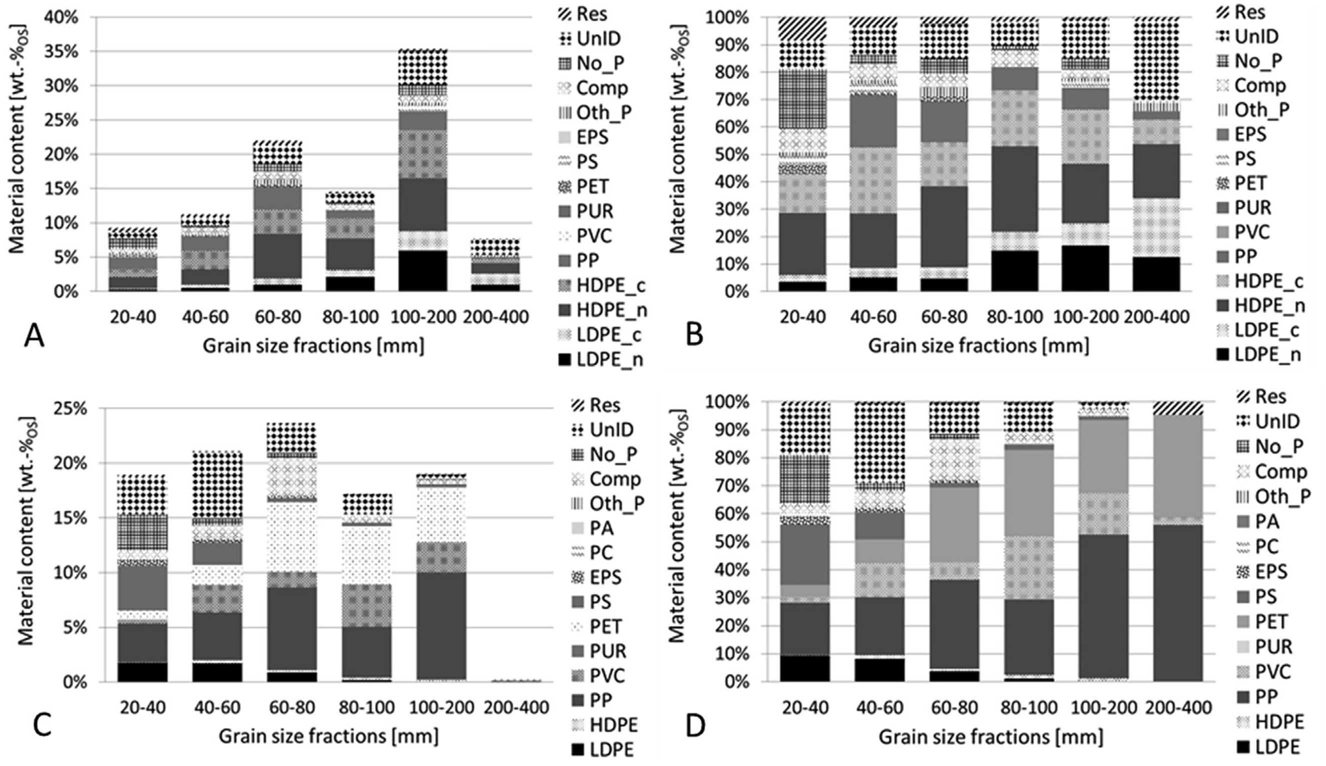

Fig. 7. Plastic type distribution of plastics-2D in investigated GSC in MMW (A); normalised to 100% (B). Plastic type distribution of plastics-3D in investigated GSC in MMW (C); normalised to 100% (D).

plastics-3D (Fig. 7C) shows a relatively uniform mass distribution of 17.2% to 23.6%, which is very distinct from the plastics-3D of MCW, except for an outlier of 0.2% at 200–400 mm. The mass ratios of the sorting fractions within the individual grain size classes are very different for both wastes and for both dimensional fractions and do not show any common trend.

3.5. Distribution of GSC in investigated material types

Fig. 8 shows the distribution of the generated GSC over the investigated material types for plastics-2D (A and B) and plastics-3D (C and D) of MCW. Diagrams A and C give the grain size distribution within the sorting fractions. In diagrams B and D, the data of the left graphic are normalised to 100% to give a more detailed insight.

In Fig. 8A and C, data from the top of Fig. 6 are additionally analysed per GSC. The graphs confirm that LDPE, HDPE and PP contents are significantly present in plastics-2D. In contrast, plastics-3D has higher relative contents of PP, PET and PS (PS and EPS). Normalised to 100%, data in Fig. 8B also disclose that, for example, the PE types accumulate mainly in the 100–200 mm GSC. This may be a starting point for targeted discharge. In contrast, PP can be found in all GSC <200 mm at similar relative contents (14–24%) but predominantly in 20–40 mm. Considerable relative contents of PVC (26–40%) are present in the 100–200 mm, 80–100 mm and 20–40 mm GSC. In other words, if these GSC are further processed, say, to recover recyclable material, then PVC extraction should be essential (e. g. compliance with Cl limits). PUR was observed only in the 20–40 mm and 60–80 mm GSC. These are also suitable for enrichment of the PET fraction (30% content). PS tends to accumulate in the smaller GSC (<100 mm). EPS was detected only in GSC <60 mm. The high Oth_P amount (74.8%) observed in 80–100 mm is striking.

Normalised data of Fig. 8D show clearly that LDPE and HDPE are present in different GSC. LDPE is chiefly enriched in 40–60 mm but HDPE in 60–80 mm. PP is included in all GSC as it is in the plastics-2D. The 40–60 mm and 100–200 mm GSC contain a high PVC content. In contrast to the plastics-2D fraction, PUR mainly accumulates (72.7%) in the 100–200 mm GSC. A higher PET content (about 30%) is observed for larger GSC (60–80 mm and 80–100 mm) of the plastics-3D than of the plastics-2D. Likewise, the highest contents of PET, PS and EPS vary from 20 to 40 mm to 40–60 mm in larger GSC. While the amount of PC rises in the small GSC <60 mm, PA is increasingly present in the grain size range from 80 mm to 200 mm.

Fig. 9 shows the distribution of the generated GSC over the examined material types for plastics-2D (A and B) and plastics-3D (C and D) of MMW in the same way as in Fig. 8. Diagrams A and C show the grain size distribution in the sorting fractions. Respective diagrams B and D show the data of A and C normalised to 100%, giving a more detailed insight.

The graphs confirm that large quantities of LDPE and PP are also found in the plastics-2D fraction in addition to the high relative content of HDPE. This observation is equivalent to that of plastics-2D in MCW. In contrast, plastics-3D contains higher levels of PP, PET, PVC and PS (PS and EPS). From data normalised to 100% in Fig. 9B follows that the PE types are mainly present in the 100–200 mm GSC. This coincides with plastics-2D in MCW. PP is found mainly in the 60–80 mm and 100–200 mm GSC. PVC was only detected in the small 20–40 mm and 40–60 mm GSC. PUR was not detected in any GSC. PET was found only in grain sizes <80 mm. The 100–200 mm GSC constitutes the largest relative amount in PS while EPS was only found in 20–40 mm.

As in the case of plastics-3D in MCW, normalised data of Fig. 9D show that LDPE is predominantly found in grain sizes <60 mm. HDPE can be found at approximately equal levels in 40–60 mm, 60–80 mm and 100–200 mm GSC. PP and PVC were distributed across all GSC. PP was mostly found in 100–200 mm and PVC mainly in 80–100 mm. PUR and PA plastics were not found in

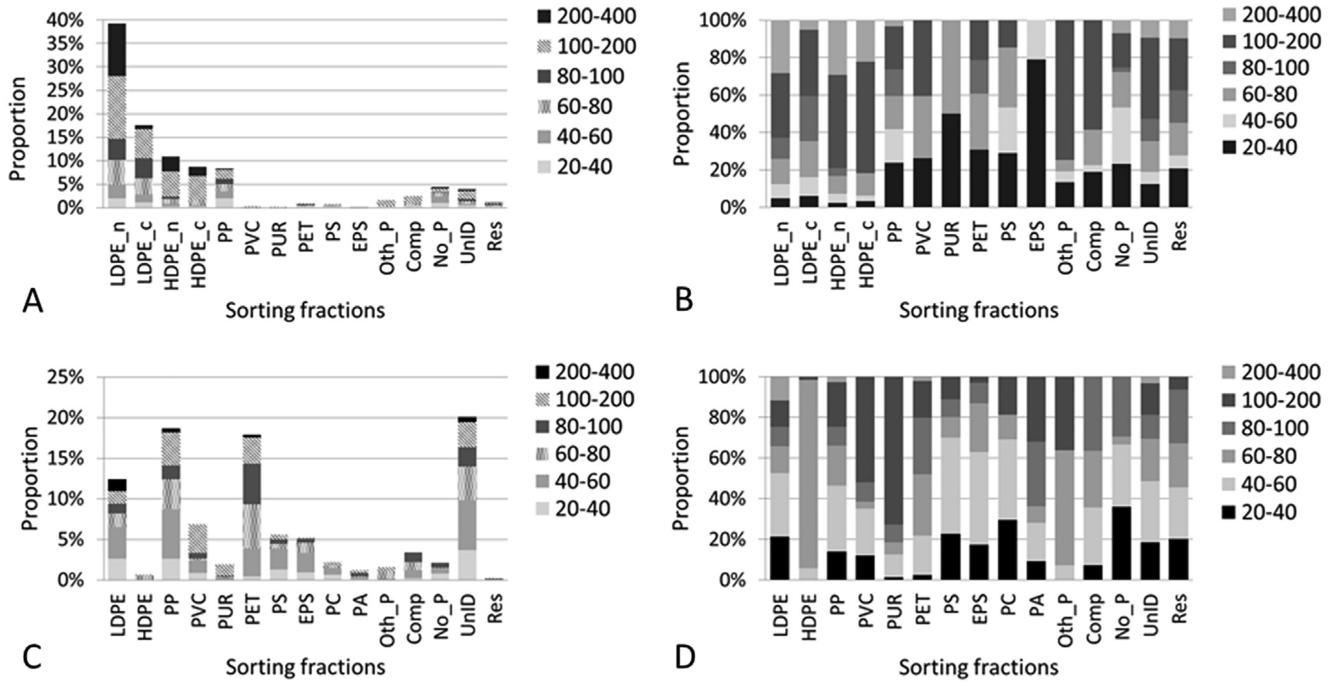

Fig. 8. Grain size distribution in investigated material types for plastics-2D of MCW (A); normalised to 100% (B). Grain size distribution in investigated material types for plastics-3D of MCW (C); normalised to 100% (D).

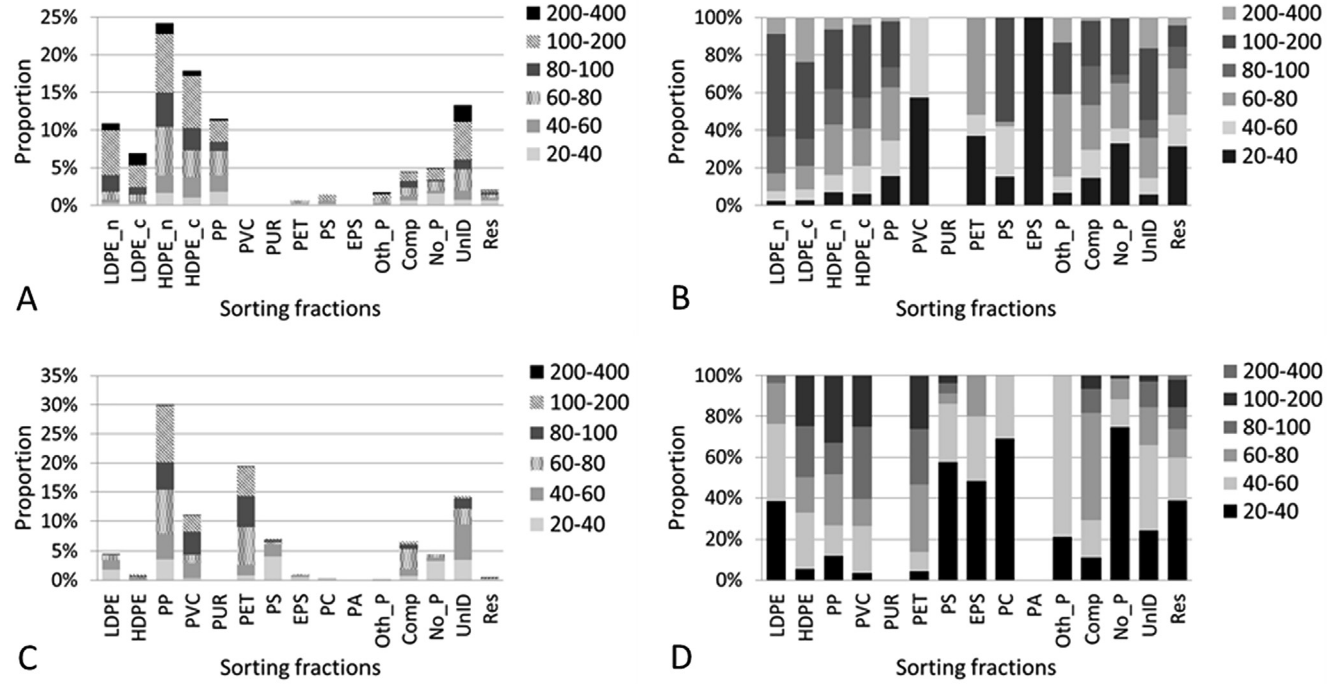

Fig. 9. Grain size distribution in investigated material types for plastics-2D of MMW (A); normalised to 100% (B). Grain size distribution in investigated material types for plastics-3D of MMW (C); normalised to 100% (D).

any GSC. PET was detected mainly in the medium-sized 60–100 mm GSC.

For completeness's sake, note that neither MCW nor the collection area of MMW underwent a sector-specific selection although representative samples of waste were used. Significant influencing factors on their composition, and thus on the results presented, are the origin of waste, the collection system, the socioeconomic structure of the population and seasonal conditions. Discarding the fraction <20 mm which represents >30% of the waste samples had a significant impact on the results. Probably these fractions also contain plastics of secondary importance for large-scale sorting followed by recycling. The moisture content and the influence of its mass on the results was not investigated but visually assessed as representative. The moisture content for MCW is <20 wt% and for MMW it is 20–40 wt% (AdSLR, 2012). The fractions investigated do not absorb water to the extent of, for example, paper fractions. Moisture is therefore mainly present forming superficial organic adhesions.

Likewise, the UnID sorting fraction affects the results presented. This fraction consists mainly of black plastics that were not assignable, therefore containing sorted plastic types that were thus excluded from investigations. In addition, the results will be slightly (2–4%) influenced by the errors (No-P fraction) of manual sorting performed to obtain plastics-2D and plastics-3D because they alter the population.

4. Conclusions

This paper presents a variety of interesting results for the examined wastes. First of all, investigated wastes evidently have a non-negligible plastic content (>15%). The total potential amount of plastics for MCW is higher than it is for MMW. This applies in particular to plastics-3D. Comparing the total plastic content of MCW (33.6%) with the data collected (SRF fraction 73.8%) by Wellacher and Pomberger (2017) is meaningless because the SRF fraction does not contain plastics only but also other high-caloric materials. The determined total plastic content of MMW, 23.5%, is consistent with the sorting result of 17.6% according to BMLFUW (2018). There are no publications that would examine the contents of different plastic types more profoundly. The investigations have confirmed that the compositions of the sorting fractions investigated are different for both wastes as well as for plastics-2D and plastics-3D. It was found that the plastics-2D and plastics-3D grades for both types of waste are distributed differently among the investigated GSC. This confirms that the different properties and material types of the plastics-2D and −3D parts affect the shredded output fraction. For example, the grain size of large films was incompletely reduced by the shredder used. For this reason, films and the like are predominantly detected in grain sizes >100 mm. Information on the frequency of plastic types in specific grain size classes can be used to concentrate and discharge them by means of targeted screening. One potential application was the concentration and discharge of PE-types, PP or PET from MCW and MMW as these are often present and recycling options are available. Also, removing a PVC concentrate by screening would be a technically possible alternative to NIR-sorting in SRF processing plants for reducing the chlorine load. Reasons for the presence of certain types of plastics of certain sizes in specific GSC are not the subject of this paper and should be examined in further investigations. For the above reasons, the data is not representative of all MCW and MMW but similar dependencies can be suspected for comparable wastes. The type of shredder used is likely to impact particle-size distribution more than waste composition would.

Note that legal regulations such as the ban on disposable plastics and plastic carrier bags (EC, 2019) will affect future compositions of waste. Under increasing legal pressure, future waste like the type examined here will be used as a valuable source for certain types of plastic to reach recycling targets. This will require generating basic knowledge about the composition of such wastes, which will need to be continuously extended and updated.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2019.12.037.

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Grain Size dependent Distribution of different Plastic Types in coarse-shredded Mixed Commercial and Municipal Waste

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Supplementary material

Table I: List of sensor-based sorted fractions of analysed wastes.

Plastic fraction	Abbreviation	Description	Found objects - examples
3D	LDPE	Low-density polyethylene	Trays and containers, household goods
2D	LDPE_n	Low-density polyethylene nature	Food packaging films, different types of bags, agricultural films, shrink and stretch hood films
2D	LDPE_c	Low-density polyethylene coloured	
3D	HDPE	High-density polyethylene	Toys, different types of bottles and containers, pipes, household goods
2D	HDPE_n	High-density polyethylene nature	films, tapes, technical textiles
2D	HDPE_c	High-density polyethylene coloured	
2D and 3D	PP	Polypropylene	Toys, microwave containers, sweet and snack wrappers, food packaging films and trays, household goods, medical and sanitary products
2D and 3D	PVC	Polyvinylchloride	inflatable toys, cable insulations, floor covering, pipes, different profiles and frames, hoses, packaging tapes
2D and 3D	PUR	Polyurethane	pillows, mattresses, insulating foams soft and hard, sponges
2D and 3D	PET	Polyethylene terephthalate	different types of bottles, trays, boxes, textiles, household goods
2D and 3D	PS	Polystyrene	cups, disposable cutlery, boxes, household goods
2D and 3D	EPS	Expanded polystyrene	food trays, thermo cups, building insulation, upholstery material

Table I: Continued.

3D	PC	Polycarbonate	transparent glasses and plates, different profiles, films
3D	PA	Polyamide	Technical parts, textiles, hoses and cables, profiles, ropes
2D and 3D	Oth_P	Other plastics (e.g. Elastomers, polymethylmethacrylate, polyoxymethylene, biodegradable plastics, etc.)	
2D and 3D	Comp	Composites: Objects made of different materials (e.g. coated objects (i.e. antistatic bags), multi-layer films, etc.)	
2D and 3D	No_P	No plastics (metal, wood, paper, cardboard, inert, textile)	
2D and 3D	UnID	Unidentified (e.g. black objects filled with carbon black, polymerblends with unidentifiable spectrum)	
2D and 3D	Res	Residue (e.g. fines)	

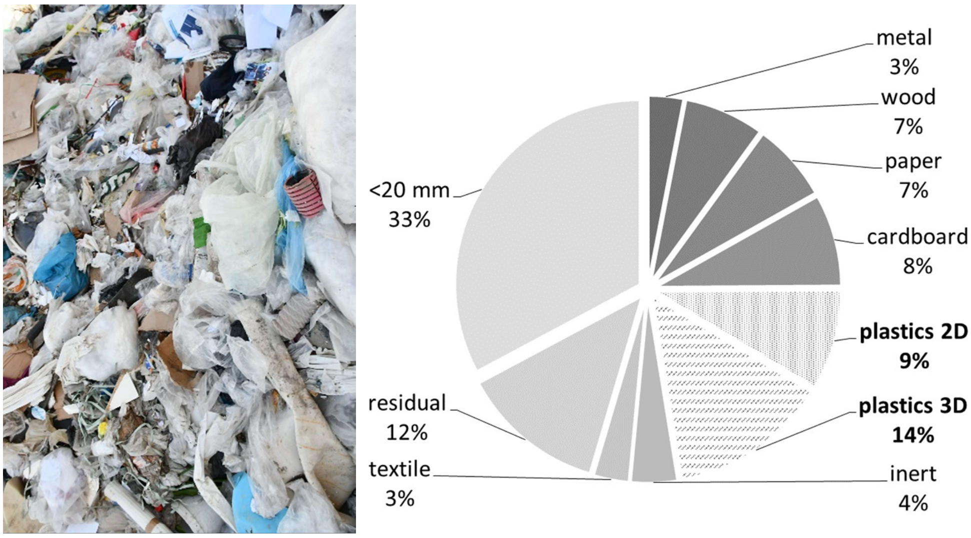

Figure I: Investigated MCW before shredding – photo and data on its composition. (Note: „plastics-2D“ and „plastics-3D“ are in focus of the present contribution).

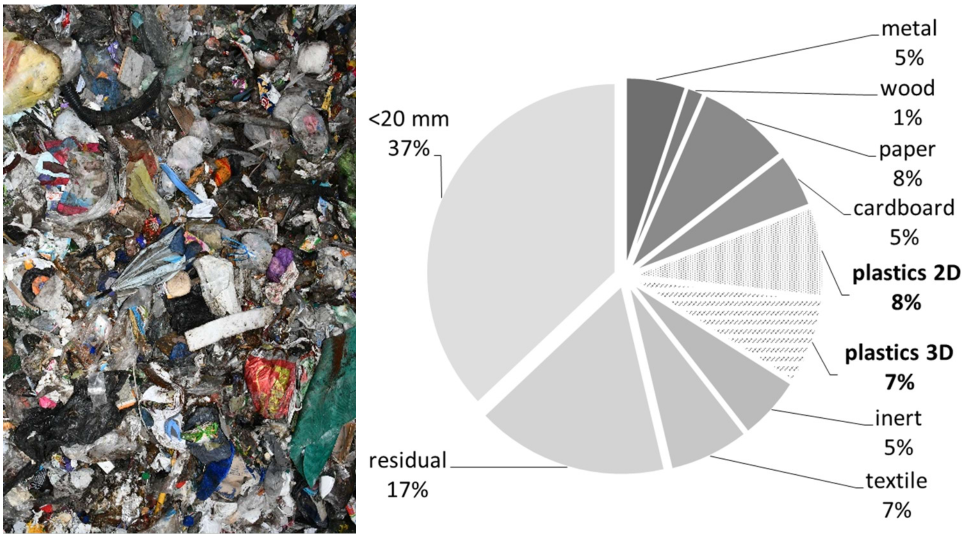

Figure II: Investigated MMW before shredding – photo and data on its composition. (Note: „plastics-2D“ and „plastics-3D“ are in focus of the present contribution).

Figure III: Exemplary photos of the manually sorted material fractions from the generated grain size fractions.

Figure IV: Exemplary photos of the sensor-based sorted plastic-2D fractions.

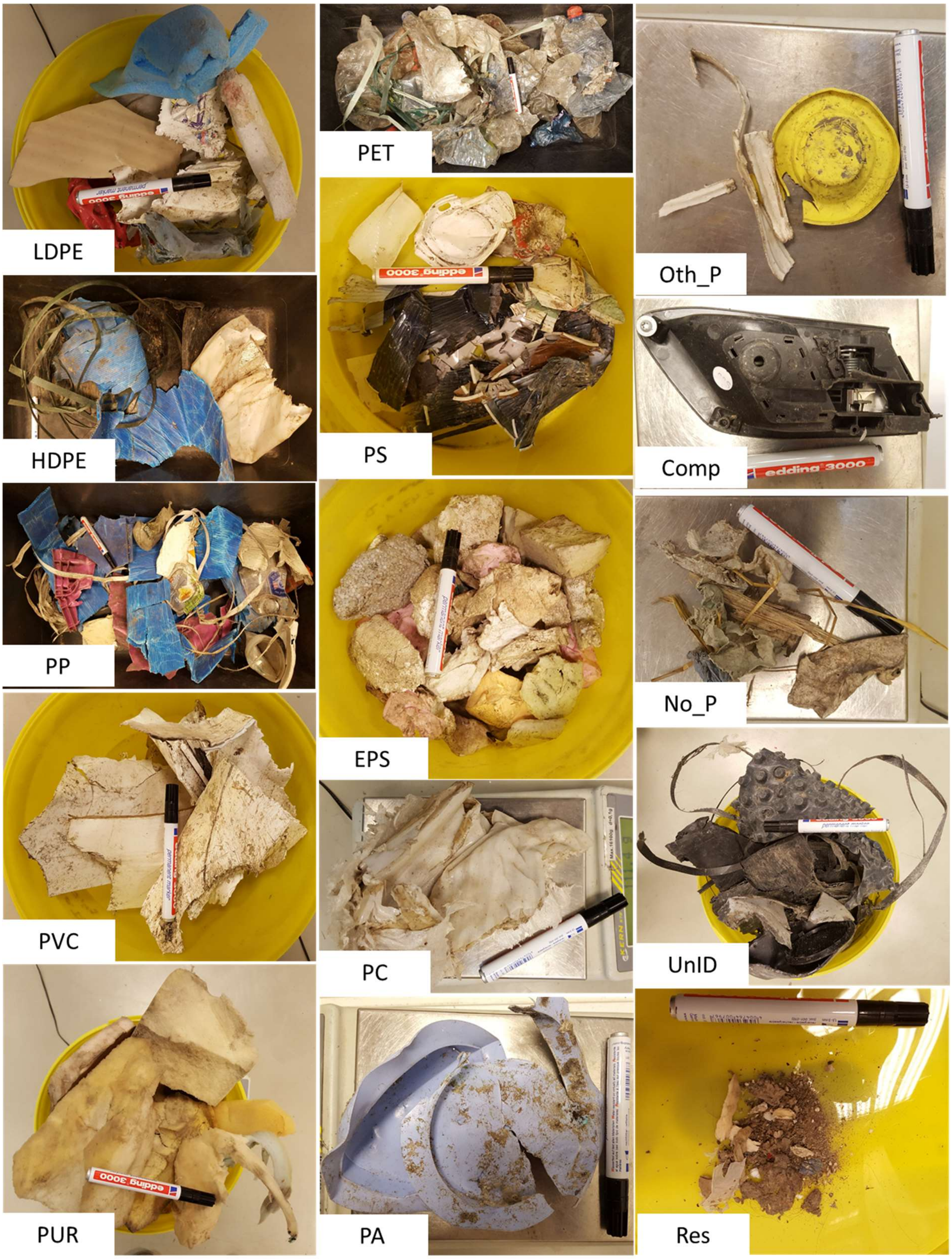

Figure V: Exemplary photos of the sensor-based sorted plastic-3D fractions.

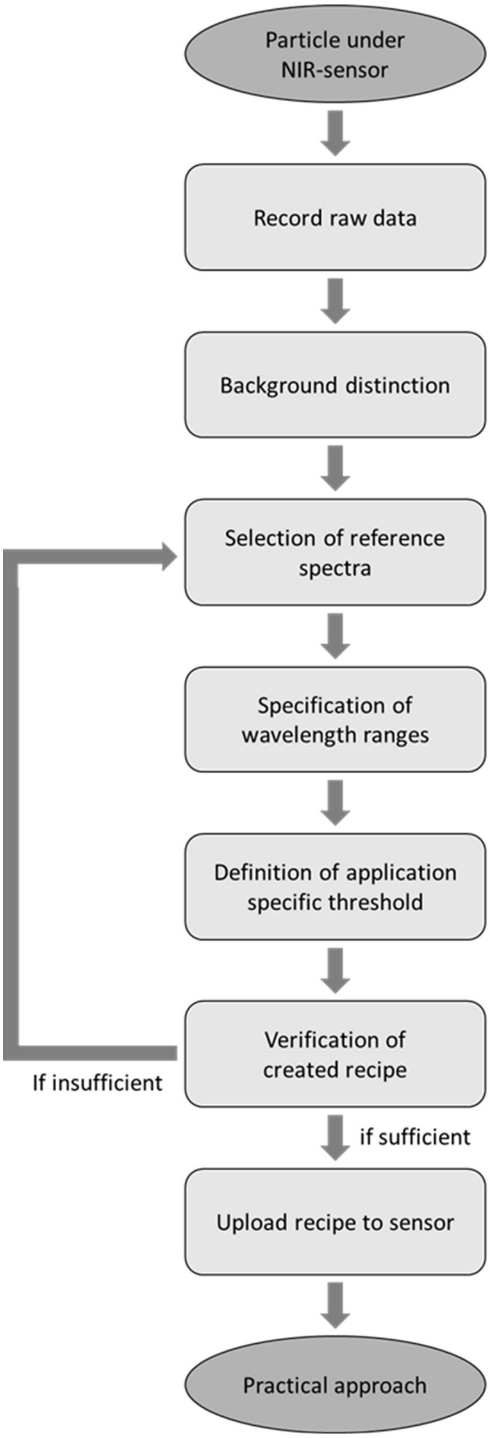

Figure VI: Flowchart for creation of a sorting recipe.

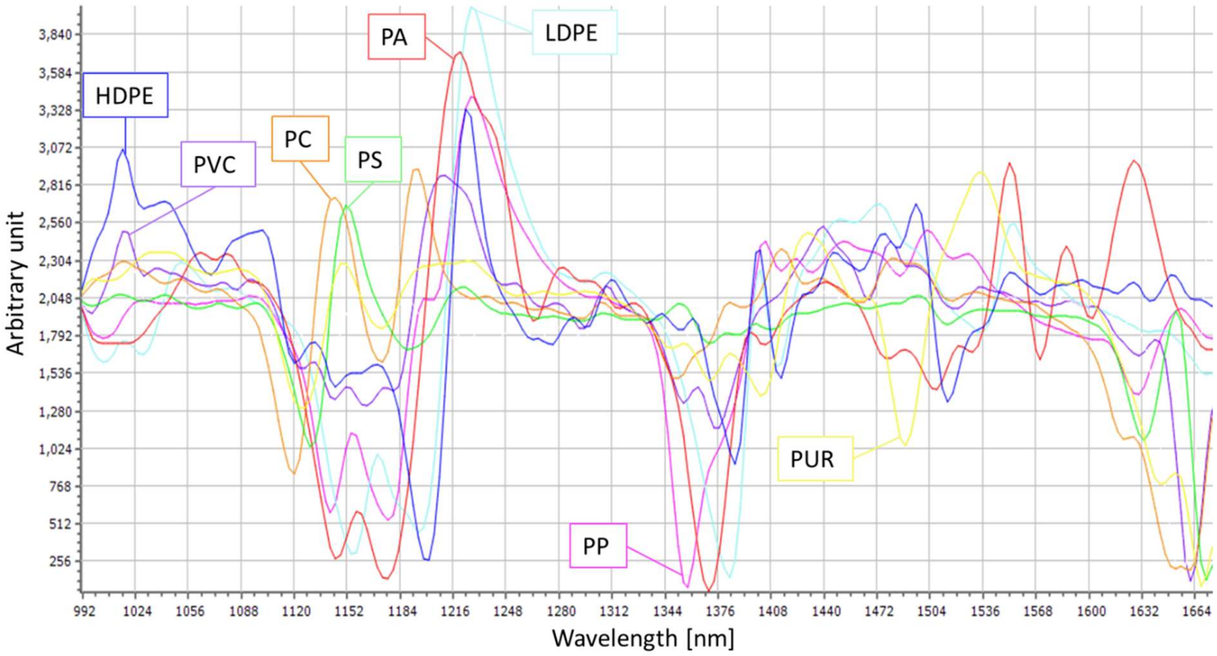

Figure VII: Exemplary reference spectra of the sorted plastic types.

4.2 Processing and Concentration of Plastics

Since, based on publication 1, sufficient plastics are present in the wastes investigated, this chapter deals with different aspects of the enrichment and discharge of plastics from these mixed wastes. In the following three publications, large-scale experiments were carried out to demonstrate how plastics can be enriched, separated, and wet-mechanically processed. The influence of screening on downstream processing and mass and volume flow fluctuations on the processing are shown. Finally, samples of the produced plastic pre-concentrates are processed and qualitatively evaluated in an innovative wet-mechanical cleaning and separation unit, the "centrifugal force separator", for the thermochemical conversion process "ReOil" of OMV AG.

4.2.1 Publication 2

Influence of pre-screening on down-stream processing for the production of plastic enriched fractions for recycling from mixed commercial and municipal waste

Möllnitz, S., Küppers, B., Curtis, A., Khodier, K., Sarc, R.

Waste Management 119 (2021), 365-373, https://doi.org/10.1016/j.wasman.2020.10.007

Author Contributions:

MS: Conceptualisation, Methodology, Formal Analysis, Investigation, Data curation, Writing – original draft, Writing – review and editing, Visualisation, Project Administration.

KB: Conceptualization, Methodology, Recources, Investigation, Data curation, Writing – review and editing, Project Administration.

CA: Investigation, Writing – review, and editing.

KK: Writing – review, and editing.

RS: Resources, Writing – review and editing, Supervision, Funding acquisition.

Due to confidentiality agreements with project partners, not all original data were included in the paper or its appendix. These can be found in Appendix B of the present thesis.

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Influence of pre-screening on down-stream processing for the production of plastic enriched fractions for recycling from mixed commercial and municipal waste

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ABSTRACT

The use of plastic waste as resource gains more and more attention. In this context, material recycling is especially focused on packaging plastics. Further waste streams that contain a significant amount of plastics are mixed commercial and municipal solid waste. To assess the potential of plastics for recycling and energy recovery from these material streams large-scale experiments were conducted. The potential of mechanical pre-processing with the aim of generating a 3D-plastics pre-concentrate was assessed. The focus of these investigations was put on the relevance of the screening stage and its influence on down-stream material processing via ballistic separation and sensor-based sorting. Results demonstrate not only that the screening of both waste streams leads to enrichment of plastics in coarse particle size ranges (especially >80 mm) and transfer of contaminants, organics and minerals to fine fractions (especially <10 mm), but also that sensor-based sorting performance can be significantly enhanced due to cleaning effects on plastics, induced by the material circulation and the resulting interparticle friction in a drum screen. On the downside, the material rotation in a drum screen leads to tail-formation that can create plant down-time through clogging as well as material losses and impairment of pre-concentrates.

1. Introduction

The European Directive on waste (2008/98/EC) (Waste Framework Directive – WFD) established definitions and stipulated the basic concept for the development of sustainable waste management in Europe (EU) (EU, 2011). They include the definition of different wastes, e.g. Mixed Municipal Solid Waste (MMW), that is relevant for this paper. MMW is waste that cannot be attributed to any of the separately collected waste fractions because it is contaminated or mixed. A definition of Mixed Commercial Waste (MCW) is given only in Germany that has stipulated the Commercial Waste Regulation (GewAbfV, 2017): MCW is non-municipal residual waste not collected separately, such as office wastes, industrial wastes, etc.

The following waste hierarchy should be applied to sustainability in waste management (i.e. proper waste treatment and production of secondary raw materials and energy resources) according to the directive (EU, 2018): '*Prevention, Preparing for re-use, Recycling, Other recovery,* e.g. *energy recovery; and Disposal.*' Hence, waste management is currently transforming with regard to Austria from a thermal recovery to a recycling economy (Pomberger et al., 2017). It has been estimated that only 9% (Parker, 2018) of all the plastics that have ever been produced have been recycled. 12% (Parker, 2018) are burnt and the rest ending up in soils, oceans

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Abbreviations: η_B, screening efficiency of the ballistic separator; η_S, screening efficiency of the drum screen; η_{total}, overall screening efficiency; 2D, two-dimensional; 3D, three-dimensional; approx., approximately; B_, ballistic separation without screening; DM, dry mass; DMFMS, Digital Material Flow Monitoring System; e.g., for example; EU, Europe; FF_{2D}, fine fraction of the 2D-fraction; FF_{3D}, fine fraction of the 3D-fraction; FF_B, fine fraction of the ballistic separator; FF_S, fine fraction of the drum screen; FF_{total}, total fines content; kJ, kilo joules; M, mass; max, maximum; m^2, square meters; m^3, cubic metres; MCW, mixed commercial solid waste; mm, millimetres; MMW, mixed municipal solid waste; MSW, mixed solid waste; m_{total}, total imput mass; $\dot{m}_{total}$, throughput rate; NIR, Near Infrared; OS, original substance; P, purity; P&C, paper and cardboard; PE-LD, polyethylene low density; PE-HD, polyethylene high density; PP, polypropylene; PET, polyethylene terephthalate; PS, polystyrene; PU, polyurethan; PVC, polyvenyl chloride; rpm, revolutions per minute; S+B_, screening and ballistic seperation; SBS, sensor-based sorting; SRF, solid recovered fuel; $\dot{V}$, volume flow; V1/V2, test run number 1/2; wt.-%, percentage by weight; Y, yield.

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and landfills. In 2018, the global average for plastics recycling is less than 20% (PlasticEurope, 2020) with the EU recycling less that 15% (PlasticEurope, 2020) of its total plastic waste production. Therefore, the EU has introduced recycling rates for certain wastes, including plastics, to protect the environment and conserve resources through recycling. According to EU (2018), municipal solid waste (MSW) recycling rates of 65% need to be achieved by 2035. Currently, there is no attempt made by the EU to introduce recycling rates for (mixed) commercial waste (MCW).

Accordingly, the focus of plastic waste recycling has been on comparatively homogeneous and clean fractions such as light weight packaging waste in Austria, but worldwide too. Currently, most plastics present in MCW and MMW end up in energy recovery and are irrevocably lost for recycling (Bauer, 2013). Future recycling rates can only be met by upgrading relevant plastics from '*Other recovery*, e.g. *energy recovery*' to '*recycling*'. There are various recovery and recycling options for plastic waste with different quality requirements for the input material.

The most common method for the recycling of plastic waste is *mechanical recycling* (Al-Salem et al., 2009; Letcher, 2020; Ragaert et al., 2017). In mechanical recycling, the chemical structure (macromolecules) remains unchanged with the exception of chemical and physical ageing processes and mainly mechanical/-physical treatment takes place. The plastic collected as waste is usually sorted, shredded, washed, dried, and processed into recycled plastic according to the value chain given by Friedrich et al. (2019). Mechanical recycling is mainly used if large quantities of a single type of material are available. Quality criteria for recyclates for the final plastic processing companies are not standardised but defined individually by the recycling and processing companies. Criteria include e.g. exceptionally pure colour and low content of contaminations (EU, 2006; Friedrich et al., 2019; Vilaplana & Karlsson, 2008). For example, in recycling plants, plastic recovery rates decrease due to too high contents of attached grime in the input, which have not been sufficiently removed by pretreatment, losses of plastics into finer particle fractions, which cannot be sorted adequately due to unintentional shredding and because most products are still not designed for recycling that impedes the recovery of plastics with state of the art technology (e.g. full sleeve on PET bottles) (Küppers et al., 2019). Of particular importance for mechanical recycling are contaminants (e.g. heavy metals, halogenated flame retardants, plasticisers) (Groh, 2019; Hahladakis, 2018) in the input material. Depending on the product, these are only permitted in very small quantities. For this reason, the removal of contaminants must already be taken into account in the pre-treatment and sorting of the input fractions. In Germany, quality standards for sorted plastic waste applied in the plastic waste recycling companies have evolved within the plastic industry (Grüner Punkt, 2019). The strict quality requirements for plastic waste have an effect not only on the downstream processing but also on the price development of the plastic wastes and the regranulates produced from them. (Friedrich et al., 2019).

In addition to mechanical recycling of plastics, pyrolysis and thermal or catalytic cracking processes are further options that enable *raw material recycling* (also known as chemical or feedstock recycling) of used plastics (Angyal et al., 2007; Bauer et al., 2013; Garforth et al., 2004; Lehner et al., 2016): This type of recycling has a high potential for heterogeneous and selected contaminated plastic waste material (e.g. polyolefines) if more intensive separation and processing than in case of mechanical recycling is neither economically nor technically feasible. In chemical recycling, the polymer chains are split (e.g. through the use of heat), whereby monomers or petrochemical basic materials such as oils and gases are obtained, e.g. in a conventional crude oil refinery (Bauer et al., 2013; Lehner et al., 2016). These can be used to produce new plastics or for other petrochemical purposes. Other important processes are pyrolysis, hydrogenation, gasification and use as substitute reducing agents in the blast furnace process. In addition to specifications for water content, calorific value, grain size etc., different limit values are specified for inorganic, organic contaminants, heavy metals and other elements. The specific quality requirements for the input material for the different processes can be found in the literature (Al-Salem et al., 2017; Lechleitner et al., 2019; Lehner et al., 2016; Lahl, 1995; Letcher, 2020; Solis et al., 2020).

To achieve the required input qualities for the respective recycling process, specific pre-treatment of the waste and enrichment of valuable fractions is essential. The task of conditioning or pre-treatment of waste is to prepare it in such a way that the best possible conditions are produced for subsequent sorting processes. Essential requirements are the reduction of particle size and breakdown of material agglomeration, the removal of impurities such as fine or heavy materials, the division of material streams into specific, narrowly distributed particle sizes ranges, separation according to shape characteristics such as 2D- and 3D-objects, and the production of a concentrated material stream that enables reliable separation by particle-based sorting steps. (Letcher, 2020).

Drum screens are state of the art in the pre-treatment of mixed commercial, municipal and packaging wastes. The input material is loosened and redistributed by the rotary motion, thereby exposing enclosed particles and separating the undersize particles from fine to coarse.

Ballistic separators are also state of the art in sorting and classification plants for light weight packaging waste, before singe particle-based, sensor-based sorting steps. The material flow is separated into two or three fractions. By combining different object properties such as weight, dimension, density and shape, a separation into a "rolling fraction" (stones, wood, cans, heavy plastic parts, etc.) and a "flat light fraction" (foils, textiles, paper, cardboard, etc.) takes place. Depending on the paddle perforation, a third screening fraction according to grain size is possible. (Letcher, 2020).

Mechanical recycling almost always involves wet-mechanical processing for material preparation and sometimes also for chemical recycling. Fine material (<10 mm), which mainly contains organic and inorganic impurities and heavy metals (Viczek et al., 2020), is washed off. This leads to very costly wastewater treatment (Vollprecht et al., 2019). Residual impurities can also be carried over into the process and cause damage in the process itself (e.g. corrosion) or in the material (e.g. reduction in material properties). It is also known that, in material recycling, free fines (e.g. dust formation) and adhering impurities lead to lower material recognition efficiency when sensor-based sorting is applied. (Küppers et al., 2019).

Therefore, the use of various screening technologies in mixed waste pre-processing is of essential importance for quality assurance to produce plastic pre-concentrates. The cleaner these are, the higher is the performance of downstream process steps. Hence, this study investigates the relation between pre-processing steps, the efficiency of subsequent sorting steps and the quality of the final products. It will do so for two types of wastes (MMW and MCW) and two types of pre-processing (in- vs. excluding the pre-screening stage directly after coarse shredding).

2. Materials and methods

2.1. Materials

The materials used for the investigations in the present manuscript were MCW and MMW from Austria (Upper Styria and Graz)

Table 1
Overview of the input masses and throughput rates for the investigated setups (Note: B = ballistic separator; S = pre-screening; V1 = test run number 1; V2 = test run number 2).

Setup description	Waste type	Pre-screening	Test run number	m_{total} [t]	$\dot{m}_{total}$ [t/h]
B_MCW_V1	MCW	No	1	9.5	10.7
B_MCW_V2	MCW	No	2	10.9	14.1
S + B_MCW_V1	MCW	Yes	1	10.8	12.4
S + B_MCW_V2	MCW	Yes	2	8.8	12.0
B_MMW_V1	MMW	No	1	21.3	21.7
B_MMW_V2	MMW	No	2	14.3	21.4
S + B_MMW_V1	MMW	Yes	1	13.4	17.1
S + B_MMW_V2	MMW	Yes	2	17.4	18.2

(Fig. I in supplementary material) and was collected immediately before the experiments. As Khodier et al. (2019) showed in an extensive study on sampling quality, the inhomogeneity of MCW is already exceptionally large within the lot used in 1 h and 47 min of experimentation. A further variation of waste composition – that also influences the investigated target values – is expected between single experimental runs.

The total input masses (m_{total}) used for the individual experiments and the resulting throughput rates ($\dot{m}_{total}$) are shown in Table 1. Both waste types were treated in four experimental runs of about 40–60 min each during October and November 2019.

2.2. Methods

In this section, the experimental and analytical procedures are described. Fig. 1 shows the material flow from the dry-mechanical processing line with drum screen (S+B_) and without drum screen (B_) as well as the sampling of the output fractions, the analytical screening and the sorting analysis.

2.2.1. Dry mechanical processing line

For the tests, a dry-mechanical process line with mobile large-scale machines (see Fig. 1) was set up in the open area of a test site, consisting of the following machines and components:

Wheel loader: The input material was fed to the continuously operating processing line via a wheel loader with a shovel volume of 3.2 m^3.

Shredder: Komptech Terminator 5000SD F (radial cutting gap: 4 cm, shaft speed 60% of max. 32 rpm for MCW and 30% for MMW, length of the discharge: belt 6 m, speed of the discharge belt: 2.5 m/s). The cutting gap has been chosen to achieve a maximum grain size of the input material of 300 mm. With these settings, agglomerates should be broken up and through selective comminution with subsequent screening, the valuable materials (e.g. 3D-plastics) as coarse material and the impurities (inert and organic) as fine material should be obtained.

Drum screen: Komptech Nemus 2700 (screen drum diameter: 2000 mm, length of the drum: 5500 mm, active screen surface: 9 m^2, drum speed: 10 rpm of max. 23 rpm, mesh size: 80 mm). During the trials, an optimal filling level of 15% was targeted as proposed by Feil et al. (2019). The screen cut was chosen to ensure a grain size ratio of 1/3–1/4 (Bunge, 2012) in the generated 3D-fraction. In several experiments, the drum screen was utilized as an additional screening stage prior to the ballistic separator.

Digital Material Flow Monitoring System (DMFMS): Komptech prototype consisted of a conveyor belt (speed: 0.5 m/s) and mass flow measurement: integrated weighing belt scale (Kukla EBW-A-1400/6200, ±2% in the range of 25–100% for throughput rates of 5–100 t/h).

Ballistic separator: Stadler STT5000_6_1 (active screen area: 8.8 m^2, adjusted angle of the sieve paddles was for all test runs 12.5° (possible setting range: 7.5–25°)). This flat angle was chosen to put the focus on a high purity 3D-fraction.

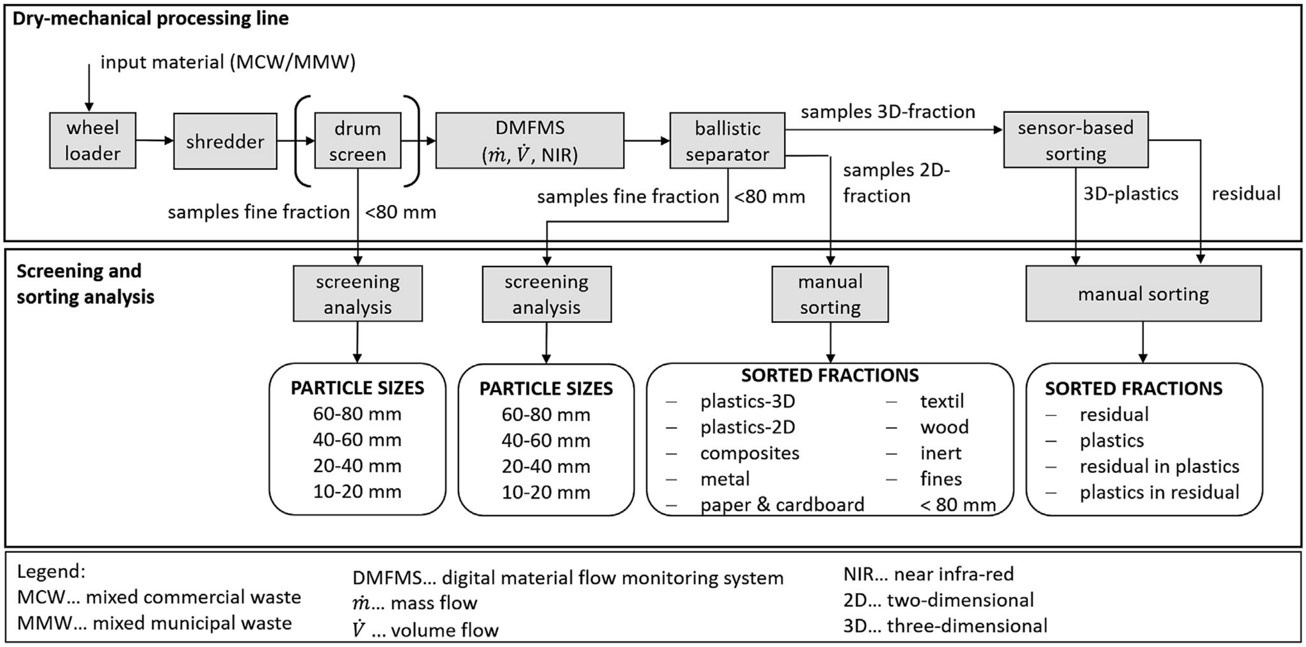

Fig. 1. Flowchart for the methodology of mechanical treatment and field investigations of MCW and MMW.

First, the processing line was configured without a drum screen for both wastes (MCW and MMW). The drum screen was then placed between the shredder and the ballistic separator (see Fig. 1) to investigate the influence of the pre-screening on the output fractions of the processing line. For each set-up of the processing line, two test runs were carried out with both waste types (in total four test runs per waste type). One experiment lasted between 40 and 60 min, with samples of all output streams (see Fig. 1) being taken from the falling stream based on the standard ÖNORM S 2123–3 (Austrian Standards Institute, 2003) at certain intervals. At the end of a test run, all output streams were weighed with the weighing device integrated in the wheel loader and the drawn sample masses were added. From these data in combination with the mass flow data from the DMFMS, the respective total mass balances were created. As the dry-mechanical tests were carried out in the open air depending on the weather, small but from a technical point of view, acceptable deviations can be expected in the treated quantities.

Decoupled from the process line, a sensor-based sorting (SBS) machine was set up for further processing of the samples of the 3D-fraction. The 3D-samples were continuously fed onto the acceleration belt (speed: 3 m/s) of the SBS, simulating an ideal material feed. It was sorted at low throughput rates to prevent particles from overlapping. The used SBS machine was a Near Infrared (NIR) sorter (REDWAVE 2i) with 1400 mm working width and a nozzle distance of 12.5 mm. The sorting recipe (sorting algorithm) was set to distinct and separate plastics (PE-LD, PE-HD, PP, PET, PU, PS and PVC) from non-plastic materials and carbon blackened plastics via positive sorting.

2.2.2. Sampling procedure of the outputs

Sampling of all below mentioned fractions was carried out considering the standards ÖNORM S 2123–3 (Austrian Standards Institute, 2003).

All generated *2D-fractions* of each test run were sampled every 10–15 min with two stacking boxes (volume: 600 L each) on the forklift to ensure sampling over the entire working width. The sampling time was approx. 10 s each. In total, six samples per test run were taken from the falling material stream of the 2D-fraction.

All generated *3D-fractions* of each test run were sampled over almost the entire test period, due to the low material throughput with two stacking boxes (volume: 600 L each) on a forklift to ensure sampling over the entire working width. In total, at least four samples per test run were taken from the falling stream of the 3D-fraction of the ballistic separator.

All *fine fractions* were sampled every 10–15 min from the falling stream. The fine fraction of the drum screen (FF_S) was sampled using a BigBag (volume: 1 m^3) attached to the tines of a forklift over a time period of 5–10 s. To ensure a uniform sampling of the fine fraction of the ballistic separator (FF_B) over the discharge area, the forklift with a stacking box (volume: 600 L) was first placed in the discharge box on the far left, then in the middle and finally far right. This process took about 5 min each.

2.2.3. Screening and sorting analysis

All samples of the *2D-fraction* were analysed by manual sorting. The samples were sorted into nine fractions (see Fig. 1). A detailed description of all sorting fractions is given in Table 1 in the supplementary material. All sorted fractions were weighed to determine the composition of the respective 2D-fraction.

In the experiment B_MMW_V2, portions of improperly disposed medical waste were found in sample 4. The same was found in sample 1 and sample 6 of the experiment S+B_MMW_V2. Accordingly, the manual analysis of these samples could not be conducted and the respective samples were discarded, based on safety considerations regarding the sorting personnel.

All samples of the *3D-fractions* were fed to an SBS separately (see Section 2.2.1) to distinguish and separate 3D-plastics form non-plastic materials and carbon blackened plastics via positive

Table 2
Mass balance of both plant setups for the investigated wastes.

	MCW				MMW			
	B_MCW_		S+B_MCW_		B_MMW_		S+B_MCW_	
	V1	V2	V1	V2	V1	V2	V1	V2
2D-fraction	51%	52%	28%	30%	49%	41%	29%	35%
3D-fraction	5%	4%	7%	9%	3%	6%	3%	3%
FF_B	44%	51%	3%	2%	52%	47%	5%	6%
FF_S	–	–	56%	63%	–	–	60%	61%
Deviation	1%	−8%	7%	−4%	−3%	6%	2%	−4%

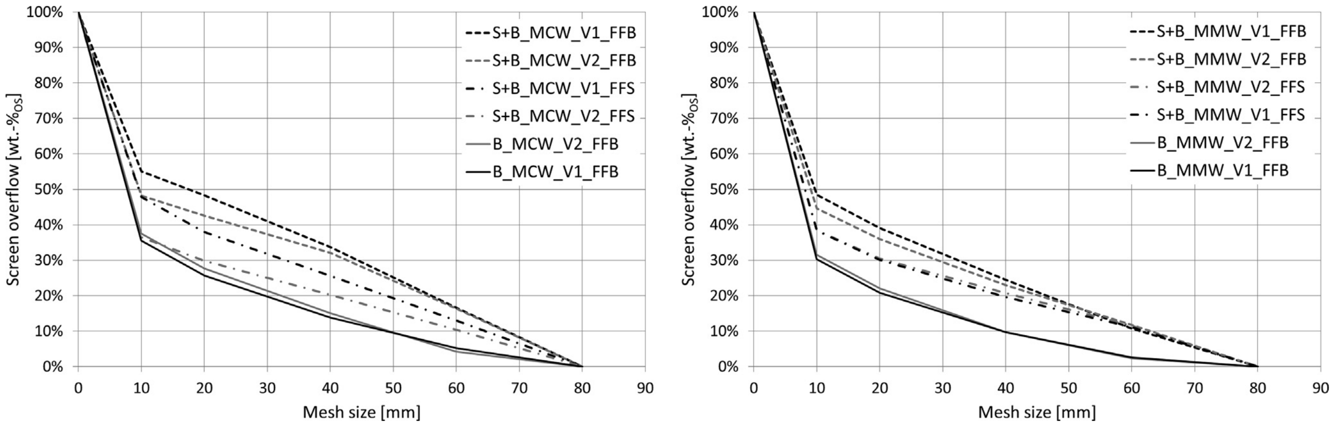

Fig. 2. Cumulative particle size distribution of the screen overflow over investigated mesh sizes for all generated fine fractions for both investigated setups and test runs for MCW (left) and MMW (right).

sorting. After separation with the SBS into a target (3D-plastics - eject) and a residual fraction (reject), both output streams were sorted manually. Also, 2D-objects that were incorrectly discharged into the 3D-fraction were sorted out manually.

All samples of both *fine fractions* (FF_S & FF_B) were subjected to an additional screening analysis. The screening analysis was performed with an equilateral octagonal prism-shaped batch drum screen (side length: 454 mm, depth: 1,000 mm) featuring 30 mm high carriages between the edges of the prism for improved material transport. A schematic drawing of the analytical sieve can be found at Khodier et al (2019). Operating at a rotation speed of 5 rpm, the screening time for each screen cut was 120 s. The screen plates have circular holes corresponding to the grain size classes shown in Fig. 1. An optimal filling level of 15% was targeted as proposed by Feil et al. (2019).

2.2.4. Evaluation and presentation of results

From the volume flow data of the DMFMS and the corresponding test durations, the masses of the generated output fractions and mass balances were generated for each test run. The results are presented in tabular form (Table 2) in mass percent.

The sorting results of each individual sample of the *2D-fraction* were evaluated with respect to mass. For each test run, the mean

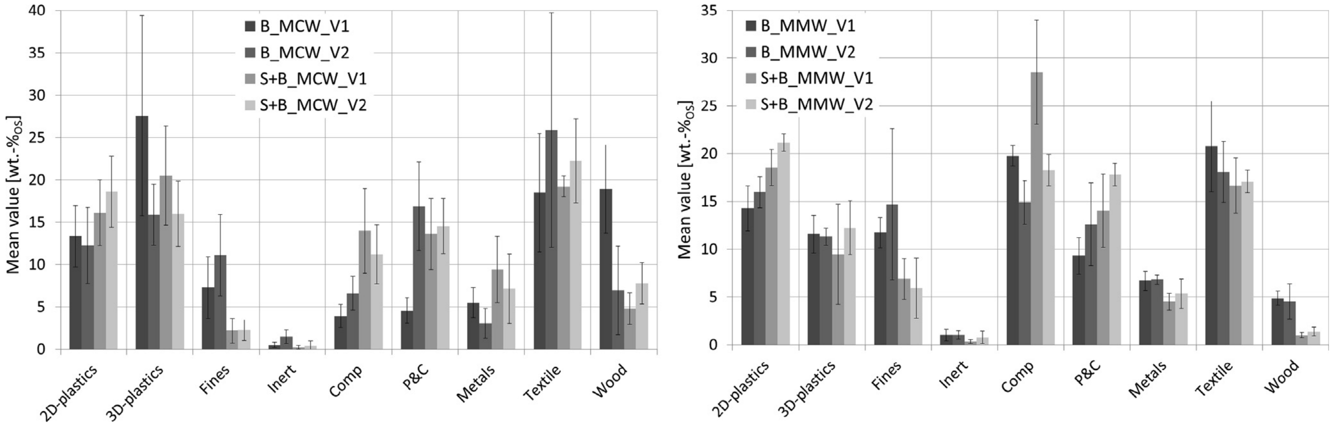

Fig. 3. Total composition of the 2D-fractions from the ballistic separator for MCW (left) and MMW (right) each with and without pre-screening for both test runs - whiskers represents the standard deviation.

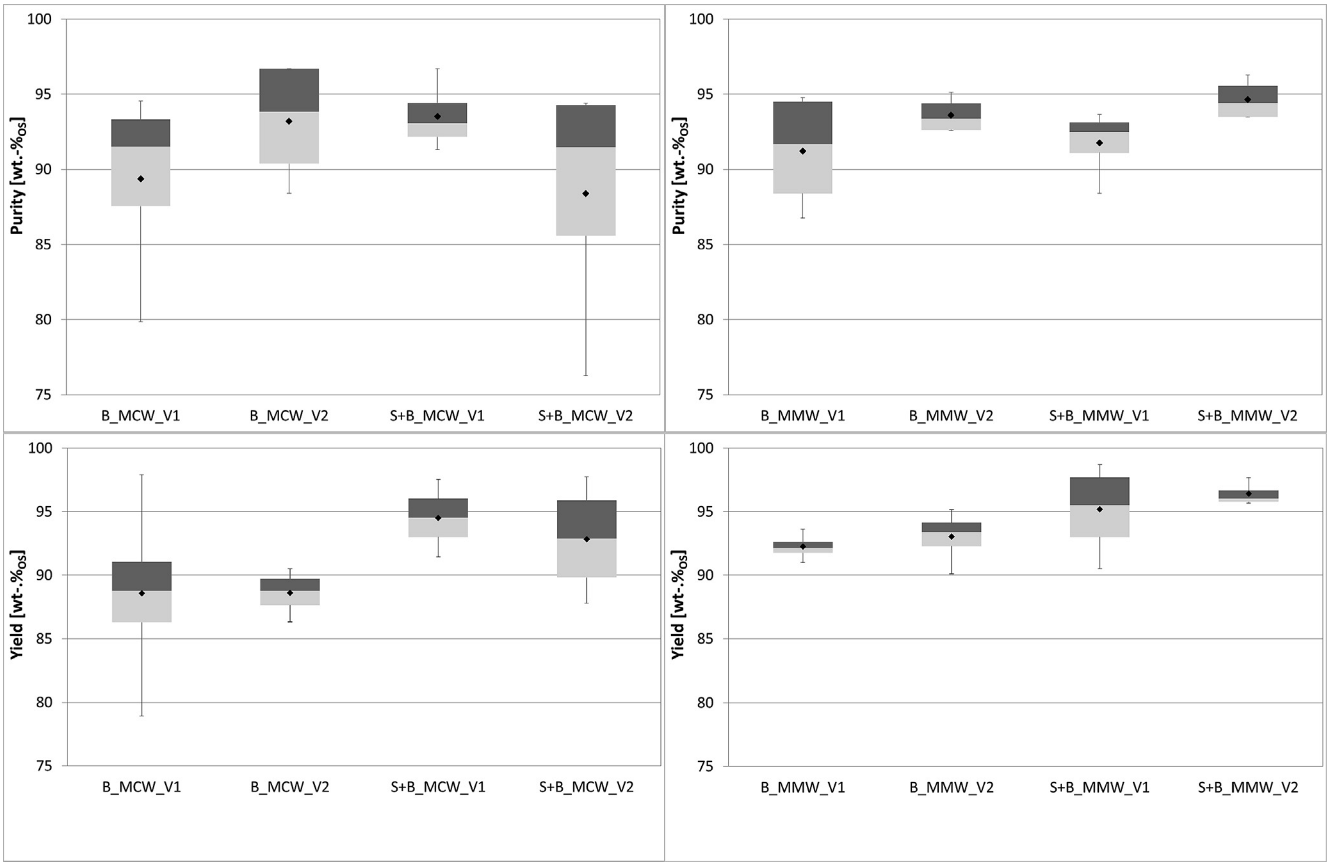

Fig. 4. Effects of pre-screening on purity and yield of the 3D-plastics out of the 3D-fraction from ballistic separator of the investigated wastes (MCW – left and MMW – right).

Table 3
Fines output and contents for the calculation of the screening efficiencies for the drum screen and the ballistic separator for all test runs.

Material	FF_S [%]	FF_B [%]	FF_{2D} [%]	Σ FF [%]	η_S	η_B	η_{total}
B_MCW_V1	–	44	4	48.2	–	0.92	0.92
B_MCW_V2	–	51	6	57.2	–	0.90	0.90
S+B_MCW_V1	60	3	1	63.9	0.94	0.82	0.99
S+B_MCW_V2	68	3	1	71.0	0.95	0.78	0.99
B_MMW_V1	–	52	6	57.3	–	0.90	0.90
B_MMW_V2	–	48	6	54.7	–	0.89	0.89
S+B_MMW_V1	63	5	2	70.1	0.90	0.71	0.97
S+B_MMW_V2	64	6	2	71.7	0.89	0.74	0.97

values were formed over the six sorted samples. These were compared separately for MCW and MMW with the standard deviation in bar charts (see Fig. 3).

The sorting results of the output fractions, generated by the SBS (eject and reject) from the *3D-samples*, were evaluated concerning purity (P) (Equation (1)) and yield (Y) (Equation (2)). (Feil et al., 2016)

$$P = \frac{M_{Eject}[kg]}{M_{Eject}[kg] + M_{Reject\ \ in\ \ Eject}[kg]} * 100\% \qquad (1)$$

$$Y = \frac{M_{Eject}[kg]}{M_{Eject}[kg] + M_{Eject\ \ in\ \ reject}[\%]} * 100\% \qquad (2)$$

The sorting results of each individual sample were evaluated mass-specifically with regard to the assessment factors mentioned above. The medians, the 25- and 75-quartiles, the upper and lower whiskers were calculated and box-whisker graphs were generated for each assessment factor and all test runs. The graphics for MCW and MMW are compared with each other in Fig. 4 in Section 3.5.

Based on the mass of the respective 2D-fraction and the share of fines (<80 mm) within (FF_{2D}) and the masses of the other fine fractions from the ballistic separator (FF_B) and the drum screen (FF_S) the total fines content (FF_{total}) in the input of a test run was calculated (see Table 3). Furthermore, the screening efficiency of the drum screen (η_S), the ballistic separator (η_B) and the overall screening efficiency (η_{total}) of the respective setup for both wastes were calculated according to Equation (3) (Bunge, 2012). The results are presented in Table 3 in Section 3.2.

$$\eta_n = \frac{FF_n}{FF_S + FF_B + FF_{2D} + FF_{3D}} * 100\% = \frac{FF_n}{FF_{total}} * 100\% \qquad (3)$$

3. Results and discussion

For the examined wastes (MCW and MMW) for both test setups (with and without pre-screening), the following aspects are included: mass balances, screening efficiency for drum screen and ballistic separator, screening analysis of the generated fine fractions, manual sorting of 2D-fractions and sensor-based sorting of the 3D-fractions.

All stated values are wt.-$\%_{OS}$ (OS: original substance), given in full percent only for clarity purposes.

3.1. Mass balance of both setups and investigated wastes

Three types of outputs were produced during the experiments: 2D-, 3D- and fine fractions (FF_B and FF_S). The mass balance for each test run is shown in Table 2. The deviation from 100% for each test run can be explained by weighing inaccuracies (scale of the wheel loader, the belt scale, the scale that was used for sample weighing), mass losses on transfer and discharge belts (especially fine material) as well as water absorption or losses depending on weather conditions.

In the B_MCW tests, the 2D-fractions with 51% (V1) and 52% (V2) was the largest fraction. By screening step, this fraction was respectively reduced by 23% (V1) and 22% (V2). The share of 3D-fraction amounted to 5% (V1) and 4% (V2) of the total input respectively. By pre-screening, 2% (V1) and 5% (V2) more 3D-material was discharged into the 3D-fraction. In total the fine material is removed better by the combination of pre-screening and ballistic separation. This significantly improves the overall screening and ballistic separator performance, which leads to an increase in the output of the 3D-fraction. With pre-screening, 12% more fines were discharged in both test runs. 56% (V1) and 63% (V2) of the total mass was removed into FF_S before the ballistic separator and approx. another 3% were removed into FF_B by the ballistic separator. Simultaneously the 2D-fraction decreased by approx. 20%.

The results for B_MMW tests show a very similar trend as for MCW. The fine (52% (V1) and 47% (V2)) and 2D-fraction (49% (V1) and 41% (V2)) also form the largest fractions by mass. At 3% (V1) and 6% (V2), the share of the 3D-fraction is similar as for MCW. The pre-screening (S+B_MCW) separated about 60% of the total mass into FF_S before the ballistic separator and about another 5% were separated by the ballistic separator into FF_B. The amount of the 2D-fraction is reduced by 20% (V1) and 6% (V2) by pre-screening.

The FF_S share always proved to be ca. 8–14% higher than the FF_B share in the respective experiments without a pre-screening stage. This indicates a slightly higher screening efficiency of the drum screen in comparison to the ballistic separator (see Table 3).

The higher share of the 2D-fraction without pre-screening, compared to the 2D-share in experiments with pre-screening, indicates that more fines remain in the 2D-fraction if no pre-screening is conducted with the drum screen. For both wastes it is found that the contained fines (<80 mm) are largely removed by pre-screening, thus significantly improving the overall screening performance and separation performance of the ballistic separator.

The data suggests that pre-screening reduces the amount of faulty sorted fines in the 2D-fractions, as the ballistic separator was adjusted to achieve maximum purity of the 3D-fraction.

3.2. Screening efficiency for drum screen and ballistic separator

The masses of the generated fine fractions and the screening efficiencies (see Equation 3) for the drum screen η_S and the ballistic separator η_B are shown in Table 3 for both wastes used in the processing line setups.

Without pre-screening, the screening efficiency of the ballistic separator (η_B) for MCW (0.92 (V1) and 0.90 (V2)) is lower than the screening efficiency of the drum screen (η_S = 0.94 V1 and 0.95 V2) with a similar active screen surface. For MMW the screening efficiencies of both machines (η_B and η_S) are the same (0.9 (V1) and 0.89 (V2)).

The screening efficiency of the (then down-stream) ballistic separator appears to be reduced after pre-screening to 0.82 (V1) and 0.78 (V2) for MCW and 0.71 (V1) and 0.74 (V2) for MMW. The reason for this can be found in the increase of near mesh size particles that remain in the coarse fraction after pre-screening: In screening stages, statistically, the smallest particles are prone to pass the screening mesh first, while coarser particles (especially near mesh size fine-particles) take more time to pass into the fines fraction.

Accordingly, the overall screening efficiencies (η_{total}) increased with pre-screening for both input materials as a much higher active screening surface was generated with 9 m^2 from drum screen plus 8.8 m^2 from ballistic separator. The overall efficiency is slightly better for MCW at 0.99 than for MMW at 0.97, which can be explained by the higher share of coarse particles in MCW. The increased overall screening efficiencies in the experiments with pre-screening also explain the mass reduction of the 2D-fraction (see Table 2): The ballistic separator was operated in such a way that a pure 3D-fraction was produced. Thus, fine particles that had not passed the 80 mm screen mesh before or during ballistic separation were discharged into the 2D-fraction. Due to the pre-screening (and accordingly higher active screening surface), the proportion of fines in the 2D-fraction is reduced for both wastes (MCW: 17–25%; MMW: 33%), which leads to a reduction in the total mass of the 2D-fraction.

Due to selective comminution inert, organics and various contaminants are expected to end-up in the fine fraction, especially into the particle size fraction <10 mm (Viczek et al., 2020). As results indicate that the FF_S predominantly consists of fine particles, while FF_B contains more near mesh size particles, FF_S is expected to contain most minerals, organics and contaminants (heavy metals and chlorine), except cadmium, antimony and chlorine (Viczek et al., 2020). Accordingly, the valuable materials (e.g. plastics) are more likely to be found in the 2D- and 3D-fractions. Similarly, near mesh size particles in FF_B are expected to contain more valuable materials, as opposed to fines <10 mm (Möllnitz et al., 2020).

3.3. Screening analysis of the generated fine fractions

The particle size distributions of the generated fine fractions (FF_S and FF_B) are shown in Fig. 2. The differences of the screening curves with drum screen and ballistic separator (Fig. 2 - left) confirms that the share of fines in MCW fluctuates, displaying the tremendous heterogeneity of the waste itself. In contrast, the relatively similar curves of MMW (Fig. 2 - right) from trials with drum screen and ballistic separator reflect the homogeneity.

The content of fines (<10 mm) is approx. 64% for MCW and approx. 70% for MMW without pre-screening. Pre-screening reduces this share by 19–30% for MCW and 12–26% for MMW. This observation confirms the assertion, that more near mesh size particles passed into the fines fraction resulting in increased screening efficiencies (η_{total}) with pre-screening (see Table 3), which also confirms the reduced screening efficiency of the ballistic separator due to the higher share of near mesh size particles in its input. For both input wastes, the remaining masses are distributed relatively evenly over the remaining grain size ranges.

As a result of this and the particle size distribution of the feed material, as well as selective comminution, it is assumed that the FF_B contains an increasingly valuable material content (e.g. plastics) (Möllnitz et al., 2020). Viczek et al. (2020) show that by removing the fraction <10 mm, not only the contaminants concentrations can be significantly reduced, but that the lower calorific value for the remaining fraction is between 15,000 and 20,000 kJ/kg_{DM} (DM: dry mass) and will therefore increase. After screening of the <10 mm fraction for removal of pollutants and metals, the fine fraction (<80 mm) could, therefore, be suitable as a solid recovered fuel (SRF) having more stable water content and improved combustion-related properties due to the improved particle size distribution etc. (Sarc et al., 2014; 2019) or for recovery of plastics. Another option is to test for the tendency of the fines to recover contained plastics (Möllnitz et al., 2020) and metals for recycling. In contrast, the FF_S fractions are expected to have a significantly reduced content of valuable materials and high pollutant content. It should therefore be further examined whether this fraction is suitable for use as SRF or other recovery options.

3.4. Influence of pre-screening on the composition of the 2D-fraction from ballistic separation

The manual sorting analysis is used to assess the quality of the 2D-fractions based on the parameters fine fraction <80 mm (FF_{2D}) and material composition. FF_{2D} represents a relevant impurity due to the high concentration of contaminants (Viczek et al., 2020) for subsequent treatment steps of following recycling processes. Fig. 3 shows the results of the manual sorting analysis of each generated 2D-fraction from the ballistic separator for both input materials with and without pre-screening.

The deviations in the results, especially of test runs V1 and V2, of MCW and MMW can be explained by the inter-experimental heterogeneity of the material, especially since the same input material could not be used in every experiment for logistical reasons. The deviations are smaller for MMW which indicates that MMW is more homogeneous than MCW. The strong inhomogeneity of MCW can e.g. result from different collection routes.

Overall textiles, 3D-plastics, 2D-plastics, paper and cardboard (P&C) and composites form the largest fractions for both wastes with each more than 10% in both plant setups. The fines and 2D-plastics content in the MMW are both in average 5% higher than in the MCW. The content of 3D-plastics, on the other hand, is approx. 5% lower than in MCW. It can be seen that also the metal (approx. 5%) and inert content (approx. 1%) are in a similar range for both waste types. The wood and P&C content of MMW is slightly lower (approx. 3%) than in MCW. A reason for this can be, that there were less large packaging boxes and wood trays in MMW, compared to MCW. MMW contains about 15% more composites which can be attributed to the high share of diapers, being regarded as composites.

The influence of the pre-screening is most visible in the reduction of the fines (approx. 80% for MCW and approx. 50% for MMW) and inert fraction (approx. 50%) in the 2D-fractions of both wastes. Additionally, also the shares of wood and metal in the 2D-fractions were slightly reduced by the additional screening step. Conclusively, these fractions are predominantly present in the grain size <80 mm and their proportions can be reduced by pre-screening. A slight increase in 2D-plastics, composites and metals (only for MCW) can be seen as a complementary effect. Screening had no visible influence on the share of the 3D-plastics in the 2D-fractions. This indicates that 3D-plastics end-up in the fines by pre-screening to the same extent as the fines and inert. The relatively high content of 3D-plastics in the 2D-fractions can be traced back to the ballistic separator being set to a flat angle, generating a 3D-fraction of high purity, being the target fraction of this study. If both products were of equal relevance, a throughput reduction and steepening of the paddle angle would have resulted in increased purity of the 2D-fraction as well.

During screening with the drum screen, the formation of tails was observed, especially for MCW. The tails occurred due to wires, ropes, large foils and nets being wrapped around other particles due to the rotation of the material in the drum screen. The tails were mostly discharged through the ballistic separator into the 2D-fraction contributing to further contamination of the 2D-fractions. Tails partly clogged the discharge of the drum screen.

3.5. Sensor-based sorting of the 3D-fractions from ballistic separator in a 3D-plastic and residue fraction

No 2D-objects were found in any of the 3D-fractions, as the ballistic separator was set to a low inclination to generate a high purity 3D-fraction. Similarly, the amount of free fines was $\ll$1% for all 3D-fractions. Fig. 4 shows the purities and yields of all generated 3D-plastics fractions.

The average purities of the 3D-plastics fractions of both wastes were between 90% and 95%. No major improvement of the purity was achieved by pre-screening, based on the given data. For MCW and MMW yields of approx. 89% and 95% respectively were achieved without pre-screening. With pre-screening, the yields were increased by 3–5% for MCW and MMW. This indicates that SBS performance is better when the drum screen and ballistic separator are both used before the sorting stage, even though no significant free fines could be found in the 3D-fractions. A possible explanation, based on the visual assessment during trials, for this improvement is that the additional material circulation in the drum screen introduces greater friction between the objects than in the ballistic separator, removing adhering fines from the particle surfaces. Due to the cleaner surfaces, the objects of the valuable fraction are better identified by sensors and therefore classified as well as correctly separated (Küppers et al., 2019).

In an industrial scale process, reduced purities and yields should be expected for both wastes as occurring fluctuations will result in temporal overfeeding of the SBS stages, thus reducing the overall SBS performance (Curtis et al., 2020). If higher purities and yields must be achieved, a multi-stage sorting process with rougher, scavenger and cleaner stages should be considered. (Letcher, 2020)

4. Conclusion

This paper presents several findings with relevance for mechanical processing and the plastic recycling potential of MCW and MMW.

Results on mass balance investigations show that by pre-screening with a drum screen, approximately 12% more fines were separated from the free fines for both wastes investigated. This improved the screening and separation performance of the down-stream ballistic separator, leading to a lower 2D-output with higher quality at the same or slightly increased 3D-output of the same quality as without pre-screening.

The results of the screening efficiencies in combination with those of the screening analyses of the fine fractions have shown that particle size distribution of the feed material, as well as selective comminution in combination with pre-screening, enhances the enrichment of valuable materials (e.g. plastics) in coarse fractions and FF_B, while various contaminations, minerals and organics are yielded into fine fractions FF_S (especially <10 mm). So, the sieving effect of the ballistic separator leads to enrichment of a second valuable potentially recyclable fine fraction and a concentration of a contaminant-rich fine fraction produced by pre-screening. This allows a more targeted concentration and quality improvement of both plastic rich fractions.

The sorting of the 2D-fraction clearly shows that the variable input composition leads to fluctuations in product quality. An average of 5% more 2D-plastics was enriched by pre-screening.

Depending on the size of an existing screening stage (here: ballistic separation), a pre-screening stage can significantly improve the overall screening efficiency and consequently enhance the performance of the entire down-stream processing line. The material circulation, induced through a rotating drum screen, causes the separation of adhesive fines from coarse particles, resulting in improved classification via NIR-sensor, thus enhancing SBS performance (e.g. increased yield). On the other hand, the utilization of a drum screen for material streams, containing large foils, ropes and nets (e.g. MCW), results in tail-formation, which can lead to clogging, plant downtime and material losses as well as performance reduction of down-stream processing machinery (e.g. ballistic separation). Therefore, in further research work, the upstream installation of different screening technologies (e.g. circular or linear vibratory screen) instead of the drum screen should be investigated concerning their effects on SBS, as these could be more advantageous for the processing of waste, containing large ropes, foils and nets (especially MCW).

Furthermore, the generated output streams are to be further characterised and examined for their suitability for possible post-treatment steps. The suitability of the 3D-fraction shall be tested after further size reduction as a substitute reducing agent in the blast furnace process. The suitability of the 2D-fraction for wet-mechanical processing and subsequent use in thermochemical conversion shall also be examined. Finally, the fines from the ballistic separator should also be examined with regard to their residual valuable material content (e.g. plastics and metals) and their recoverability or the applicability as SRF should be tested.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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4.2.2 Publication 3

Real Time Material Flow Monitoring in Mechanical Waste Processing and the Relevance of Fluctuations

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MS: Investigation, Data Curation, Writing - Review & Editing, Project administration.

KK: Methodology, Software, Investigation.

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Real time material flow monitoring in mechanical waste processing and the relevance of fluctuations

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ABSTRACT

To achieve the goals of the circular economy, significant improvements in non-hazardous solid waste processing/treatment must be made. Large deficits in the digitalization of mechanical waste treatment plants (smart waste factory) offer great potential for improvement. Real-time material flow monitoring is carried out in very few plants, thus wasting considerable potential for improving plant performance.

This article describes results from the authors' own practical analyses using sensor-based technologies for monitoring material flows, an on-site investigation in a large waste treatment plant and also in a pilot-scale plant (Technical Line 4.0) using mixed commercial waste (MCW) from Austria. The obtained data shows that the quantitative monitoring of volume and mass flow (via laser triangulation as well as near-infrared (NIR) based monitoring) and material composition (NIR sensor) is possible. The observed fluctuations were categorised in short-, mid- and long-term fluctuations and were led back to their causes, i.e. discontinuous feeding process, material and machine-specific characteristics. Using the quotient of the 90% (Q90) and 10% (Q10) quantiles of time-resolved volume-flow data for the assessment of fluctuations, for the considered time-intervals, resulted in **Q90 / Q10 ratios between 3.39 and 4.58**. If short-term fluctuations (within the observed time-intervals) are related to the 29.6 s moving average, **deviations between 1.8% and 6.8%** result. To verify the relevance of such fluctuations, sensor-based sorting (SBS) experiments were conducted, revealing a **reduced product purity of 6%** due to short-term fluctuations in the feed of the SBS-Machine using light packaging waste (LPW).

Abbreviations

c_{PET}	concentration of PET
c_{REST}	concentration of rest
c_{REST} in Eject	concentration REST in eject
DMFMS	digital material flow monitoring system
e.g.	example given
HSI	hyperspectral imaging
L	liter
LPW	light packaging waste
LIPS	laser induced plasma spectroscopy
MCW	mixed commercial waste
$\dot{m}_{Eject}$	mass-flow eject
$\dot{m}_{Input}$	mass-flow input
$\dot{m}_{PET\ in\ Eject}$	mass-flow PET in eject
$\dot{m}_{REST\ in\ Eject}$	mass-flow rest in eject = incorrect particle discharges
NIR	near-infrared
OD	occupation density
OD90	90%-Quantile of OD
OD10	10%-Quantile of OD
OD90/OD10	fluctuation intensity
PE	polyethylene
PET	polyethylen terephtalate
P_m	purity
PP	polypropylene
PS	polystyrene
PU	polyurethane
PVC	polyvinyl-chloride
Q75	75% quartile
Q25	25% quartile
R	recovery
R_w	yield
SBS	sensor-based sorting
SRF	solid recovered fuels
VIS	visually

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WFD	Waste Framework Directive
3D	three dimensional

1. Introduction

The European Directive on waste (Waste Framework Directive - WFD) presents the basis for the development of waste management to resource management regarding municipal solid waste of which recycling rates of 65% have to be achieved by 2035 (European Union, 2018). In the last 25 years, Austrian waste management has developed from a landfill oriented sector to the more modern "waste as resource management" (Sarc et al., 2014). This means that waste management for mixed non-hazardous municipal and commercial waste has evolved from a logistics-heavy industry to a manufacturing industry. Quality assurance of the solid recovered fuels (SRF) and secondary raw materials produced have been established and are based on the relevant legal framework and customer requirements. A good overview of system concepts and quality assurance can be found at Sarc and Lorber (2013), Sarc et al. (2016), Sarc et al. (2019b) and Gerassimidou et al. (2020). In particular, the production of quality-assured secondary raw materials (i.e. recyclables) and solid recovered fuels (SRF) and their use in suitable facilities (e.g. cement kiln) has reached a high level of maturity but there is still a long way to further develop mechanical waste treatment to become a cyber-physical system and therefore a so-called "smart waste factory" (Sarc et al., 2019a). The concept of the smart waste factory follows several approaches from e.g. material flow detection and regulation via the application of new sensor technologies, machine to machine communication for dynamic plant control and monitoring, implementation of new sensor technologies for sorting units, e.g. LIPS (laser-induced plasma spectroscopy) and TERRA-Hertz and use of new actuator technologies in form of e.g. robotics (Sarc et al., 2019a) in the area of waste treatment plants to increase the capacity and sorting efficiency and also the quality of the recycled materials (Feil and Pretz, 2018).

In currently operated waste treatment plants for mixed non-hazardous municipal and commercial waste, there is almost no communication between individual machines, and the digitalized generation and collection of material flow specific data hardly takes place. Many machines are highly developed (e.g. eddy current separators) but are hardly equipped with sensors and actuators, which provide the opportunity to react based on the detected material changes. Sensor-based sorting machines or shredders in turn contain several sensors and collect large amounts of data, but often this information is not used for dynamic plant operation (Sarc et al., 2019a). Even relatively simple measurements such as volume and mass flow measurements are often discarded for monetary reasons (Sarc et al., 2019a). This means that there is no real-time information on the load factor of conveyor belts or concerning the quantities that are being fed to certain machines (e.g. Sensor-Based Sorting Machines (SBS-Machines)) whose performance can be affected by such fluctuations. Accordingly, it is very difficult to assess the sorting efficiency of singular processing or sorting units in plants. The qualities of generated recyclable fractions and the evaluation of material losses can only be determined after the production process by extensive and cost-intensive sampling and analysis. Interventions (e.g. change of the shredder cutting gap) in the production process are, therefore only possible afterwards.

Fluctuations in the volume and mass flows have major influences on the machine and plant performance as well as on the quality of the recyclable materials (Feil and Pretz, 2018), e.g. the higher the occupation density (degree of coverage on a conveyor belt), the worse the sorting performance of SBS-Machines (Küppers et al., 2020). These fluctuations can be caused by the irregular material discharge of individual machines such as drum sieves or by discontinuous feeding of the processing chain using men-operated wheel loaders, etc. (Feil and Pretz, 2018). The data provided in this manuscript obtained quantitative information regarding fluctuations of the material flow in a waste processing plant by the implementation of various sensor technologies. By extending trials in a Technical Line 4.0 under use of non-hazardous solid waste, a deeper understanding of the formation and causes of fluctuations is enabled. To assess the relevance of real-time information on material flow fluctuations, experiments with SBS-Machinery were conducted, enabling the quantification of such variations regarding SBS performance.

The investigations presented in this work are an essential contribution in smart waste factory development and improvement of the present mechanical waste treatment.

2. Materials and methods

The following sections describe the used materials, experimental setups, and the chosen methodological approaches. Fig. 1 shows the trial scheme of the three different test series (A), B), C)) performed in the period September – December 2019.

In test series A), the on-site material flow monitoring was carried out in a waste treatment plant (treatment capacity: 20 t/h) by utilizing a hyperspectral imaging (HSI) near-infrared (NIR) camera above a conveyor belt in the 3D-material processing line. In test series B), volumetric and mass flow fluctuations were recorded in a pilot-scale processing line (i.e. Technical line 4.0) for mixed commercial waste (MCW), using a **d**igital **m**aterial **f**low **m**onitoring **s**ystem (**DMFMS** consists of laser triangulation, HSI NIR sensor, VIS camera, and belt scale). In test series C) it was investigated how manually generated material flow fluctuations affect the sorting performance (purity and yield) of an industrial-scale SBS-Machine. With the Technical Line 4.0 the fundamental processing chain (pre-shredder and screen), used in most mechanical waste treatment plants, was used for pilot plant scale processing trials. Further information can be found in section 2.2 Methods.

2.1. Materials

The waste that was processed in test series A), B) and C) is described in the following subsections.

2.1.1. Test series A: On-site investigation - material processing and online monitoring in a waste treatment plant

The material utilized for the throughput measurements in a real waste treatment plant was mixed commercial waste (MCW) from Austria (Upper Styria and the region of Graz; collected Dec. 2019) and was fed to the plant immediately after the arrival. The storage period between collection and delivery could not be determined (depends on the collection intervals). The material was shredded with a pre-shredder (Komptech Terminator) with a throughput rate of approximately 20 t/h. After the shredded material undergoes two-stage sieving, magnetic separation and wind sifting, the remnant is the heavy fraction (grain size 60 – 240 mm), which is then fed to the Digital Material Flow Monitoring System (DMFMS). The test lasted for 8 h.

2.1.2. Test series B: Material processing and online monitoring in a Technical Line 4.0

The material used for the throughput measurements in the Technical Line 4.0 was MCW from Austria (Upper Styria and the region of Graz; collected Oct. – Nov. 2019) and was delivered to

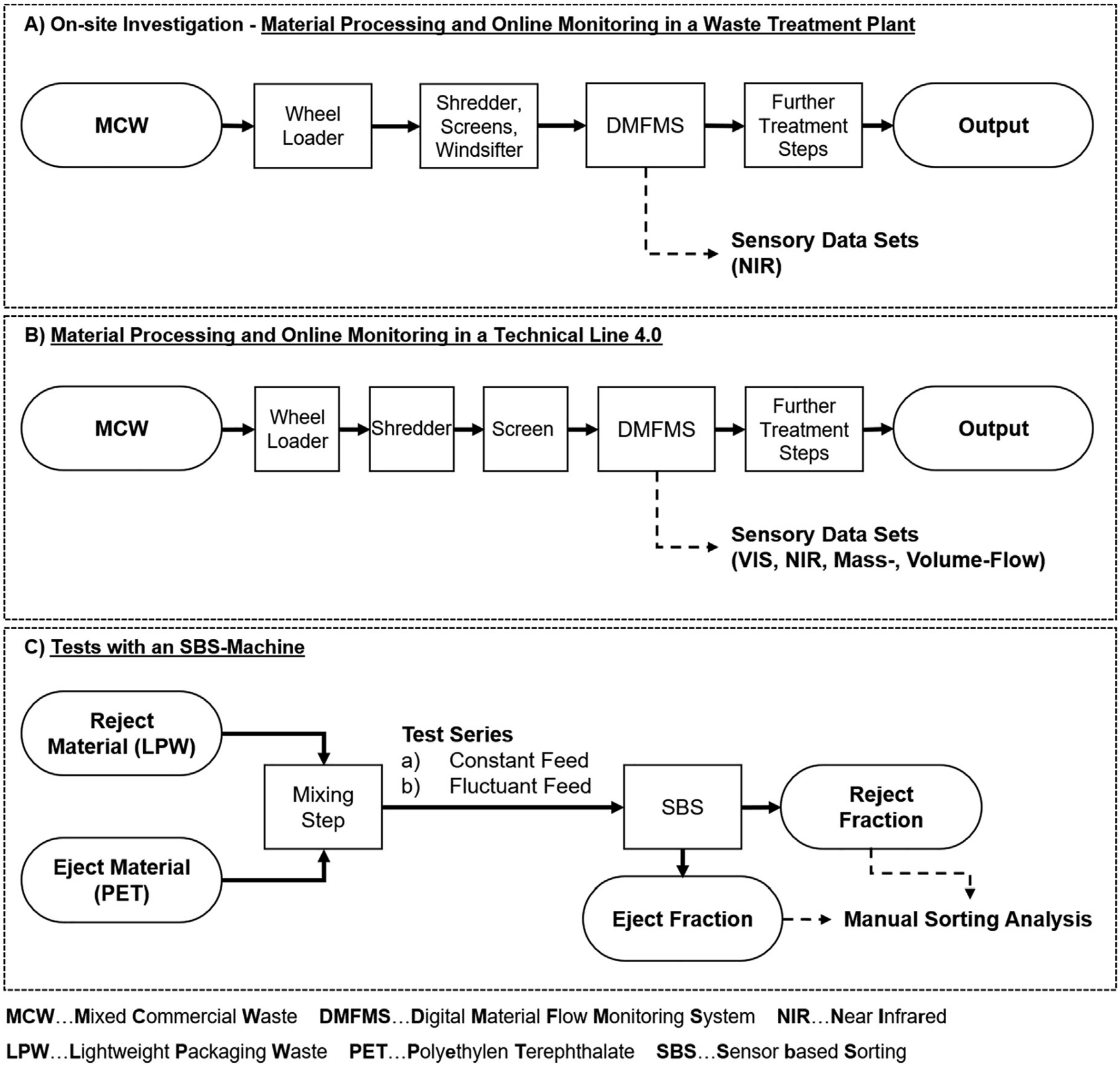

Fig. 1. Trial scheme of the conducted test series.

the Technical Line 4.0 just in time, cf. further material description in section **2.1.1**. In total, 41.5 t of MCW was used in four large scale experiments (in total approx. 3.5 h of shredding time).

2.1.3. Test series C: Tests with an SBS-Machine

The material used for the throughput measurements in the tests with an SBS-Machine was sorting residue (grain size 60 – 240 mm; approx. 2 m^3 or 48 kg) with a polyethylene terephthalate (PET) content of 0.0 mass-% from an Austrian light packaging waste (LPW) sorting plant (region of Graz; collected in Oct. 2019, storage period about two months). This fraction was used as the reject fraction and consisted of lightweight plastic packaging, hollow plastic articles, beverage composite boxes, screw caps, metals, etc. The PET content of 0.0 mass-% was ensured by manually sorting out PET containing materials. By mixing with a pure PET fraction (eject fraction), which consisted of PET (bottles), a defined PET content of 32.3 mass-% was set and ensured for all tests with the SBS-Machine.

2.2. Methods

The implemented methods for each test series are described in the following sub-sections. For the assessment of fluctuations occurring in test series A), B) and C), a distinction between short-, mid- and long-term fluctuations was made. Each type of fluctuation can be displayed graphically, using the moving average for a certain time interval. The extent of each type of fluctuation was assessed based on its deviation from the moving average generated for the next larger time interval.

2.2.1. Test series A: On-site investigation - material processing and online monitoring in a waste treatment plant

To quantitatively assess the material flow, an HSI NIR line scan camera from EVK (EVK Helios G2-320) was used. The camera was installed in the 3D-material processing line above a conveyor belt to analyze the generated MCW 3D-fraction in-line. The conveyor belt was operated at a speed of 1 m/s. Based on the obtained spectral data, each pixel was classified as one of the following material classes:

Background (i.e. conveyor belt; soot-blackened), **Pulp-based material** (wood, cardboard, paper, handkerchiefs, corrugated board, kitchen roll, toilet paper, paper labels, paper bags), **Plastic** (Polyethylene (PE), PET, polystyrene (PS), polypropylene (PP), polyurethane (PU), polyvinyl-chloride (PVC), polyurethane (PU), **Others** (materials that could not be assigned to material classes background, pulp-based material and plastic). The distinction between objects and material class **background** (in this case the conveyor belt) - was enabled based on differences in the detected spectral intensity. The soot-blackened conveyor belt reflected significantly less NIR radiation than other materials, presenting the distinctive feature for background identification. Accordingly, soot-blackened plastics located on the conveyor belt were also classified as background. To create a sensor database for **pulp-based material** and **plastic,** the spectral fingerprints of in total 28 recurrent particles (5 PE, 3 PET, 4 paper/cardboard, 3 wood, 6 PVC, 4 PP, 1 PU, 2 PS) from the input material were recorded.

The composition of the material flow and fluctuations in its composition and throughput rate were determined based on the number of false-color pixels recorded which (with a low material layer thickness) are proportional to the material occupation density (OD) on the conveyor belt. The temporal resolution is 3.7 s. Several moving averages were calculated from these sets of data (e.g. 29.6 s) to assess recorded fluctuations in material composition and throughput rate.

2.2.2. Test series B: Material processing and online monitoring in the Technical Line 4.0

In total, four trials were carried out with MCW. Technical Line 4.0 consisted of the following mobile machines:

Wheel loader: The material was discontinuously fed to the continuously operating processing line via a wheel loader with a shovel having a volume of 3.2 m^3, **Shredder:** Komptech Terminator 5000SD F (cutting gap 4 cm, shaft speed 60% of max. 32 rpm, length of the discharge belt 6 m, speed of the discharge belt 2.5 m/s), **Drum screen:** Komptech Nemus 2700 (sieve drum diameter: 2000 mm, length of the drum: 5500 m, effective sieve area: 30 m^2, active screen surface: 9 m^2, drum speed: max. 23 rpm, used speed 10 rpm, mesh size 80 mm square). During the trials an optimal filling level of 15% was targeted as proposed by Feil et al. (2019, p. 122), **DMFMS:** Komptech prototype consisted of a conveyor belt and the following components: **Mass flow measurement:** integrated weighing belt (speed: 0.5 m/s) scale (Kukla EBW-A-1400 / 6200, +/- 2% in the range of 25 – 100% for throughput rates of 5 – 100 t/h, **Volume flow measurement**: optical belt scale from H-Sensortechnik (laser triangulation). The volume flow is calculated from the determined contour of the scanned material and the belt speed, **VIS Camera:** GoPro Hero 7 Black camera installed for verification of volume flow data.

Following treatment steps consist of different processing machines and sensor systems but are not relevant for the scope of the present investigation. The sensors in the DMFMS were calibrated before each test. The shredder was fed with the wheel loader, targeting the optimal filling level of the drum screen. The shredded material was then transported to the drum sieve with the integrated discharge belt of the shredder. The built-in magnet separator was deactivated for the experimental procedure. The screen overflow > 80 mm was transported to the DMFMS using the integrated discharge conveyor belt of the drum sieve. The underflow of the drum sieve was separately discharged. The conveyor belt of the DMFMS ran at 0.5 m/s.

2.2.3. Test series C: Tests with an SBS-Machine

The experimental setup used in the two test series a) constant feed and b) fluctuant feed consisted of the following machines:

Bunker conveyor: The maximum filling volume was approx. 3 m^3. The discharge speed of the conveyor belt could be continuously adjusted from 0 m/s to 0.5 m/s using a frequency converter. The material was fed to the SBS in all test series a) and b) with an overall throughput of 120 m^3/h, **SBS-Machine:** The SBS-Machine used was a NIR sorting machine with 2800 mm working width and a nozzle distance of 12.5 mm. For the tests, one NIR sensor (out of two) was installed so that the utilized working width was 1400 mm. The speed of the acceleration belt was 3 m/s. The sorting recipe (sorting setting) was set to PET (positive sorting).

Before each sorting experiment, the test material with a defined PET content of 32.3 mass-% was produced by manually mixing a PET-free light fraction (reject material) with the pure PET fraction (eject material).

The overall throughput rate in all tests was approx. 84.7 m^3/h (equating to approx. 2 t/h) per meter working width. The test material was fed constantly to the SBS-Machine via the bunker belt (Test Series C), cf. a) in Fig. 1). The purity and the yield of the eject (PET fraction) were determined by manual sorting after each test run. In total, twelve tests were carried out: Six tests were carried out with a) constant feed, and six tests were performed with b) fluctuant feed. In order to generate a constant material feed, the test material was evenly distributed over the 6 m long bunker belt. The amount of material and the conveyor belt speed were adjusted to a test duration of approx. 60 s (volume throughput: 120 m^3/h, mass throughput: 2.9 t/h). The conveyor belt speed was kept constant (0.1 m/s). The material transfer from the bunker conveyor belt to the acceleration belt on the SBS-Machine was managed with an approx. 50 cm long chute. Due to the material-specific feeding characteristics, particles did not come off the conveyor belt constantly. Thus, by manually breaking up material bulks to a constant particle flow the constant feed was ensured. For the fluctuant feed trials, 0.8 m^3 (19.2 kg) of the material was removed from the pre-mixed test material during each test run and divided into ten equally grand subfractions. The remaining test material (1.2 m^3 or 28.8 kg) was evenly distributed over the 6 m long bunker belt. During the test, the subfractions were manually added into the constant material flow from the bunker conveyor belt in a 6-second interval (cf. Fig. 2), thus creating defined short-term fluctuations. By adapting the filling level of the bunker conveyor belt the same test duration (approx. 60 s) and overall throughput rate ($\dot{V}$ = 120 m^3/h, $\dot{m}$ = 2.9 t/h) were attained as in test series a) despite the defined temporary fluctuations. Due to the reduced filling level of the bunker conveyor belt manual dosing of the input material to create a constant feed was not necessary. The conveyor belt speed was kept constant (0.1 m/s). A total of 6 individual tests was carried out in this test series.

2.2.3.1. Sorting analysis of the output fraction of test series C. The two output flows of the SBS-Machine, eject (PET) and reject (rest), were analyzed. For this, the amount of PET and rest in the eject and reject fraction was mass-specifically determined by manual sorting. The following assessment factors (Feil et al., 2016) for the evaluation of SBS performance in test series C) were used:

$$\text{Recovery } R = \frac{\dot{m}_{Eject}\left[\frac{t}{h}\right]}{\dot{m}_{Input}\left[\frac{t}{h}\right]} * 100\%$$

$$\text{Yield } R_w = \frac{\dot{m}_{Eject}\left[\frac{\mathrm{t}}{\mathrm{h}}\right] * c_{PET\ in\ Eject}\,[\%]}{\dot{m}_{Input}\left[\frac{\mathrm{t}}{\mathrm{h}}\right] * c_{PET\ in\ Input}\,[\%]} * 100\%$$

$$\text{Purity } P_m = \frac{\dot{m}_{PET\ in\ Eject}\left[\frac{\mathrm{t}}{\mathrm{h}}\right]}{\dot{m}_{Rest\ in\ Eject}\left[\frac{\mathrm{t}}{\mathrm{h}}\right] + \dot{m}_{PET\ in\ Eject}\left[\frac{\mathrm{t}}{\mathrm{h}}\right]} * 100\%$$

$$\text{Incorrect particle discharges } Rest_{Eject} = \frac{\dot{m}_{Eject}\left[\frac{t}{h}\right] * c_{Rest\ in\ Eject}\,[\%]}{\dot{m}_{Input}\left[\frac{t}{h}\right] * c_{Rest\ in\ Input}\,[\%]} * 100\%$$

c_{PET}...concentration of PET; c_{REST}...concentration of Rest

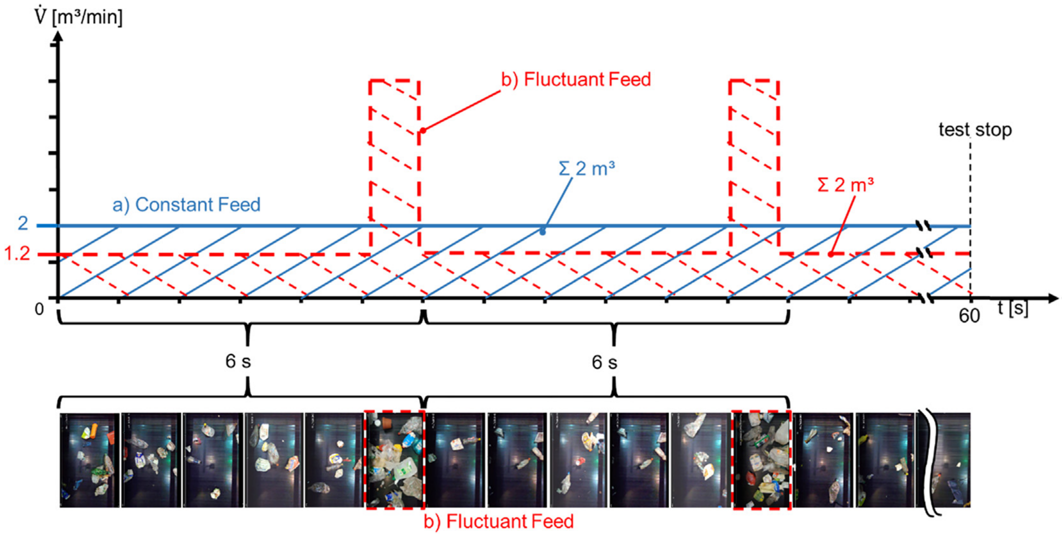

Fig. 2. Scheme of the tests with the SBS-Machine. Generation of volume and mass flow fluctuations by manually adding a defined volume (80 L) of test material in a defined time interval (6 s). Quantitative representation of the volume flows for a) constant feed and b) fluctuant feed. The marked frames display the throughput maxima in the fluctuant feed.

3. Results and discussion

The findings of the investigations conducted for this manuscript are divided in accordance with the presented test series.

3.1. Test series A: Material processing and online monitoring in a waste treatment plant

To quantify fluctuations regarding the throughput-rate, the time-resolved material independent occupation density is displayed in Fig. 3 for a 25-minute time interval. By utilization of moving averages, the occurring fluctuations are displayed (cf. Fig. 3).

To some extent, significant fluctuations were recorded at varying time intervals. Based on the results presented in Fig. 3, authors propose to distinguish between concise brief changes in occupation density (moving average of 3.7 s intervals) and overlaying longer-lasting fluctuations (moving average of 29.6 s intervals). In this manuscript, the former is considered as short- and the latter as mid-term fluctuations. Accordingly, authors propose the definition of short-term fluctuations as throughput changes that occur in intervals < 15 s, while mid-term fluctuations are in the range of 15–600 s and long-term fluctuations are in the range > 600 s. The short-term fluctuations are caused by the varying discharge of material from up-stream processing machinery (shredder or screen) based on the rotation speed of the shaft of a shredder or the drum of a drum-screen. Mid-term fluctuations are resulting from the discontinuous feed of the continuously operating processing line. Lastly, the long-term fluctuations are the throughput variations that occur due to plant breakdown or changes in the cutting gap of a shredder.

This type of assessment, based on the differentiation of short-, mid- and long-term fluctuations, allows the distinction of fluctuations by means of their temporal expansion. This is particularly relevant as the performance of different downstream processing machines may be affected differently, depending on the type of fluctuation occuring. Additionally, the potential of various processing machines to smoothen different types of fluctuations indicates that a distinction of short-, mid-, and long-term fluctuations might entail advantages to the concept introduced by Feil and Pretz (2018), using the quotient of the 90% and 10% quantiles for the assessment of fluctuations (cf. Fig. 3). The assessment of the four-time intervals displayed in Fig. 3 based on this procedure leads to Q90/Q10-ratios between 3.39 and 4.58. However, this does not generate any information on the type of fluctuations (short-mid-, or long-term) that persist in the given time intervals.

The benefit of the chosen approach can be illustrated in Fig. 4, which shows the time-resolved deviation of short- and mid-term fluctuations. The displayed data is generated on the basis of deviation from the next larger moving average, for short term fluctuations the deviation of the 3.7 s moving average is calculated from the 29.6 s moving average. For mid-term fluctuations, the deviation of the 29.6 s moving average is calculated from the overall average. This calculation is relevant since in practice plants are usually designed for an average material throughput whereby some aggregates are selected larger in order to be able to process larger amounts of material.

The temporal course of deviations (Fig. 4) can be divided into the same four time intervals as in Fig. 3. Comparatively low average interval deviations were recorded for the first and third interval (2.42% and 1.80%), while relatively high average interval deviations were recorded for the second and fourth interval (4.16% and 6.55%). When this assessment of the time intervals is compared to the evaluation based on quantiles, more distinct differentiation is apparent based on the proposed method, enabling the assessment of the fluctuations as short-term. The approach introduced by Feil and Pretz (2018) bears the advantage of excluding outliers. While the advantage of this approach is that the overall evaluation of the throughput fluctuations is more reliable, the relevance of extreme throughput peak values for certain machines is neglected. It can be noted that the low short-term deviations occurred at relatively low throughput rates while the high short-term deviations occurred at high throughput rates (see Fig. 3 and Fig. 4). Mid-term fluctuations can be led back to the discontinuous feed of the waste treatment plant using a wheel loader as exemplary displayed in Fig. 5.

The vertical lines mark the points in time at which the wheel loader fed the pre-shredder of the waste processing plant. The length of the horizontal arrows complies with the transportation time of material after discharge from the shredder to the measurement point (DMFMS) in the plant. This transportation time was

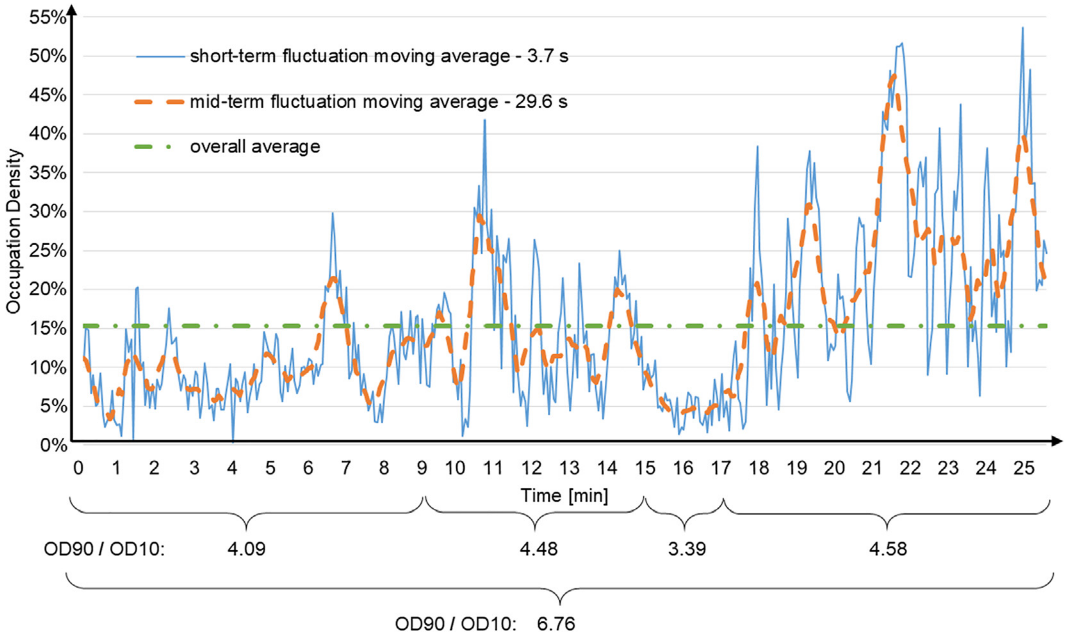

Fig. 3. Time-resolved occupation density (OD), on a conveyor belt with 1 m/s transport speed, and assessment of the fluctuation intensity (OD90/OD10). OD90 = 90%-Quantile of OD, OD10 = 10%-Quantile of OD.

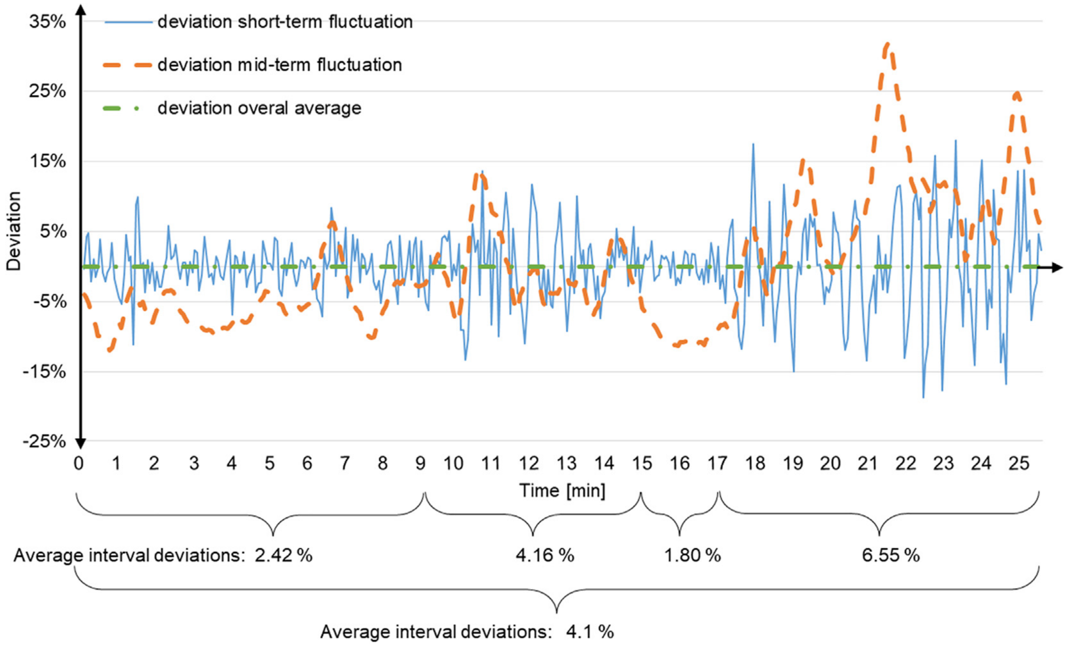

Fig. 4. Time-resolved deviation of short- and mid-term fluctuations; **average interval deviations** are given for **short-term fluctuations** only.

measured on-site, allowing for the conducted correlations. As the residence time of waste in the shredder, screens, etc. is dependent on waste characteristics (particle size, elasticity, brittleness, agglomeration, etc.) (Pretz and Feil, 2015), the time between feeding the shredder to the arrival of the material at the measurement point can vary, but it amounts in these tests to at least 135 s. Accordingly, the colour-marked areas attached to the arrowheads in Fig. 5 cover the time in which material from the respective feeding process reached the measurement point. The extent and width of peaks are expected to be dependent on the waste characteristics: A load of waste that is discharged evenly over a broader time period results in a peak with low extent but large width, while a load that is shredded comparatively fast creates a high peak (extent) that is rather narrow.

Additionally, material-specific fluctuations were recorded with the HIS NIR camera. Fig. 6 displays the detected material occupation density at the measurement point of the DMFMS.

It can be seen that the material composition changes strongly. During the first 10 min, plastics make up approx. 32.4% of the detected material pixels. Subsequently, the share of detected plastics is reduced to 7.6% (time interval 10–17 min) and finally to 1.5% on average for the time interval 17–25 min. The detected share of unknown pixels also decreases from 16.8% to 5.6% and 2.6% respectively. This correlation between detected plastic pixels

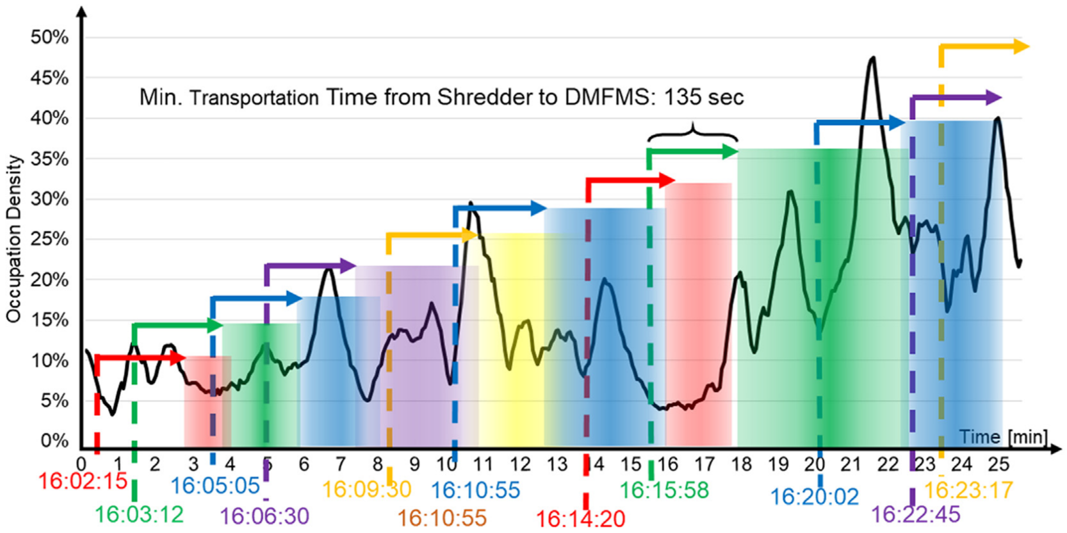

Fig. 5. Time-resolved correlations between mid-term fluctuations and feed pattern of the wheel loader (29.6 s moving average).

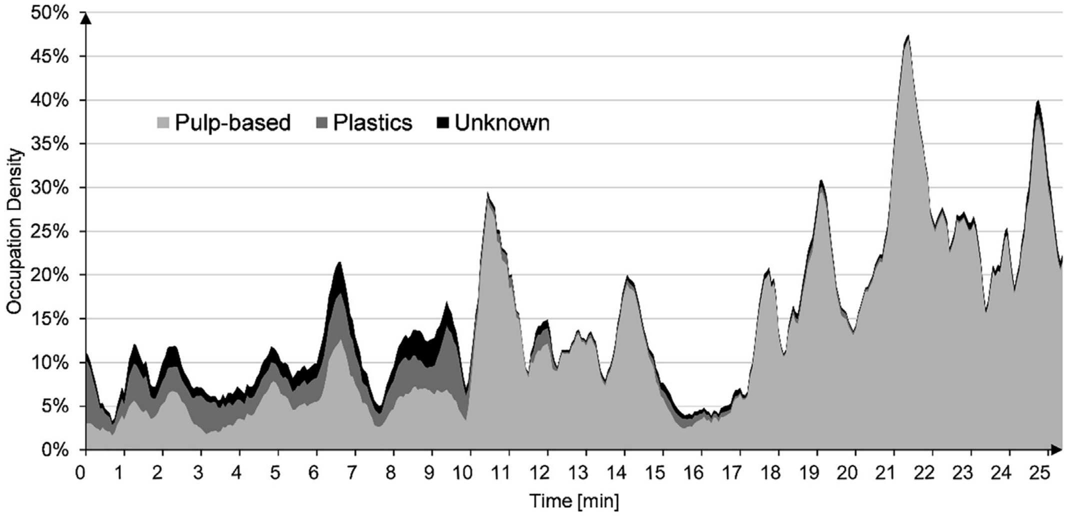

Fig. 6. Time-resolved course of the detected material-specific occupation density on the conveyor belt (29.6 s moving average) for the chosen exemplary time segment of 25 min.

and unknown pixels indicates that mostly plastics generate unknown pixels. This could be led back to edge effects on plastic particles as indicated by Küppers et al. (2019). With decreasing plastics share the throughput rate (high peaks) increases. These observations result from the change of the feeding material. Paper (partly paper rolls with a diameter > 70 cm) from industrial residues was fed to the monitored processing plant. Overall, this waste was shredded faster than the rather mixed input material. The paper rolls that were found in the input repeatedly lead to the variations in throughput rate as the behavior of these massive objects in the shredder was noticeable: Often, at the beginning of the shredding process, only small pieces of these objects were removed from the paper rolls. This reduced the rigidity of the paper rolls, thus, accelerating the shredding process within a short time.

The gathered information displays fluctuations regarding the throughput rate and waste stream composition. However, the correctness of the recorded data is subject to several conditions. Since only areal information can be used for the assessment of the throughput rate, it is reasonable to assume that especially at high material layer thickness the accuracy of the tested system decreases since no height information is recorded. On the other hand, the mass related throughput rate might be better predictable than only on basis of volumetric information, as the (bulk) density of different materials varies severely and material-specific correction factors could be given to different material types on basis of the NIR classification. This benefit only applies if relatively a low material layer thickness can be realised at the measurement point. The recording of material-specific fluctuations allowed quantitative assertions concerning the waste stream composition. Depending on the average grammage (mass per unit area) of the material types that shall be distinguished correction factors should be applied. Authors presume that the correctness of this quantitative analysis is not only highly dependent on the correction factors but also on the classification recipe used for the distinction of materials. For instance, one might only want to distinguish plastics from pulp-based materials but the grammages of plastics and the grammages of wood and paper might differ tremendously, which is why such materials should also be distinguished even though this might not be necessary for the actual application.

3.2. Test series B: Material processing and online monitoring in the Technical Line 4.0

Conclusions that are more precise can be drawn from the trials with the Technical Line 4.0 as this experimental setup allowed for direct insights into the running machinery. The supplied test material (mixed commercial waste) was heterogeneous and contained a wide range of different materials which is characteristic according to Feil and Pretz (2018), Khodier et al. (2020), and Weissenbach and Sarc (2019). The wide variety of materials showed different shredding (selective shredding) and conveying behaviors (Schönert, 2002), resulting in the short- and mid-term fluctuations, displayed in Fig. 7.

In general, fluctuations in both, volume and mass flow, were recorded. Temporal deviations between both graphs can be attributed to the variations in bulk density of the processed waste. Selected examples of mid-term fluctuations are highlighted with short and long dumbbell-shaped markings in Fig. 7. The mid-term fluctuations that can be led back to the discontinuous feed with the wheel loader are tagged with the short markings (time interval of 1.5–2.5 min), while larger mid-term fluctuations are tagged with long markings representing time intervals of 2.5 to 7 min. The latter formed because the output boxes of the Technical Line 4.0 had to be emptied to allow for the ongoing of the waste processing. Accordingly, in such cases, the shredder could not be fed as regularly as usually (feed interval of approx. 1.5–2.5 min), resulting in brief drops of the throughput that were more pronounced (e.g. at minutes 40 and 46). Mid-term fluctuations of the material shown in Fig. 7 are expected to be typical for waste treatment plants in which the shredder is fed directly with the wheel loader that is also used to manipulate other material flows and therefore larger gaps arise in the feed. The recorded short- and mid-term fluctuations derived from various causes that could be observed during the trials are shown in the next subsections.

3.2.1. Braid formation

Repeatedly large foils, tapes and wires formed braids (2–5 m long) due to the rotating movement of the drum screen (see the height of the volume-flow peak with approx. 400 m^3/h in Fig. 7). These braids generated high short-term volume peaks at irregular time intervals, potentially leading to down-stream blockages as discussed in Kaufeld et al. (2017). Improved shredding (cutting system, integrated screen) can prevent the output of large foils from the shredder and subsequently prevent braid formation. Regular maintenance intervals of the shredder knives and a narrow setting of the cutting gap ensure that the shredding efficiency increases, thus less coarse foils but also long wires get into the shredder output. Iron separation, directly after the pre-shredder, can remove part of the long iron wires (bale wire) and is considered as state of the art. As this is an issue with drum screens in particular, the use of linear vibrating screens poses an option to reduce this risk with wastes, prone to braid formation according to plant operators.

3.2.2. Bridging

Bulky goods (e.g. long boards, pipes, large hollow bodies, etc.) and materials that can become entangled formed bridges in the feeding hopper of the shredder, impeding the shredding process. The evaluation of the measurement and video data show that this creates short- to mid-term fluctuations. With the automated feed (dosing bunker) of a shredder that is controlled based on the filling level in its feed hopper, this can, in extreme cases, lead to completely collapsing of the throughput. A combination of volume flow data and machine data can help identify material bridges and initiate countermeasures. The operating state with which bridging can be identified would be the following: the rotor runs at normal speed, the feed hopper is full and the volume flow is significantly reduced. Manipulation of the material in the hopper with the wheel loader shovel allowed the waste to be pulled in by the shredding tools or caused the bridges to collapse (according to plant operators).

3.2.3. Type of material and shape of objects

The type of material and the shape of individual objects also have a significant impact on their shredding behavior (Fig. 6), as evidenced by the evaluation of the video files. It could be observed that round, three-dimensionally stable objects are very difficult to feed into the cutting unit of the utilized shredders (e.g. large paper

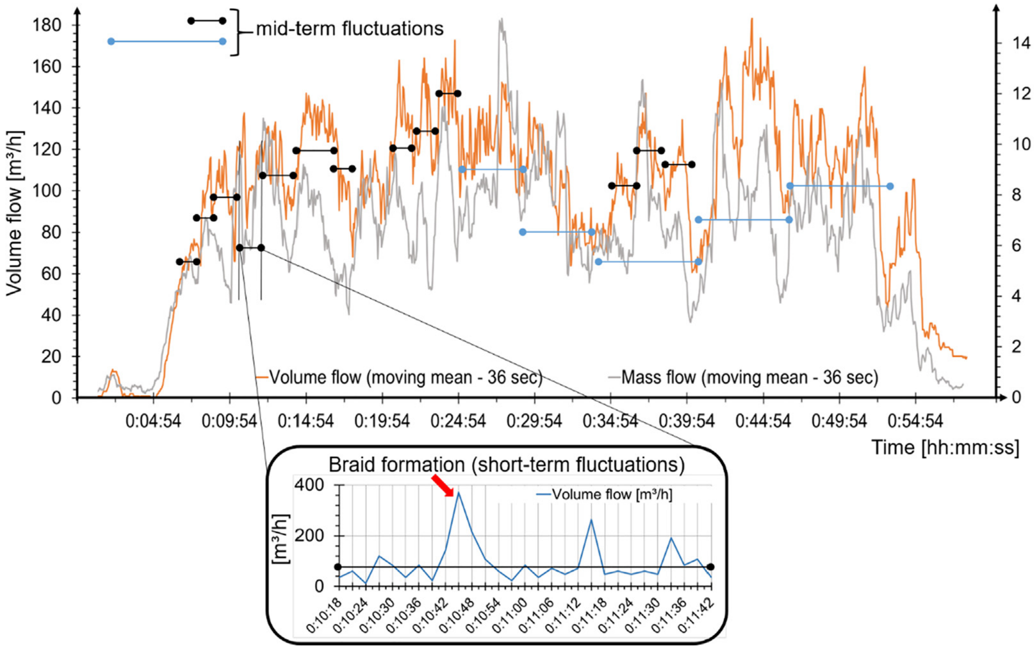

Fig. 7. Time-resolved volume and mass flow analysis of the Technical Line 4.0.

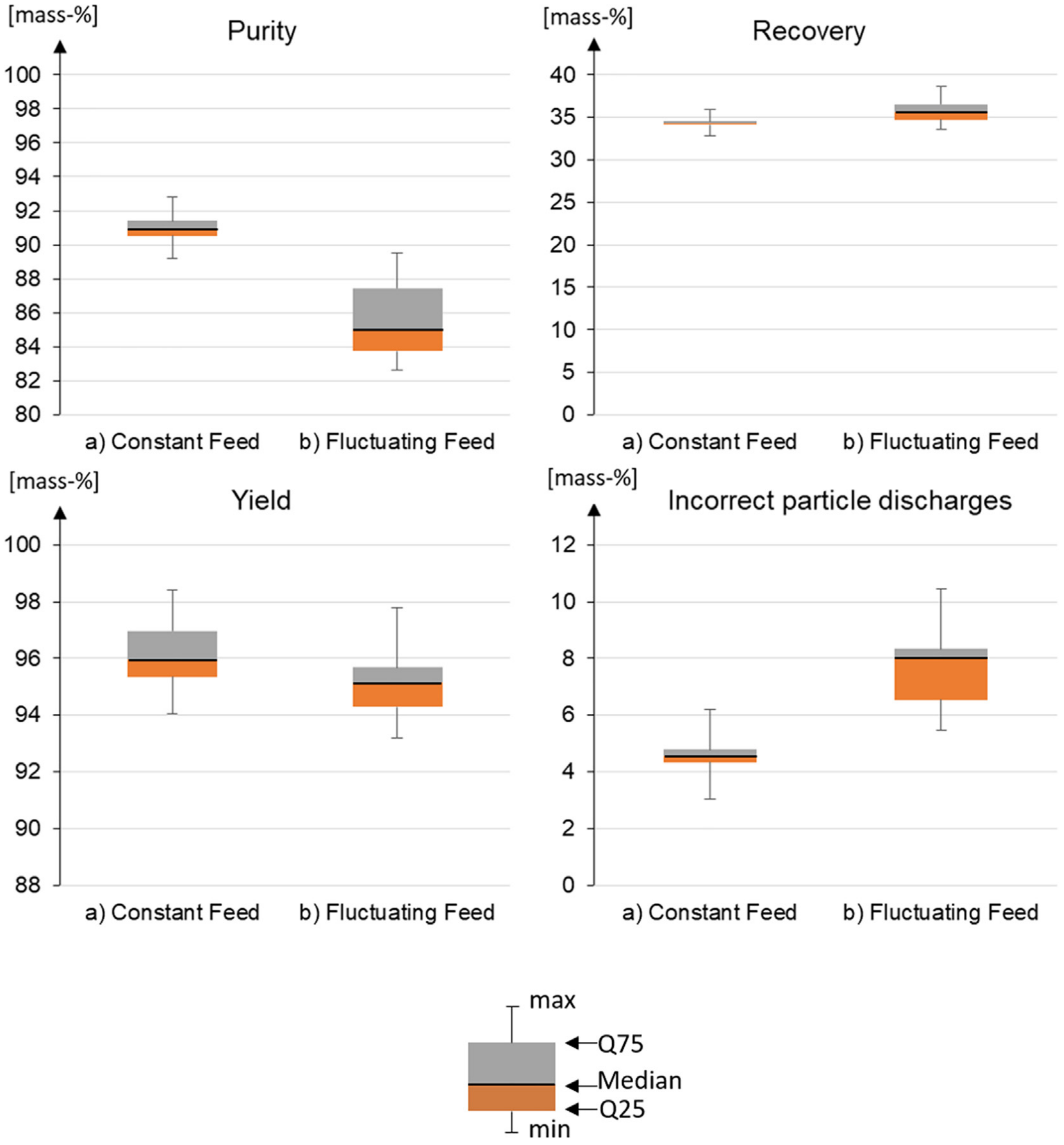

Fig. 8. Impact of constant (test series a)) and fluctuating feed (test series b)) on SBS performance on basis of purity, recovery, yield, and incorrect particle discharges.

rolls, 220 L plastic drums). This effect was most pronounced when the feed hopper was almost empty. Mixing with other material can help here as observed from the video recordings. Impurities like massive / thick-walled objects (e.g. engine blocks, crankshafts, stones) are difficult or impossible to shred and can lead to several reversing processes, which can lead to fluctuating material discharge (mid-term fluctuations) or complete machine stoppages (according to plant operators).

3.2.4. Shredder configuration

The shredder settings such as reversing intervals and shaft speed (shredder speed), cutting tool geometry, cutting gap, etc. can alter volume-flow fluctuations. Depending on the selected shredder and shredding program, reversing processes run automatically at defined time intervals. This results in regular fluctuations in the volume flow in addition to reversing processes at irregular intervals whenever impurities clog the cutting unit. Long-term (in the range of > 600 s or longer) fluctuations arise, for example, when machine parameters change, e.g. regarding cutting gap or shaft speed. No such fluctuations were observed since all shredder settings were kept constant.

3.2.5. Machine specific discontinuous material discharge

The integrated screw conveyor in the sieve drum caused a discontinuous discharge of material (confirmed by volumetric and visual data) in six-second intervals (short-term fluctuations) and corresponds to the duration of one revolution of the drum.

3.2.6. Feeding process

The markings in Fig. 7 label time intervals of approx. 2 min (short markings) and approx. 6 min (long markings) which can be led back to the feeding pattern of the wheel loader used for the displayed trial and comply with the concept of mid-term fluctuations. The ~ 2 min time intervals resulting from the discontinuous "normal" feeding process, as established in test series A). The ~ 6 -minute time intervals resulted from the fact that the wheel loader was used in addition to feeding to manipulate the generated material flows of the test facility. Such fluctuations can persist throughout the entire process chain. The automation of the system feed (e.g. controllable dosing bunker), better training of the wheel loader drivers, provision of technical aids (guided loading), and the selection of optimal shredding technology can help minimize these fluctuations (Feil et al., 2019). The tests with the Technical Line 4.0 confirmed the established assumptions and indications concerning short- and mid-term fluctuations from test series A). Short-term fluctuations resulted from material (waste composition, particle size, etc.) and machine (drum screen speed, reversing intervals of shredder, etc.) specific characteristics, while mid-term fluctuations originated from the discontinuous feeding process with the utilized wheel loader.

3.3. Test series C: Tests with an SBS-Machine

Data from test series C) can be used to quantify the relevance of fluctuations for the performance of a processing chain. The results in Fig. 8 shown as a box-whiskers diagram with median, 75% quartile (Q75), 25% quartile (Q25), min and max values demonstrate this with regard to the sorting performance of an SBS-Machine, being affected by realistic fluctuations (six-second intervals) resulting from an up-stream drum screen, in comparison to a steady throughput rate.

In the tests with constant feed, the purity of the PET fraction (recyclable material fraction) with a median of 90.9 mass-% was approx. 6 mass-% higher than in the tests with fluctuant feed (purity of 85.1 mass-%). The median yield at a constant feed was 96.0% and at a fluctuating feed, it was 95.1 mass-%. This indicates that the sorting recipe was adjusted to maximise the yield of the product fraction (in this case the PET fraction). In the tests with constant feed, the median for the incorrect discharges was 4.6%, well below the values for the fluctuant feed with 8.0 mass-%. This increase of ejected non-PET particles into the product fraction PET at fluctuant feed can be attributed to the temporary higher occupation densities on the acceleration belt. This resulted in more overlapping particles and consequently in misclassification of particles from the rest fraction which leads to the decreased purity at increasing occupation density (Küppers et al., 2020), as the focus of the sorting recipe was set to yield and not purity. The increase in incorrectly discharged particles results in a slight ascent of the recovery for this sorting stage at a fluctuant feed.

To ensure the significance of the described observations, inference tests were performed on the experimental data. As the standard tests for doing so require normality of the data, in a first step, each set of measurements (e.g. the 6 purity-values for the constant feed) were tested on normality, using the Shapiro-Wilk test (Shapiro and Wilk, 1965) with the “shapiro.test()” function in R. The tests proved the normality of all measurement sets, with p-values ranging from 0.18 to 0.94.

The tests on equality of the arithmetic means were performed, using the Welch-two-sample-*t*-test (Welch, 1947), which – in contrast to the standard two-sample-*t*-test does not require homoscedasticity. This is desirable, to avoid having to prove homoscedasticity from only six measurements per data set.

The tests showed significant differences ($p < 0.05$) for all values but the yield, which still shows a p-value of 0.065. Considering the resulting confidence intervals of the differences, constant feed leads to higher purity, lower recovery and lower incorrect particle discharches, potentially equal but more likely higher Yield (with a 95% confidence interval from −0.1% to + 3%). The values of the tests are shown in Table 1 in the appendix A, supplementary material. The p-values and 95% confidence limits are shown in Table 2 in the appendix A., supplementary material.

In sorting systems, fluctuations can massively deteriorate the quality of the machine-made plastic concentrates. The purity of PET transparent (after the first SBS sorting stage) in a modern austrian sorting-plant is approx. 95%. In order to achieve the required (in Austria) 98% purity (Rundgehts, 2020) of this valuable material, impurities must be removed in additional sensor-based sorting stages or manually. In recent years, great progress has been made in robotics technology for sorting as well as for quality assurance (Sarc et al., 2019a). A prerequisite for this is material flow monitoring and corresponding actuators (e.g. dosing bunker, control of the conveyor belt speeds, etc.). Waste treatment plants are usually built oversized in order to be able to process load peaks in the material flow to some extent. If it is possible to generate a constant material flow in these waste treatment plants, they could be of smaller dimension and more efficient.

4. Conclusion

Waste treatment plants are subject to fluctuations of volume and mass flow and material composition. The obtained data from the test series indicates that differentiation between short-term and mid-term fluctuations and the assignment to the causes (e.g. braid formation, bridging, impurities, machine-specific discontinuous material discharge, discontinuous feed) can be made. These fluctuations can run through the entire waste treatment plant and have a negative impact on all processing stages, e.g. SBS-Machines. In the tests, carried out with a model mixture, the manually generated fluctuations caused a significant drop in product purity of approx. 6 mass-%, while the yield was barely affected. Some causes could be reduced by technical aids like guided loading, implemented by means of instructions to the wheel loader driver (Feil et al., 2019) or automatic material hopper. The authors propose to distinguish between concise brief changes in occupation density (here: moving average of 3.7 s intervals) and overlaying longer-lasting fluctuations (here: moving average of 29.6 s intervals) and calculation of the average deviation for a certain time interval from the next larger moving average, e.g. for short term fluctuations the deviation of the 3.7 s moving average is calculated from the 29.6 s moving average. This method of assessment of the time intervals leads to a clearer differentiation and can have advantages over the concept introduced by Feil and Pretz (2018) (the quotient of the 90% and 10% quantiles).

The combination of online and ontime material flow monitoring system with processing machine surveillance (shredder parameters like applied motor torque, shaft speed, etc.), both equipped with data collection and management as well as intelligent interconnection tools, could enhance this approach furthermore and actively contribute to the development of the so-called smart waste factory solutions for the waste treatment branch. The experiments described in this paper and the results presented come from the first practical investigations. Further validation will require large-scale tests which will run over a longer period of time. These tests will be presented in a further article.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2020.10.037.

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4.2.3 Publication 4

Wet-mechanical processing of a plastic-rich 2D-fraction from Mixed Wastes for chemical recycling

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WET-MECHANICAL PROCESSING OF A PLASTIC-RICH 2D-FRACTION FROM MIXED WASTES FOR CHEMICAL RECYCLING

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Abstract
The recycling of source separated polyolefins (PO) (e.g., light weight packaging waste is already state of the art. Therefore, further plastic materials contained in mixed wastes have become more important due to increasing legal pressure. Mixed commercial and municipal solid wastes contain large amounts of POs. These mixed wastes would usually be treated in waste incinerators or processed to Refused Derived Fuel for cement plants. Large-scale experiments were conducted to assess the potential of such POs from these waste streams for recycling processes. The potential and applicability of a dry- and subsequently wet-mechanical processing with the aim of generating a PO concentrate for chemical recycling purposes was assessed. These investigations' focus was put on the centrifugal force separator technology as the core element of wet-mechanical processing. In addition to the input material, all output materials and process water streams were chemically and physically characterized to estimate potential treatment or recycling paths. Results demonstrate that a two-stage purification is necessary to produce POs with sufficient purity out of both wastes. Chlorine and heavy metal levels are simultaneously reduced. The increased amount of impurities only slightly changes the density of the process waters. Process water analyses show that wastewater treatment is necessary before discharge into receiving water or sewage treatment plant. The sediment does not fulfill any hazard-relevant properties, and different thermal treatment options are possible.

Keywords
Wet-mechanical processing, polyolefin recycling, mixed commercial waste, mixed municipal waste, Circular Economy, centrifugal force separator

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Introduction

In 2018, 359 million tonnes of plastic were produced worldwide – 61.8 million tonnes in Europe (EU28+NO/CH) (PlasticsEurope 2020). The total European plastics converters demand was about 51.5 million tonnes in 2018 (PlasticsEurope 2020). The majority (approx. 40%) was used in the packaging sector and 19.8% (PlasticsEurope 2020) in the building and construction sector. The plastic demand distribution by plastic type from 2018 shows that mostly (39%) polyolefins – POs – (polypropylene-PP and polyethylene-PE) (PlasticsEurope 2020) were used. These are also the plastics that are mainly used in the packaging sector and after PVC also in the building and construction sector. POs are therefore of great interest to the recycling economy of plastics. Plastic products differ significantly in their life cycles. Some products have a life span of less than one year (some even hours or days), while others have more than 15 years, and some have a life span of 50 years or more (cf. plastics in the construction sector). This is one reason why the quantities of collected plastic waste differ from the current year's plastics demand (PlasticsEurope 2020).

In 2018, 29.1 Mt plastic post-consumer waste was collected in the EU, which ended up in three waste management paths (PlasticsEurope 2020):

1. Landfilling: 24.9% were still landfilled throughout Europe,
2. Energy recovery: 42.6% were used as SRF (solid recovered fuel) for energy recovery and
3. Recycling: 32.5% (81% within the EU) were recycled.

The focus of waste management in Austria is currently shifting incineration to recycling (Pomberger et al. 2017). Currently, most plastics present in mixed wastes like commercial (MCW) and municipal solid waste (MMW) end up in energy recovery and are irrevocably lost for recycling (Bauer 2013). According to EU (2018), municipal solid

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waste recycling rates of 65% are to be achieved by 2035. There is no attempt made by the EU to introduce recycling rates for (mixed) commercial waste. Future recycling targets can be achieved by recycling plastics present in waste streams currently used for energy recovery. First of all, the plastics are sorted out from the mixed wastes in a material recovery facility (MRF). Then the sorted plastics are transported to a plastics recovery facility (PRF). In the MRF, different recyclable materials (e.g., paper, cardboard, metals, plastics) are separated dry-mechanically from the mixed waste stream. Aggregates such as screens for grain size separation, ballistic separators for separation by shape, magnetic and eddy current separators for metal removal, and NIR-sorters for sorting plastic types are used for this purpose. In PRF, after size reduction, additional sorting steps like air classification, metal removal, hot washing, sink/float separation, optical, and NIR-sorters are used for the enrichment of pure plastic types, often separated by colour (Feil & Pretz 2020).

There are various recovery and recycling options for plastic waste with different quality requirements on the input material:

Mechanical recycling of waste plastics: This is the most common method for the recycling of plastic waste (Ignatyev et al. 2014, Feil & Pretz 2020, Ragaert et al. 2017, Soto et al. 2018). In mechanical recycling, the chemical structure (macromolecules) remains unchanged, and only mechanical/physical treatment is utilized to process recycled plastics. Mechanical recycling is mainly used if large quantities of a single type of material are available. Quality criteria for recycled plastics for the final plastic processing companies are not standardised but defined individually by the recycling and processing companies. Criteria include, e.g., exceptionally pure colour, low content of contaminations (EU 2006, Friedrich et al. 2019, Vilaplana & Karlsson 2008) but also foreign matters like fillers, which also has a tremendous influence on the purity of recycled plastics (Thoden van Velzen et al. 2017, Brouwer et al. 2018). Of particular importance for mechanical recycling are contaminants (e.g., heavy metals) in the input material. Depending on the product, these are only permitted in minimal quantities (Friedrich et al., 2019). For this reason, the removal of impurities and pollutants must be carried out as far as possible in pre-treatment.

Chemical or feedstock recycling (Bauer et al. 2013, Ignatyev et al. 2014, Nomura S. 2020, Pohjakallio & Vuorinen 2020, Ragaert et al. 2017, Soto et al. 2018): This type of recycling has a high potential for heterogeneous and contaminated plastic waste material if more intensive separation and processing than in case of mechanical recycling is neither economically nor technically feasible. A dry-mechanical pre-treatment of input materials is also necessary for chemical recycling. In chemical recycling, the polymer chains are split (e.g., through the use of heat), whereby monomers or petrochemical raw materials such as oils and gases are obtained, e.g., in a conventional crude oil refinery (Bauer et al., 2013). These can be used to produce new plastics or for other petrochemical purposes. Other important processes are pyrolysis, hydrogenation, gasification, and substitute reducing agents in the blast furnace process. The strict quality requirements for the input material are shown below in Table 1, for example, for thermochemical conversion (ReOil-process) (Lechleitner et al. 2019) and the use as a reducing agent in the blast furnace process (Nomura 2020).

Waste pre-processing for subsequent treatment plants or thermal recycling is carried out dry-mechanically. There are several different types of plants for this purpose. Depending on the input material and the treatment target, different combinations of aggregates are used in the plants. The subsequent mechanical recycling of the plastics discharged in these plants almost always involves wet-mechanical processing for material refinement and sometimes also for chemical recycling. Most wet-mechanical aggregates separate a light and a heavy fraction depending on the separation medium's density used so-called sink-float separators (e.g., gravity separator, sorting cyclone, sorting centrifuge). Bauer et al. (2018) give a good overview of the most common wet-mechanical processes and their advantages and disadvantages. Due to the advantages compared to other wet-mechanical aggregates (e.g., very high forces in the centrifugal force field, negligible influence of the particle shape, no rotating, wear-prone machine elements, simple plant design, small space required, surface purification resulting from increased shear forces between particles and liquid ring, insensitive to input material quality and mass flow, low operating costs (Bauer et al. 2018)), a centrifugal force separator (a pilot-scale plant) was selected for these investigations. This separation principle with water as separation medium is ideal for separating polyolefins from other plastics because of their lower density (PE: 0.87- 0.97 g cm^{-3}; PP: 0,895 and 0,92 g cm^{-3}) (Koltzenburg et al. 2014). Also, in the process, fine material, organic and inorganic adhesions are washed off. These impurities could, if the removal is insufficient, cause damages in the follow-up processes. Inorganic impurities can be abrasive, and harm conveyor systems and processing units (e.g., extruders), and organic impurities can lead to an exceedance of tolerance levels, e.g., ReOil-process (see Table 1) or corrosion (e.g., through PVC) of plant components. Organic and inorganic impurities can also negatively affect the quality of the output material produced (e.g., reduction in material properties).

This paper investigates the applicability of the wet-mechanical centrifugal force separator (CFS) process to highly mixed and contaminated dry-mechanically pre-processed waste fractions (MCW and MMW), which would generally be used as SRF in cement plants or incinerators for thermal recovery. The aim of the investigations is the separation of a polyolefin fraction from the two investigated mixed wastes by applying the CFS and the evaluation of its quality parameters to estimate its suitability for a chemical recycling process - the ReOil process. It will be determined whether a single-stage treatment is sufficient or whether a second treatment stage, i.e., simulation of a cascade connection of two CFSs through two runs, is necessary since wet-mechanical treatment processes also generate residual materials such as heavy fractions, sediments and also process water. The quantities of these materials for the investigated input materials are determined, and detailed chemical analyses are carried out to estimate potential treatment or recycling paths.

Materials and Methods

Materials

The materials used for the investigations in the present manuscript were pre-treated MCW and MMW from Austria (Upper Styria and Graz). Figure 1A (MCW) and B (MMW) shows the original, untreated wastes collected in October and November 2019. The mechanical pre-treatment of both wastes resulted in plastic-rich 2D-fractions (Figure 1C (MCW) and D (MMW)), which are the investigation material for this work.

Table 1. Quality requirements for plastic waste input for two different chemical recovery processes (Note: DM – dry matter).

Parameter	**ReOil-Process** (Bauer 2013)	**Substitute reduction agent** (Kieberger 2019)
Particle size [mm]	<30-40	granules: 5-10
Bulk density [kg m^{-3}]$_{DM}$	50-100 (mainly 2D-objects)	300 (exclusively 3D-objects)
Moisture content [%]	<20	1.5
Calorific value [MJ kg^{-1}]$_{DM}$	>30	33-35
Halogen content	Cl: <2%$_{DM}$	Cl: ≤1%$_{DM}$; Br: ≤250 mg/kg$_{DM}$
PP, PE, and PS content [%]	>90	-
Polymer impurities [%]$_{DM}$	PET: ≤3; PVC: ≤2	
Inorganic contaminants [%]$_{DM}$	≤3	-
Organic contaminants [%]$_{DM}$	≤5	-
Heavy metals [mg kg^{-1}] $_{DM}$	-	Zinc, chrome, nickel: ≤500, Copper: ≤1,000 Lead: ≤125 Mercury: ≤0.5 Cadmium: ≤7.5 Antimony: ≤250
Sulphur [%]$_{DM}$	-	≤0.5
Other elements [mg kg^{-1}]$_{DM}$	-	Arsenic: ≤5 Bromine: ≤250 Aluminum: ≤0.5

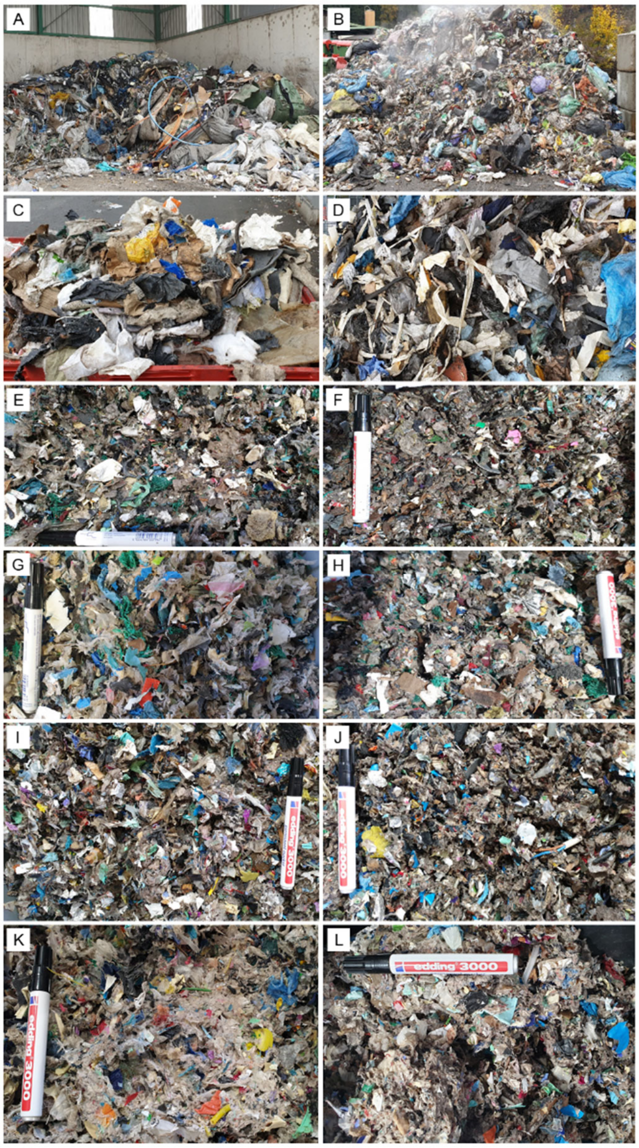

Figure 1. Exemplary photos of the input, intermediate, and output materials: **A**: MCW original waste; **B**: MMW original waste; **C**: plastic rich 2D-fraction from MCW; **D**: plastic rich 2D-fraction from MMW; **E**: light fraction (LF) of the first run (I) from MCW; **F**: heavy fraction (HF) of the first run (I) from MCW; **G**: LF II from MCW; **H**: HF II from MCW; **I**: LF I from MMW; **J**: HF I from MMW; **K**: LF I from MMW; **L**: HF II from MMW.

Exemplary photos of the generated output materials (light and heavy fractions) after the first and second wet-mechanical processing stage are shown in Figure 1 E-H for MCW and in Figure 1 I-L for MMW.

Methods

In this section, the experimental and analytical procedures are described. Figure 2 shows the material flow of MCW and MMW from the dry- to the wet-mechanical processing line. The sampling points for all output fractions are also shown, including chemical analysis.

Dry-mechanical treatment

For the investigations, a dry-mechanical process line with large-scale mobile machines was set up in the open area of a test site, consisting of the following machines and components: Wheel loader, shredder, drum screen, and a ballistic separator. The detailed methodology, machine settings, and the sampling procedure are described in Möllnitz et al. (2021). Only the 2D-samples from the experiments with drum screening before the ballistic separator were used for further investigations. Samples of both 2D-fractions (MCW_2D and MMW_2D) were manually sorted into nine fractions to determine the composition (see Figure 2).

As the requirement for the input material for the investigations with the centrifugal force separator (CFS) was a particle size smaller than 20 mm, the reunited samples after sorting were shredded decoupled from the dry-mechanical treatment line. A single shaft shredder (ANTARES 1600) from Lindner-Recyclingtech GmbH, Austria, was used. The shredded material was transported to the CFS pilot plant for further wet-mechanical treatment.

Wet-mechanical treatment

The shredded 2D-fractions (MCW_2D and MMW_2D) from the pre-treated wastes were fed into a wet-mechanical treatment plant utilizing a

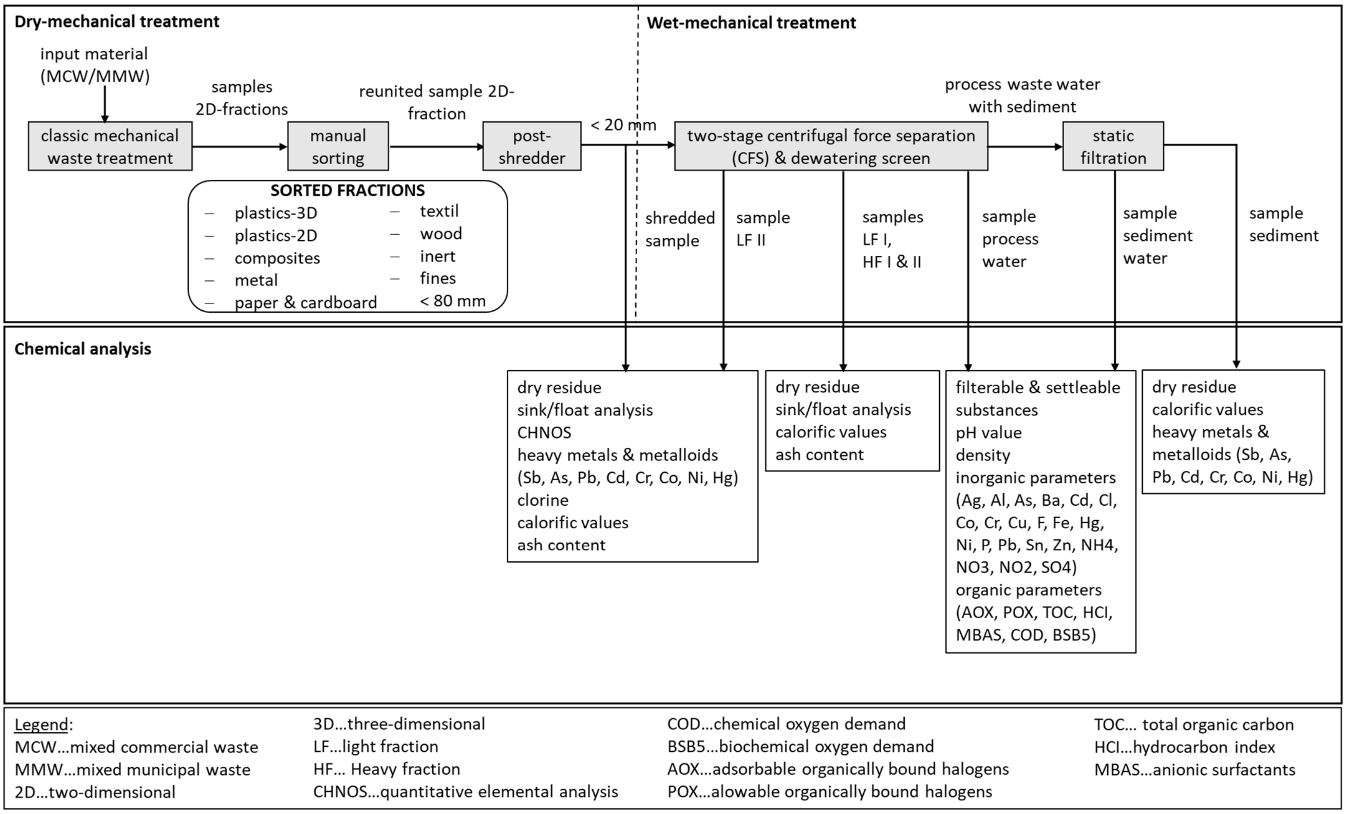

Figure 2. Flowchart for dry- and wet-mechanical treatment methodology with sampling points and chemical analysis.

CFS for further concentration of a PO-fraction with simultaneous removal of impurities (e.g., paper and textiles) and contaminants (e.g., organic and inorganic adhesions). The CFS-process in detail is shown in Figure 3. The feed amounts and test durations for all test runs are shown in Table 2.

The material was mashed with water before feeding. Pre-moistening and wetting of the particles to be separated in advance ensure greater selectivity. The particles can overcome the surface tension of the water more easily and, therefore, more quickly enter the separating zone, the water vortex of the CFS. Besides, certain impurities such as paper or wood absorb water and are thus more likely to be discharged into the heavy fraction. As a result, the probability of a faulty discharge is significantly reduced. The wet material was then conveyed from the feed chute into the feed hopper using a spiral conveyor. At the lower end of the slightly inclined CFS, the separation medium (water for these experiments) is injected tangentially, resulting in the formation of a fluid vortex with an air core in the separator. The feed material to be separated is fed directly into the vortex at the separator's upper end. To avoid material bridges and ensure a constant feed, the material bunker is equipped with a stirrer. The material is fed into a water-rinsed feed hopper using a dosing screw. Those particles, which are specifically heavier than the separating medium, move outwards towards the separator wall due to the centrifugal forces acting and are tangentially discharged as a heavy fraction with the majority of the separating medium at the upper separator end. The specifically lighter particles remain in the close boundary layer (separating water/air core). They are discharged as a light fraction with a small amount of separating medium at the lower end of the separator. Both material flows are discharged separately via a dewatering screen (a linear vibrating screen with longitudinal slots: 0.5 mm x11 mm). To achieve a further concentration of the POs of the LF I fractions, they were fed into the CFS once again, simulating two CFS plants' cascade connection.

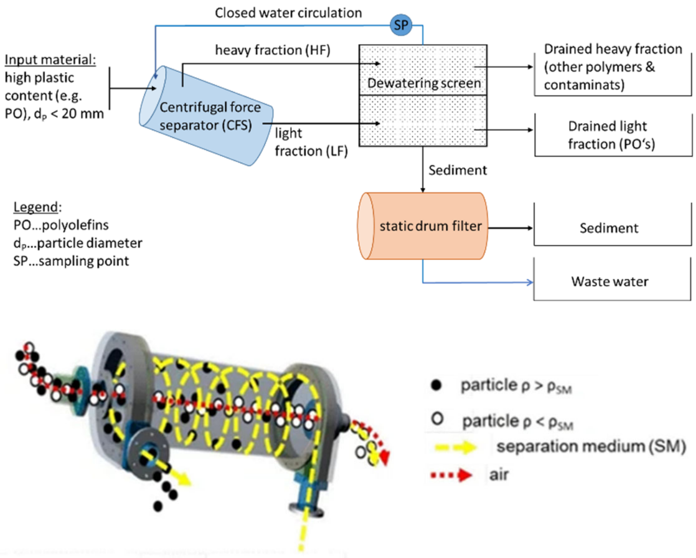

Figure 3. Detailed flow chart of the wet-mechanical treatment process (top) and the CFS in standard countercurrent operation (below) (Bauer et al. 2018).

Table 2. Listing of the feed amount and test duration for both materials and runs (Note: OS - original substance; DM - dry matter).

Test material	Feed amount (kg_{OS})	Feed amount (kg_{DM})	Test duration (hh:min)
MCW_2D test run I	51.7	44.8	01:20
MCW_2D test run II	62.71	28.9	00:53
MMW_2D test run I	56.9	42.3	01:37
MMW_2D test run II	52.66	23.2	00:45

The required process water is circulated throughout the entire experiment and only replaced by freshwater when the material is changed. The process water was collected and decoupled from the treatment line, fed to a static drum filter (Fa. ABZ-Zierler GmbH & Co KG) to separate the liquid and solid phases. The screen had a mesh width of 127 µm.

Bauer et al. (2018) give a detailed functional description of the used CFS. The plant settings and test parameters were determined in previous tests and were the same for all experiments with both materials. The pump capacity was 85% (corresponds to approx. 22 m^3 h-1). The inclination angle of the CFS was 30°, and its length is 1,250 mm. At the start of every test, there were 250 liters of water in the system. The dosing setting for the material feed was set at level 10 (maximum). An average pressure of 0.22 bar was measured at the entering zone of the separation medium. An average pressure of 0.07 bar was measured at the exit of the separation medium.

The input material and generated material outputs (LF I/II and HF I/II) were continuously sampled every 15 minutes, and a mixed sample was created in each case. The process water was sampled at the end of the experiments. Also, process water samples were taken, and samples of the generated sediment after static filtration.

Chemical analysis

The water content (determined according to ONR CEN/TS 15414-1) and, using manual sink/float analysis, the float and sink fraction of all material samples were determined. For the sink/float analysis, 500 g of dried material was mixed with 60 liters of water. A drop of commercial liquid soap was added to the mixture as a wetting agent and stirred well. After a waiting period of 30 minutes, the floating material was skimmed off. The sinking fraction was separated from the water using a 63 µm sieve. Both fractions were then dried in a drying cabinet at 105°C until the weight was constant (according to ONR CEN/TS 15414-1). Based on the visual assessment, it is assumed in the following that the floating particles are predominantly PO (polyolefins: polyethylene (PE) and polypropylene (PP)) with a small proportion of foamed PS. Other objects that also float are foamed materials, certain types of wood, small hollow bodies, etc. The real material compositions of the light and heavy fractions produced are not further investigated in this paper.

Furthermore, the calorific value (LHV and UHV according to DIN 51900-1) was determined. Also, the chlorine (Cl, according to DIN EN ISO 10304-1, calorimetric digestion: ÖNORM EN 14582), heavy metals, and metalloids (Sb, As, Pb, Cd, Cr, Co, Ni, Hg, with ICP-MS according to ÖNORM EN 15411) and ash contents (according to ÖNORM EN 15403) of the feed materials and the target fractions (LF II) were determined, and quantitative elemental analysis (CHNOS) was performed. These parameters are, among others, quality criteria for use in various recycling processes.

The samples of process water were also subjected to a detailed chemical analysis. In addition to general parameters such as filterable (DIN 38409-2), settleable substances (DIN 38409-9), pH value (ISO 10523) and density (using a pycnometer), inorganic parameters (Ag, Al, As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Ni, P, Pb, Sn, and Zn were determined according to ÖNORM EN ISO 17294-2 and Cl-, F-, NO3-, NO2-, SO42- according to DIN EN ISO 10304-1 and NH4 according to DIN 38406-5) and organic parameters (anion active tensides according to ÖNORM EN 903, biochemical oxygen demand in water and process water with respirometer according to DIN EN 1899-2, chemical oxygen demand according to DIN 38409-41, total organic carbon according to DIN EN 1484-3, hydrocarbon – index according to EN ISO 9377-2, adsorbable organically bound halogens according to EN ISO 9562 and blowable organically bound halogens according to EN ISO 10301) were also determined.

The sediment composite sample was chemically characterised as follows. The dry residue was determined according to DIN EN 12880-2a and the calorific value (LHV and UHV) according to DIN 51900-1. The heavy metals and metalloids (Sb, As, Pb, Cd, Cr, Co, Ni, Hg) were determined with ICP-MS according to ÖNORM EN 15411.

Results and Discussion

All the following results are to be understood in mass percentages - %(m/m).

Composition of both input materials

The detailed compositions of the two investigated waste fractions are presented in Möllnitz et al. (2021). It is shown that the composition of both waste fractions (MCW_2D and MMW_2D) is very different. Textiles, 3D-, 2D-plastics, as well as paper and cardboard represent the largest shares (>10%) in both fractions. The 2D-plastics share of MCW is approx. 17% and approx. 19% for MMW. The 3D-plastics content was also determined for MCW at approx. 17% and approx. 12% in MMW. Thus, both investigated input materials have a total plastic content of more than 30%.

Furthermore, it was found in the investigations of Möllnitz et al. (2021) that the additional pre-screening before the ballistic separator results in a significant reduction of fines (< 80 mm) and inert. Based on this finding, only the 2D-fraction of both wastes from the pre-screening experiments were further investigated wet-mechanically.

Mass balance of the centrifugal force separator

In the following section, the calculated plant balances for both test materials are presented, and product purities (corresponds to the floating content for LF and the sinking content for HF) and yields (Y) (see Equation 1 and 2) of the generated output fractions are given.

$$Y_{HF} = \frac{M_{HF}[kg] * share_{sink\ in\ HF}[\%]}{M_{Input}[kg] * share_{sink\ in\ input}\ [\%]} \quad (1)$$

$$Y_{LF} = \frac{M_{LF}[kg] * share_{float\ in\ LF}[\%]}{M_{Input}[kg] * share_{float\ in\ input}[\%]} \qquad (2)$$

Mass balance for Mixed Commercial Waste

Figure 4 shows the plant balance, calculated on the dry masses, for a simple cascade arrangement of two CFS's with MCW_2D as input. In the first test run, a throughput of 33.6 kg h^{-1} was achieved with a load of 0.18 $kg_{material}\ kg_{water}^{-1}$. In the first test run, 64% light fraction (LF I) with a purity (based on the PO-content, which corresponds to the swimming fraction) of 93.8% was separated. The heavy fraction (HF I) discharge was 35%, with a yield of 54% and a product purity of 61%. The real material composition of the light and heavy fractions produced is not further investigated in this paper.

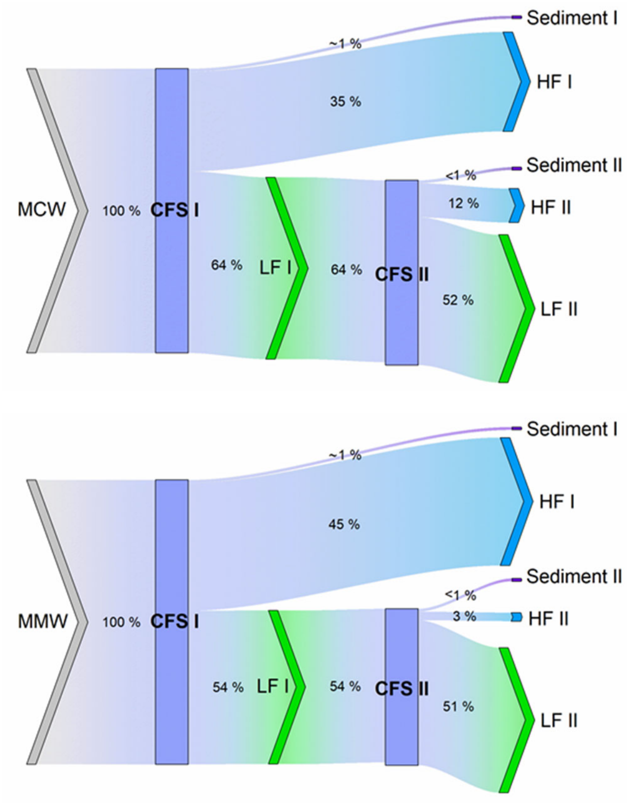

Figure 4. Flow diagram of the preparation of 2D_MCW (**top**) and 2D_MMW (**bottom**) with centrifugal force separator calculated with dry masses.

The LF I separated in the first run was fed into the CFS once again for further PO enrichment. Thereby a throughput of 32.7 kg h^{-1} was achieved with a load of 0.12 $kg_{material}\ kg_{water}^{-1}$. A LF II with 82% and a HF II with 18% share were generated. The LF II fraction product purity was 95.8%, an increase of 2% compared to the first run. HF II had a product purity of 10.6% with a yield of 30.6%.

Washed off, insoluble adhesions, and contained fines (e.g., due to the input material's comminution), accumulate as sediment during the processes. The experiments have shown that most of the sediment in the investigated material is separated in the first process, and barely any sediment formation is observed in the second run. In total, approximately 1% of sediment was produced.

Exemplary photos of the generated output materials (LF I/II and HF I/II) are shown in Figure 1.

Mass balance for Mixed Municipal Waste

Figure 4 shows the plant balance, calculated on the dry masses, for a simple cascade arrangement of two CFS's with MMW_2D as input. In the first test run, a throughput of 26.2 kg h^{-1} was achieved with a load of 0.17 $kg_{material}\ kg_{water}^{-1}$. In the first test run, 54% LF I with a purity of 77.5% was separated. The HF I discharge was 45% with a yield of 55% and a product purity of 70.8%. The real material composition of the light and heavy fractions produced is not further investigated in this paper.

For further PO enrichment LF, I was fed into the CFS once again. Thereby a throughput of 30.9 kg h^{-1} was achieved with a load of 0.09 kgmaterial kgwater-1. A LF II with 95% and a HF II with 5% share were generated. The LF II fraction's product purity was 94.9%, an increase of 17.4% compared to the first run. HF II had a product purity of 11.8% with a yield of 24.7%.

As with the MCW as input, the experiments have shown that most of the sediment in the investigated material is separated in the first process, and barely any sediment formation is observed in the second run. In total, approximately 1% of sediment was produced.

Exemplary photos of the generated output materials (LF I/II and HF I/II) are shown in Figure 1.

Analysis results for material fractions

In this section, the two input materials' analysis results and all generated output fractions are presented and discussed. Unless otherwise stated, all analytical values refer to the dry matter (DM) of the respective material fraction.

A reduction of Cl content from input material to the target fraction (LF II) by 69.9% is observed. This reduction indicates that Cl is mainly present as inorganically bound Cl, e.g., in the form of NaCl (Viczek et al. 2021), and can be washed off. This is reflected in an increase in the Cl values in the process water samples (Table 5). Another explanation is the depletion of organically bound Cl, e.g., PVC (Viczek et al. 2021), which is discharged into the heavy fractions due to its increased density (1.2 - 1.64 g cm^{-3}) (Koltzenburg et al. 2014). The results for heavy metals and metalloids show that the As content was below the detection limit (2.5 mg kg^{-1}) for input and LF II. The contents of Sb, Pb, Cr, Co, and Ni were reduced by at least 60%. Cd and Hg contents for LF II were below the detection limit (0.25 mg kg^{-1}). The quantitative elemental analysis (CHNOS) shows an increase of C (35.6%) and H (48.1%). The enrichment of plastics explains it in the LF II. The contents of N, O, and S are reduced by at least 47.1%. The results of the sink/float analysis and the water content are used, among other things, to calculate the plant balance and will also be used for discussion (yield and purity) there. The upper heating value of the input material is 27,200 kJ kg^{-1}. It is increased to 37,700 kJ kg^{-1} for LF I and 38,300 kJ kg^{-1} for LF II, representing an increase of 40.8% compared to the input material. This confirms the enrichment of high-calorific materials such as plastics in the light fraction. Simultaneously, a reduction of the upper heating value to 26,600 kJ kg^{-1} for HF I and further to 25,000 kJ kg^{-1} for HF II (decrease of 8.1% in total) is observed, which confirms that materials with high calorific values are depleted. The reduction of the ash content of 62.9% in LF II compared to the input material suggests that materials with higher ash content, e.g., paper, cardboard, liquid packaging board, and PVC (Krämer 2017) are separated and enriched in the sediment and the HF fractions.

Analysis results for mixed municipal waste before and output fractions after processing

The results of the chemical analyses of the material fractions from the experiment with MMW_2D are shown in Table 3.

As with MCW, a reduction of Cl by 73.5% is also observed for MMW. Compared to MCW, the Cl content in the input of MMW is higher by a factor of 2.4. One possible explanation would be more inorganically bound chlorine. The results for heavy metals and metalloids show that as for MCW, the detection limit (2.5 mg kg^{-1}) for input and LF II was below the detection limit. The contents of Sb, Pb, Cr, Co, and Ni were also reduced by at least 40%, and the contents of Cd and Hg for LF II were also below the detection limit (0.25 mg kg^{-1}) as for MCW. The contents of Sb, Cd, Co, and Ni are lower in MMW than in MCW input, whereas MMW has higher Cr and Hg contents. The As and Pb contents are similar for both input materials. As for MCW, the CHNOS analysis shows an increase of C (26.4%) and H (31.9%) for MMW and is linked to the enrichment of plastics in the LF II. The contents of N, O, and S are also reduced by at least 16.6%. Compared to MCW, MMW has higher C, N, and O contents, whereas H and S were detected in lower amounts. The results of the sink/float analysis and the water content are used, among other things, to calculate the plant balance and will also be used for discussion (yield and purity) there. The input material's upper heating value is 22,300 kJ kg^{-1} and is thus 18% lower than for MCW input. It is increased to 29,700 kJ kg^{-1} for LF I and 35,100 kJ kg^{-1} for LF II, representing 57.4% compared to the input material. This confirms the enrichment of high-calorific materials such as plastics. As with MCW, a reduction of the ash content from input by 56.6% to the target fraction LF II is observed. Compared to MCW, the ash contents of both MMW fractions are slightly higher.

Table 3. Results of the chemical analyses of the material fractions from the experiment with MCW and MMW (Note: DM – dry matter).

		Input	**Output fractions**				**Input**	**Output fractions**			
Sample identification		*MCW_2D*	*LF I*	*HF I*	*LF II*	*HF II*	*MMW_2D*	*LF I*	*HF I*	*LF II*	*HF II*
Parameters	**Unit**										
Cl	mg kg$^{-1}_{\mathrm{DM}}$	7,220			2,170	17,600	17,600			4,670	
Heavy metals and											
Sb	mg kg$^{-1}_{\mathrm{DM}}$	97			22	42	42			26	
As	mg kg$^{-1}_{\mathrm{DM}}$	< 2.5			< 2.5	< 2.5	< 2.5			< 2.5	
Pb	mg kg$^{-1}_{\mathrm{DM}}$	28			11	26	26			12	
Cd	mg kg$^{-1}_{\mathrm{DM}}$	2.3			< 0.25	0.5	0.5			< 0.25	
Cr	mg kg$^{-1}_{\mathrm{DM}}$	120			38	250	250			53	
Co	mg kg$^{-1}_{\mathrm{DM}}$	3.6			1.4	2.7	2.7			1.4	
Ni	mg kg$^{-1}_{\mathrm{DM}}$	340			52	22	22			11	
Hg	mg kg$^{-1}_{\mathrm{DM}}$	0.38			< 0.25	0.60	0.60			0.25	
CHNOS											
C	%$_{\mathrm{DM}}$	55.0			74.6	48.4	48.4			61.2	
H	%$_{\mathrm{DM}}$	7.7			11.4	6.9	6.9			9.1	
N	%$_{\mathrm{DM}}$	1.7			0.9	4.6	4.6			1.5	
O	%$_{\mathrm{DM}}$	20.4			7.3	24.1	24.1			20.1	
S	%$_{\mathrm{DM}}$	0.4			0.1	0.3	0.3			0.2	
sink/float analysis											
Floating fraction	%$_{\mathrm{DM}}$	59.8	93.8	39.3	95.8	41.9	41.9	77.5	29.2	94.9	88.2
Sinking fraction	%$_{\mathrm{DM}}$	40.2	6.2	60.7	4.2	58.1	58.1	22.5	70.8	5.1	11.8
Water content											
Dry residue (105°C)	%	86.6	33.6	42.6	50.5	74.4	74.4	26.7	35.7	32.9	28
Water content	%	13.4	66.4	57.4	49.5	25.6	25.6	73.3	64.3	67.1	72
Calorific value											
Upper heating value	kJ kg$^{-1}_{\mathrm{DM}}$	27,200	37,700	26,600	38,300	22,300	22,300	29,700	32,300	35,100	21,90
Lower heating value	kJ kg$^{-1}_{\mathrm{DM}}$	25,100	34,700	24,400	35,200	20,500	20,500	32,300	29,700	27,300	20,10
Ash content (550°C)	%$_{\mathrm{DM}}$	15.1			5.6	16.6	16.6			7.2	

Comparison of the measured values with the quality requirements for the ReOil process

For an evaluation of the suitability of the LF II produced as input material for the ReOil process, the measured values were compared with the quality limit values in Table 4. The specified particle size and bulk density range were achieved through targeted pre-treatment for both waste fractions. The limit value for the moisture content was not met. This means that a dewatering with linear vibrating screen is not sufficient and another or different dewatering method has to be applied. The limit values for calorific value and chlorine content were met for both waste fractions. The required content of PE, PP, PS is also met for both waste fractions with the assumption made. Since the total impurities contained in both fractions exceed 3%, compliance with the required limit values for polymer impurities, inorganic and organic contaminants is not guaranteed. Therefore, further investigations on the composition of the output fractions are necessary in more detailed studies.

Table 4. Comparison of the measured values with the quality requirements for the ReOil process.

Parameter	Unit	**ReOil-Process** (Bauer 2013)	LF II MCW	LF II MMW	Comments
Particle size	mm	<30-40	<20	<20	required grain size for CFS processing
Bulk density	kg m^{-3}_{DM}	50-100 (mainly 2D-objects)	approx. 80	approx. 60	was determined in Möllnitz et al. 2021
Moisture content	%	<20	49.5	67.1	additional dewatering equipment is required
Calorific value	MJ kg^{-1}_{DM}	>30	38.3	35.1	
Chlorine content	$\%_{DM}$	<2	0.2	0.47	
PP, PE, and PS content	%	>90	95.8	94.9	assumption that the LFII consists only of PE, PP and PS
Polymer impurities	$\%_{DM}$	PET: ≤3; PVC: ≤2			
Inorganic contaminants		≤3	4.2	5.1	total contamination content
Organic contaminants	$\%_{DM}$	≤5			

Analysis results for process waters

In this section, the produced process waters' chemical analysis results for each test run for both investigated input materials are presented and discussed. To evaluate whether the process water can be discharged into the sewerage without further treatment, it was also chemically analyzed in detail. The water parameters analyzed were selected based on the Austrian "General Regulation on Waste Water Emissions" (AAEV) (BLFUW 2020) in order to be able to compare the quality of the water with the limit values (emission limits) laid down in the AAEV (BLFUW 2020). However, not all parameters listed in AAEV (BLFUW 2020) were determined.

To determine the basic values of the water used for the experiments, a sample of the tap water was taken during system filling. Sample 1 is a sample of the process water at the end of run one. It is known from other investigations that higher water loads are to be expected in run one than in run two. Sample 2 is a sample of the water after static filtration of the mixed process waters from both runs of a test material. The chemical load on the separation medium water (process water) after-treatment of the input materials and filtration of sediments are shown in Table 5.

Table 5 clearly shows that, especially in the areas of suspended particles in water (filterable and settleable substances), the limit values for emissions to both receiving water and the sewage system are exceeded. The content of settleable substances was significantly reduced by filtration. The pH values decrease in the course of the process but are within the approved range for discharge into flowing waters and the sewage system. The density of the process waters, which plays an essential role for efficient separation, is only slightly changed by the increasing impurities. No impairment of the separation process in the CFS is expected.

In the case of the inorganic parameters, the typical bulk metals iron, aluminum, and zinc values are increased, which of course also occur to a greater extent in waste. These contents and nickel, barium, chrome, and copper, are reduced by filtration, especially for MMW. This indicates that these are particles, i.e., adhesions. The limit values for phosphorus and ammonium are also exceeded. The other inorganic parameters are below the specified limit values and are not or hardly influenced by the filtration. This is an indication that these are dissolved in the process water.

The organic parameters clearly exceed the limit values for discharge into flowing waters and the sewage system. However, an apparent reduction of the tested organic parameters by filtration can be seen. Depending on some organic substances' chemical compounds, they have a lower polarity, which makes them less water-soluble and more likely to bind to particles. Therefore, filtered process waters have a hydrocarbon index below the limit for discharge into receiving water, whereas unfiltered process waters only meet the limit for discharge into the sewerage system.

In summary, the results of the process water investigations show that despite a pre-treatment of the waste (in particular the screening of the fine fraction <80 mm) as well as a filtration of the sediment from the process waters, water treatment has to be carried out before discharge into receiving water or sewage treatment plant.

Analysis results for sediment

Due to the very low sediment contents of both input materials and the large free screw volumes of the drum filter, separate sediment samples could not be taken during static filtration. Therefore, both sediment samples were combined and chemically analysed. It is to be examined whether the sediment can be sent for thermal recycling or incineration. Consequently, Table 6 shows chemical analysis results of essential parameters of the sediment produced in the experiments in comparison with the requirements of the Austrian "Waste Incineration Ordinance" (BLFUW 2013) for the co-incineration of waste that is not a substitute fuel (Annex 8). Co-incineration is possible because the calorific value of 10,400 kJ kg^{-1} is relatively high for an ordinary waste incineration plant or sewage sludge mono-incineration plant.

Compared with the limit values in the form of a median and 80th percentile, it is recognised that except for the value for antimony, all other values exceed the limit values. Although the values listed in Table 6 are only the result of a selective consideration, it can be concluded that co-incineration in, e.g., a cement plant could become difficult due to the high contents of pollutants.

Since, after a first evaluation and consultation with experts, it is not assumed that a hazard-relevant property (i.e., hazardous properties HP-criteria (EU 2018)) is fulfilled, which would result in the required classification of the sludge as hazardous waste according to the Austrian "Waste Catalogue Ordinance" (BLFUW 2003), the options of incineration in a waste incineration plant or sewage sludge mono-incineration plant

Table 5. Analysis results of process water samples after treatment process (sample 1 - S1) and filtration (sample 2 - S2) (Note: RS - reference sample).

Sample identification		**Limit values for discharge into**		**H_2O**	**MMW_2D Process water**		**MCW_2D Process water**	
		receiving water	**sewerage**	**RS**	**S1**	**S2**	**S1**	**S2**
Parameters	**Unit**							
General parameters								
Filterable substances	mg l^{-1}	30-50*	**	<20	6500	1700	2000	2500
Settable substances	ml l^{-1}	0.3	10 or ***	<0.1	150.0	24.0	60.0	23.0
pH value	-	6.5-8.5	6.5-9.5 d)	8	7.1	7	6.8	7.1
Density	g cm^{-3}	-	-	0.997	1.001	1	1.001	1
Inorganic parameters								
Ag	µg l^{-1}	100	100	<1.0	2.9	<1.0	<1,0	<1,0
Al	µg l^{-1}	2000	****	18	1310	680	410	1150
As	µg l^{-1}	100	100	<10	<10	<10	<10	<10
Ba	µg l^{-1}	5000	5000	31	120	72	93	93
Cd	µg l^{-1}	100	100	<1	<1.0	<1.0	<1,0	<1,0
Cl	mg l^{-1}	*****	-	3.7	86	94	93	76
free Cl	mg l^{-1}	0.2	0.2	-	-	-	-	-
Cl total	mg l^{-1}	0.4	0.4	-	-	-	-	-
Co	µg l^{-1}	1000	1000	<1	9.6	7.1	11	11
Cr, total	µg l^{-1}	500	500	<2	280	130	43	45
Cr(VI)	mg l^{-1}	0.1	0.1	-	-	-	-	-
Cu	µg l^{-1}	500	500	4.3	190	60	39	39
Cyanide, easily released	mg l^{-1}	0.1	0.1					
F	mg l^{-1}	10	20	<3.0	<13	<13	<13	<13
Fe, total	µg l^{-1}	2000	****	66	7530	5990	12400	5110
Hg	µg l^{-1}	10	10	<1.0	1.9	1.4	1.2	1.3
Ni	µg l^{-1}	500	500	2.2	87	83	120	110
P	µg l^{-1}	2000 f)	-	<10	5280	3960	1190	2860
Pb	µg l^{-1}	500	500	<1.0	24	5	4.3	4.5
Sn	µg l^{-1}	2000	2000	<2.0	58	30	9.7	9.4
Zn	µg l^{-1}	2000	2000	39	650	210	1950	1920
NH_4	mg l^{-1}	10	e)	<0.05	70	48	24	43
NO_3	mg l^{-1}	a)	-	6.9	-	-	-	-
NO_2	mg l^{-1}	1	10	<3.0	<3.0	<3.0	<3.0	<3.0
SO_4	mg l^{-1}	a)	-	18	140	140	440	250
SO_2	mg l^{-1}	0.1	1	-	-	-	-	-
SO_3	mg l^{-1}	1	10	-	-	-	-	-
Organic Parameters								
Anionic surfactants	mg l^{-1}	1	**	<0.10	1.9	1.3	0.76	1.2
Biochemical oxygen demand with respirometer	mg O_2 l^{-1}	20	-	6.4	1100	680	630	600
Chemical oxygen demand	mg O_2 l^{-1}	75	-	<15	6980	1530	3160	1150
Hydrocarbon index	mg l^{-1}	10	20	<0.050	11	5.1	19	4.9
TOC	mg l^{-1}	25	-	<1.00	599	367	457	309
Adsorbable organically bound halogens	mg l^{-1}	0.5	0.5	0.011	12.8	1.41	16.8	0.135
Blowable organically bound halogens	mg l^{-1}	0.1	0.1	<0.001	<0.001	<0.001	<0.001	<0.001
Low volatile lipophilic substances	mg l^{-1}	20	100 g)	-	-	-	-	-
Phenol index	mg l^{-1}	0.1	10	-	-	-	-	-
Sum of the volatile aromatic hydrocarbons benzene, toluene and xylenes	mg l^{-1}	0.1	0.1	-	-	-	-	-

* industrial wastewater with mainly undissolved inorganic substances

** no interference with the operation of sewerage and wastewater treatment plants

*** no deposits impairing the operation of the sewage system

**** limited by settleable substances

***** limited by algal toxicity, daphnia toxicity, or fish toxicity

a) Determine if necessary
b) To be used within the scope of third-party monitoring according to Article 7 (3) in the event of well-founded suspicion or concrete indications of the flow-damaging effect of wastewater discharge, but not within the scope of self-monitoring according to Article 7 (2).
c) The discharge of wastewater into a public sewerage system must not impair the biodegradation processes in the public wastewater treatment plant. Biological degradation processes are impaired if
1. the wastewater shows an oxygen consumption inhibition of more than 50% in the oxygen consumption inhibition test according to the method concerning "toxicity - inhibition of oxygen consumption" in accordance with Appendix A Section II of the MWC; or
2. the effluent shows an inhibition of nitrification processes of more than 50% in the nitrification inhibition test carried out in accordance with the method concerning "toxicity - inhibition of nitrification" set out in Annex A, Section II of the MVW.
If in the case of a test according to Z1 or 2, the result of the test is below the criterion mentioned in each case, and the suspicion of impairment of the biological degradation processes in the wastewater treatment plant cannot be dispelled, the result of the test according to Z1 or 2 must be confirmed by means of a confirmation test. The details of this confirmatory test are to be determined by the water authority, taking into account the conditions of the wastewater discharge, in such a way that statements can be made on the long-term impairment of the degradation capacity and growth conditions of the biocoenosis of the public wastewater treatment plant affected by the discharge.
d) For applications, especially in the hospitality industry, where gravity grease separators represent the state of the art as the main cleaning step under consideration of the criteria of Article 12a WRG 1959, an extension of the emission range to 5.0-9.5 is permissible in individual cases after approval of the sewerage company.
e) In individual cases where there is a risk of odour nuisance or risk of corrosion for cement-bound materials in sewers and sewage treatment plants (technical standard concerning "Design of sewer systems" according to Annex A Section IV of the MVW).
f) In the catchment area of national or international lakes, the requirement must be increased to at least 1 mg/l.
g) An emission limit of 200 mg l^{-1} is permissible for applications, especially in the hospitality industry, where, taking into account the criteria of §12a WRG 1959, gravity grease separators represent the state of the art as the main cleaning step.

Table 6. Analysis results of sediment composite samples processing both investigated waste fractions (Note: DM – dry matter).

Sample identification		**Limit values**		**Sediment**
Parameters	**Unit**	**Median**	**80th percentile**	**composite sample**
Heavy metals and metalloids				
Sb	mg kg$^{-1}_{\text{DM}}$	35	50	15
As	mg kg$^{-1}_{\text{DM}}$	5	7.5	9.3
Pb	mg kg$^{-1}_{\text{DM}}$	75	135	93
Cd	mg kg$^{-1}_{\text{DM}}$	0.85	1.7	2.1
Cr	mg kg$^{-1}_{\text{DM}}$	95	140	270
Co	mg kg$^{-1}_{\text{DM}}$	4.5	8	17.0
Ni	mg kg$^{-1}_{\text{DM}}$	35	60	150
Hg	mg kg$^{-1}_{\text{DM}}$	0.375	0.75	1.80
Water content				
Dry residue (105°C)	%	-	-	12.5
Water content	%	-	-	87.5
Calorific value				
Upper heating value	kJ kg$^{-1}_{\text{DM}}$	-	-	11,300
Lower heating value	kJ kg$^{-1}_{\text{DM}}$	-	-	10,400

remain. This is technically feasible. Only economically, it represents a higher burden due to the expected high disposal costs.

Conclusion

A simple cascade connection of two CFS's can increase the purity of the light fraction for both investigated input materials to over 94%. In further investigations, the light fraction's real composition and thus the real PO content should be determined, for example, by using near-infrared (NIR) or Fourier-transform infrared (FTIR) spectroscopy. The comparatively low product purities of the simultaneously produced heavy fractions (60-70%) allow the conclusion that they still contain a non-negligible swimming PO content, which could be separated in a second run through the CFS. Sinking PO particles with a density greater than 1 g cm-^{3} are also expected to be present in the sinking fraction. The most likely explanation is that these particles contain inorganic fillers such as talc to improve the mechanical material properties (Thoden van Velzen et al. 2017) (Brouwer et al. 2018). This can be verified using NIR and should be included in future investigations. It was also found that little sediment is produced by the sample preparation, which is mainly produced in the first run.

Due to the wet-mechanical processing, a significant reduction of the chlorine content of the input material by at least 70% and a reduction of all investigated heavy metals and metalloids could be observed. Thus, relevant quality parameters for recycling options can be met.

The density of the process waters, which plays an essential role in efficient separation, is only slightly changed by the increasing impurities. No impairment of the separation process in the CFS is expected. The results of the process water investigations show that despite a pre-treatment of the waste (in particular the screening of the fine fraction < 80 mm) as well as a filtration of the sediment from the process waters, a water treatment (mechanical biological or chemical biological cleaning) has to be carried out before discharge into receiving water or sewage treatment plant to limit the discharge of toxic substances and their concentration, as prescribed by law.

The sediment investigations show that co-incineration is theoretically possible due to the calorific value. Nevertheless, a co-incineration in, e.g., a cement plant, could become difficult due to the high contents of contaminants for this application. It is not assumed that an HP criterion is fulfilled, so the options of incineration in a waste incineration plant or sewage sludge mono-incineration plant remain. This is technically feasible.

In summary, after minor adaptations, the CFS represents a suitable process for the production of input material for the ReOil process from mixed waste. On one side, the suitability of the fraction produced for other recycling processes is to be addressed in further research. On the other side, the recovery process ReOil is still in the developing stage: 2021: 100 kg h^{-1} acc. to OMV (2018).

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Declaration of conflicting interests

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4.3 Recovery and Recycling Aspects

Publications 2, 3, and 4 have shown that the plastics contained in mixed wastes can, in principle, be recovered. In this chapter, the next step in the process chain is to investigate the basic processability with compression moulding of these gained plastics and to determine the achievable material properties. To complete this thesis, a market study shows the quality and price correlations of plastic recyclates (flakes and granules) to virgin material.

4.3.1 Publication 5

Processability of Different Polymer Fractions Recovered from Mixed Wastes and Determination of Material Properties for Recycling

Möllnitz, S., Feuchter, M., Duretek, I., Schmidt, G., Pomberger, R., Sarc, R.

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DI: Resources, Investigation, Data curation, Writing — review and editing.

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Graphical Abstract:

polymers

MDPI

Article

Processability of Different Polymer Fractions Recovered from Mixed Wastes and Determination of Material Properties for Recycling

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Abstract: To achieve future recycling targets and CO_2 and waste reduction, the transfer of plastic contained in mixed waste from thermal recovery to mechanical recycling is a promising option. This requires extensive knowledge of the necessary processing depth of mixed wastes to enrich plastics and their processability in polymer processing machines. Also, the selection of a suitable processing method and product application area requires appropriate material behaviour. This paper investigates these aspects for a commercial processed, mixed waste, and two different mixed polyolefin fractions. The wastes are processed at different depths (e.g., washed/not washed, sorted into polyethylene, polypropylene, polyethylene terephthalate, polystyrene/unsorted) and then either homogenised in the extruder in advance or processed heterogeneously in the compression moulding process into plates. The produced recyclates in plate form are then subjected to mechanical, thermal, and rheological characterisation. Most investigated materials could be processed with simple compression moulding. The results show that an upstream washing process improves the achievable material properties, but homogenisation does not necessarily lead to an improvement. It was also found that a higher treatment depth (recovery of plastic types) is not necessary. The investigations show that plastic waste recovery with simple treatment from mixed, contaminated wastes into at least downcycling products is possible.

Keywords: mixed wastes; polymer recycling; processability; material characterisation; material properties; circular economy

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1. Introduction

The waste management industry often talks about "plastics" as if it were a single material, but this is not the case. Plastics are an extensive family of entirely different materials. Each plastic type is designed with specific characteristics that make it ideal for its intended application. Whatever their application was, at the end of their service life, plastic materials are necessary resources that should first be recycled (upstream/downstream), and only when this is no longer technically possible and economically feasible, they should be used as an alternative energy source in energy recovery facilities [1–3].

In 2019, 368 million tonnes (Mt) of plastic were produced worldwide—57.9 Mt in Europe (EU28+NO/CH) [1], and the EU converters' demand was about 50.7 Mt. "Packaging" (~40%) and "building and construction" (~20%) represent the largest end-use markets followed by the "automotive industry" with about 10% [4]. The most frequently used plastic types are the polyolefins (PO) (polyethylene—PE; polypropylene—PP) at approx. 50% [4]. These are mainly used in the packaging sector, e.g., food packaging, hinged caps, bags, trays, films, and bottles, but also for pipes, automotive parts, agricultural films, houseware parts, etc. Other common packaging plastics are polyethylene terephthalate (PET) at about 8% and polystyrene (PS) at about 6.5% [4]. The main areas of PET application are the production of fibres for the textile industry, moulding compounds, hollow bodies, and films, primarily for the packaging sector. Standard PS is mainly used to produce dimensionally stable food and other packaging products, e.g., cups, trays, caps, closures, boxes, and films. Expanded PS (EPS) and extruded PS (XPS) are also frequently used as insulation material for thermal insulation or impact sound insulation.

In 2018, 29.1 Mt plastic post-consumer waste was collected in the (EU28+NO/CH) [4], which ended up in three different waste management paths: 42.6% were used as SRF (solid recovered fuel) for energy recovery, 32.5% (81% within the EU) were recycled, and 24.9% were still landfilled in Europe [4]. However, the figures for the last ten years show that waste management is currently transforming in Central Europe, especially in Austria. It is further developing from a thermal recovery to a recycling economy [5]. Nowadays, most plastics present in mixed wastes like commercial and municipal solid waste end up as SRF in energy recovery and are irrevocably lost for recycling [6]. Only PET in bottle form for recycling and PVC (polyvinyl chloride) parts are discharged, representing a contaminant for further processing. According to the EU [7], municipal solid waste recycling rates of 65% are to be achieved by 2035. In 2018, 86.1% of mixed municipal solid waste (excluding bulky waste and separate collection) in Austria was treated thermally directly or after mechanical-biological waste treatment, and 12.3% was treated biologically. Only 1.6%, mainly metals and glass, were recycled [8]. The EU has released a plastic strategy that sets that by 2030, half of the plastic waste generated in the EU will be recycled. The sorting and recycling capacity has to be increased fourfold compared to the reference year 2015. Among others, future recycling rates can be met by upgrading relevant plastics from "Other recovery", e.g., "energy recovery", to "recycling" [3]. Recycled plastics are generally considered to be of lower quality than virgin plastics [1,2]. However, several key challenges need to be overcome. For a high recycled material quality, high purity of the input material is necessary, and external (e.g., glue) as well as internal impurities (e.g., adsorbed substances) must be removable. For pure, clean plastics, modern recycling processes can match virgin properties.

Nevertheless, many mixed waste streams (e.g., mixed commercial or municipal waste) are considered low value [9] and, therefore, not (economically) recyclable because of the high treatment costs or the high level of contamination [10]. Nevertheless, this does not mean that technical recycling is excluded. To investigate this, it is first of all necessary to determine whether a sufficient amount of plastic is contained in the mixed waste and whether separation is possible. If plastic mixtures or even individual types can be sorted out, the next step is to examine the processability with simple processing methods. If this is possible, a basic characterisation of the resulting materials follows. A suitable processing method can be selected only then, and the producible products can be determined [10].

The novelty of this research is the investigation of mixed, heterogenous, and contaminated (e.g., organic and inorganic impurities) mixtures with significant plastic amounts. Nowadays, such mixtures are declared as sorting residues (i.e., a non-recyclable fraction from material recovery facilities) and are utilised in energy recovery processes [10].

The plastic amount in the mixtures was investigated in two ways: on one side, at the polymer type (PE, PP, PET, and PS) level, and on the other side, as a varying mixture of unsorted polymers. Therefore, simple recoverability (i.e., sorting out with/without washing) and processability (i.e., compression moulding with/without homogenisation for production of recyclates) of the mentioned two ways were extensively investigated.

Next, the material properties of the plates produced from the recyclates were determined to create a material database for further research work in the linking of waste management with the plastic recycling sector. Finally, the applied strategy and the characterisation included have been widely studied and validated both at the industrial level and the research stage.

2. Materials and Methods

2.1. Materials and Sampling

A common mixed waste, i.e., SRF (approx. 200 kg) produced from pre-treated and untreated mixed wastes (mixed municipal waste, commercial waste, etc., excluding separately collected wastes such as lightweight packaging waste) from a production facility near the city Graz in Austria, was used for the studies. In spring 2018, the sample was taken from the falling material stream according to ÖNORM S 2123-3 [11]. The material sample was taken from the SRF processing line after pre-shredding (<500 mm), magnetic separation, and PVC separation using a NIR (near-infrared) sorter and had a particle size >100 mm.

At the same time, about 20 kg of a sample of a PO-rich waste fraction (sample name: PO_A) was taken at the same plant. According to ÖNORM S 2123-3 [11], the sample was taken from the falling material stream. The sampling is carried out after pre-shredding, magnetic separation, PVC discharge, separation of heavy materials by a wind sifter, and subsequent post-shredding (<35 mm).

A further PO sample (approx. 8 kg) (sample name: PO_B) was taken out from the wet-mechanical processing unit using a centrifugal force separator [12] with a particle size <30 mm. The input material was a mixture of common SRF, mixed plastics from light-weight packaging treatment, and mixed plastics from the industry.

All samples mentioned are representative samples composed of individual increments taken continuously over several hours during the plant operation or test run. Exemplary photos of the three test materials are shown in Figure A2 in Appendix I.

2.2. Methods

In this section, the experimental and analytical procedures are described. Figure 1 (I. Plant set up for investigations) shows the modular plant configuration for material preparation, as it could also look like in real processing plants. The investigation method is divided into three areas: A.) Mechanical pre-processing of the input materials; B.) Polymer processing consisting of material homogenisation, a compression moulding process, and test specimen preparation; and C.) Material characterisation with thermal, mechanical, and rheological material testing.

The mechanical pre-processing consists of a drum screen for the separation of fine material (<20 mm), a manual sorting station for the removal of non-plastics and other materials, a double shaft pre-shredder to reduce the average particle size of plastics below 100 mm, a cold washing aggregate (a self-built stirred washer), a thermal drying cabinet (drying at 105 °C up to constant weight according to ONR CEN/TS 15414-1), a sensor-based sorting system (near-infrared) for the manual sorting of the standard plastic types (PE, PP, PET, and PS), and a post-shredder (cutting mill) to reduce the particle size to <4 mm.

In the polymer processing step, one-half of the shredded plastic flakes per plastic type were fed to a counter-rotating parallel twin-screw extruder TSE 42/7D (screw diameter (D): 42 mm; screw length: 7D; model no.: 8324; type: Plasti-Corder PL2000 from Brabender® GmbH & Co. KG, Duisburg, Germany) with a three-zone screw for thermoplastics. This equipment is used for material homogenisation, e.g., thermoplastic multicomponent systems, polymer blends, or composite materials. The product (filament) was cooled in a water bath and granulated afterwards. The other half of the materials were directly processed into plates (dimensions: 160 mm × 160 mm × 4 mm) with a hot vacuum compression moulding process (vacuum press type P200PV, Dr. Collin GmbH, Maitenbeth, Germany). The material-specific four-zone temperature profile for material homogenisation is given in Table A3 in Appendix C. All materials were homogenised at a screw speed of 110 rpm. The material-specific, five-stage press profiles (temperature, pressure, and time) were determined empirically. The press profiles are presented in Table A4 in Appendix C.

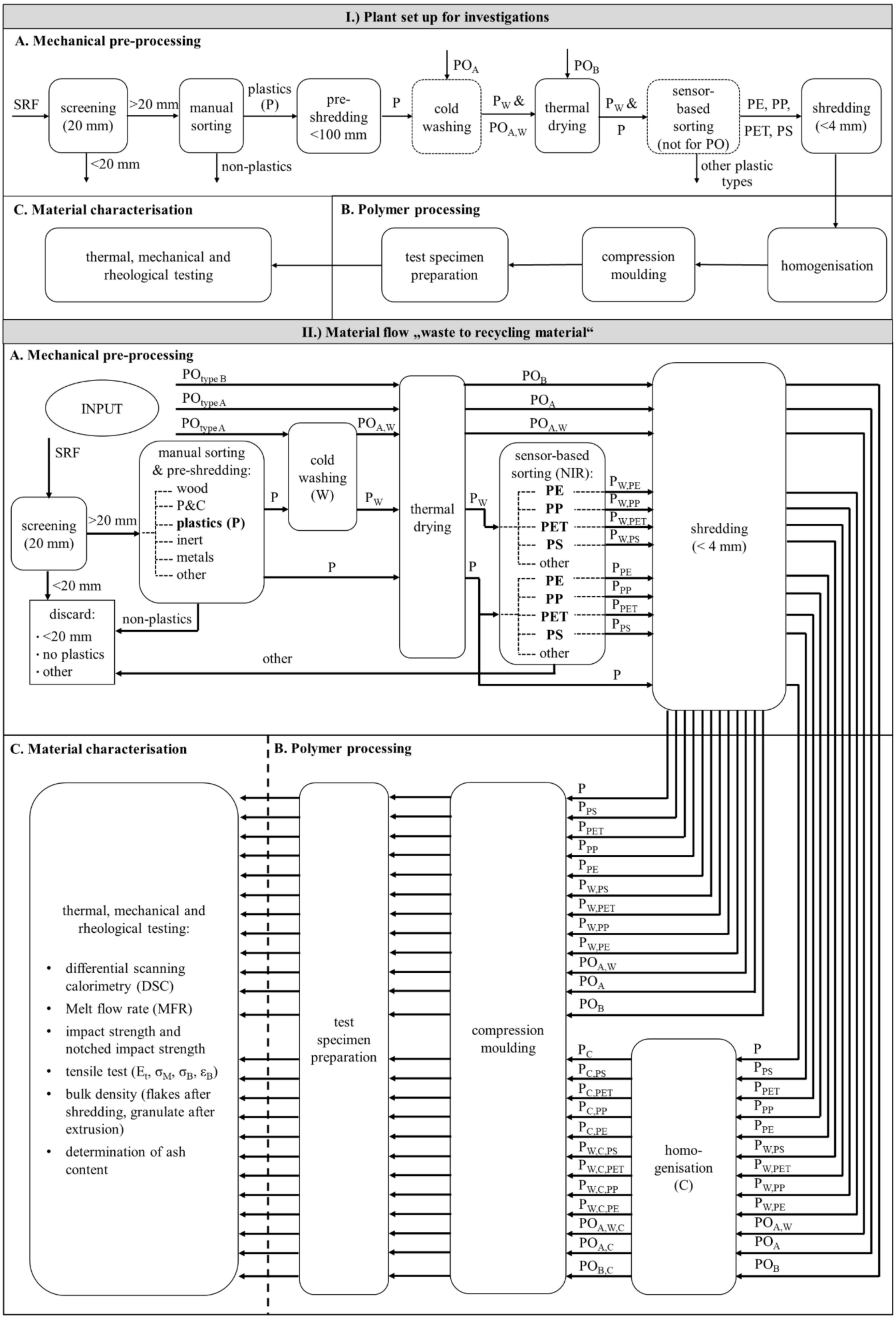

Figure 1. Flow chart for the plant set up of the investigations (**I**) and all material flows of input materials and resulting flows during the investigations (**II**); The process is divided into three sub-processes: **A**. Mechanical pre-processing, **B**. Polymer processing and **C**. Material characterisation.

Test specimens used for material characterisation were stamped or cut (CNC milling machine) from the plates. Extensive tests were carried out for this purpose: thermal characterisation with differential scanning calorimetry (DSC), melt mass flow rate (MFR), determination of ash content, mechanical characterisation with tensile tests, (notched) impact strength, and determination of the bulk density from plastic flakes after shredding and granulates after homogenisation.

Crystallinity (X_C) is calculated from the melting enthalpy (ΔH_m) measured with DSC and the approximated melting enthalpy of totally crystalline material (ΔH_0) from the literature according to Equation (1) [13,14].

$$X_C = \frac{\Delta H_m}{\Delta H_0} \times 100\% \tag{1}$$

Figure 1 (II. Material flow “waste to recycling material”) shows all material flows generated during the investigations from waste to finished test specimens.

The mixed waste, i.e., SRF, was the only input material screened and manually sorted into six material fractions (wood, paper, and cardboard (P&C), plastics, inert, metals, and other materials). Exemplary photos of the manually sorted material fractions are shown in Appendix I in Figure A3. Only the plastic fraction was further processed and investigated. The other fractions were discarded and, therefore, not relevant for further investigation. The plastic fraction was divided into three similar parts. One part was dried and shredded without NIR sorting. The second part was dried and sorted by NIR into five plastic types and the rest. Exemplary photos of plastic types sorted with NIR are given in Appendix I in Figure A4. The third SRF part was washed, dried, and NIR-sorted. The sorted plastic types were post-shredded separately.

The two PO materials were not screened and not manually sorted due to their small grain size (i.e., <35 mm and <30 mm).

The input material PO_A was divided into two similar parts. One part was washed, dried, and shredded. The other part was dried and shredded without a washing step. As the input material, PO_B came from wet-mechanical processing, it was only dried and shredded.

All material flows were divided after shredding. Half of each material went into the extruder for homogenisation, and the other half was compression moulded directly into test plates without homogenisation.

C.) Material Characterisation

For thermal characterisation of the materials, DSC measurements were performed using a DSC1 (Mettler-Toledo GmbH, Urdorf, Switzerland) in a temperature range from 0 to 230 °C for PE, PP, and PS materials, and from 0 to 200 °C for PO and P materials with a heating rate of 10 K/min in a nitrogen atmosphere (nitrogen flux rate 50 mL/min). The cooling rate was 20 K/min. To make the thermal history the same for all materials, a measuring program with one heating, one cooling, and second heating was chosen. Only the cooling and second heating curves were used for analysis. In advance, for checking the thermal stability, measurements up to 300 °C with a heating rate of 20 K/min in a nitrogen atmosphere were carried out for each material. This was used to determine the range of measurement itself. Seven reproducibility measurements for the heterogeneous and three for the homogeneous materials were carried out according to DIN EN ISO 11357-1 [15]. Standard 40 µL aluminum crucibles with pierced lids were used.

Charpy impact tests and notched impact tests (Ceast Resil 25, INSTRON/Ceast, Pianezza, Italy) according to DIN EN ISO179-1 [16] were performed at room temperature using a pendulum with 2 J (unnotched) and 0.5 J (notched) for P_PE, P_W,PE, P_W,C,PE, P_W,PP, P_W,C,PP, PO_A,W, and PO_B,C; a pendulum with 0.5 J (notched and unnotched) for P_PP, P_C,PP, all PS materials, PO_A, PO_A,C, PO_A,W,C, PO_B, and P; and a 7.5 J pendulum (unnotched) for P_W,C,PE. Tensile tests (Zwick Z010, Zwick/Roell GmbH & Co. KG, Ulm, Germany) were performed at room temperature according to DIN EN ISO

527-1 [17] and EN ISO 527-2 [18]. The ash content was determined according to DIN EN ISO 3451-1 [19]. Due to the heterogeneity, three reproducibility measurements were carried out, and the mean values were calculated for the discussion. The bulk density was determined for the plastic flakes after shredding and for the granulates after compounding, respectively, according to DIN EN ISO 60 [20]. Five measurements per material were carried out. The MFR (Modular Melt (Mass) Flow Tester, INTERON/Ceast, I) was determined according to DIN EN ISO 1133-1 [21]. The test conditions were set to 190 °C and 2.16 kg for all materials except for the PS materials. For PS, the test conditions were set to 200 °C and 5 kg.

3. Results

For the examined plastic materials, the following properties were investigated: The composition of mixed waste, i.e., SRF and its plastic type content, thermal and mechanical properties, characterisation of the flow behaviour (MFR), bulk density, and ash content.

All stated values are wt.%$_{DS}$ (DS—dry substance), given in full percent only for clarity purposes.

All PE, PP, PO, and P materials could be processed without any major problems. The PS materials emitted much gas in both processing variants, and several test runs were necessary to find a stable processing method. The PET materials could neither be homogenised nor compression moulded due to excessive contamination. Possible impurities are multilayer bottles, residual label material (PO), different non-compatible PET grades [10], diffused substances, etc. The reasons for non-processability were not further investigated in this paper. All other materials could be processed. The plates made out of the heterogeneous materials showed flow directions (see Appendix I: Figures A7–A9). These are due to material accumulations in the compression moulding process.

3.1. Total Composition of the Mixed Wastes and Plastic Type Content

The composition of the input materials does not influence the subsequent investigations and is given here only to complete the information. Further extensive and current data on typical SRF composition are given by [22]. The detailed data of the investigated material are given in Appendix A.

Of the fine material (<20 mm), 8.5%$_{OS}$ (OS—original substance) was separated by pre-screening and discarded from SRF. The subsequent manual sorting analysis revealed the following composition of SRF > 20 mm. The plastics represented the largest material fraction with 86.5%$_{OS}$. The other fraction (sorting residue and composites) represented 6.5%$_{OS}$. The share of P&C was 5.8%$_{OS}$. The share of metals and inert materials was 0.6%$_{OS}$ each, and 0.1%$_{OS}$ was the content of wood. The mass losses caused by material drying during storage, sorting losses (mobile organic material, dust formation, etc.), and screening losses were not taken into consideration for calculation here. These are in the range of 3%$_{OS}$ of the total sample.

The sorted out plastic fraction (86.5%$_{OS}$, see above) consisted of the following plastic types. The PE fraction represented the largest share with 36.4%$_{OS}$. The other fraction (black and other plastics as well as unidentified objects) represented 21.2%$_{OS}$. The PET share was 20.7%$_{OS,}$ and PP was contained with 15.7%$_{OS}$. The smallest fraction was PS with 6%$_{OS}$.

3.2. Thermal Material Properties

Table 1 displays the evaluations of the DSC measurements. Evaluated were the crystallisation temperature (T_C) with respective crystallisation enthalpy (ΔH_c), melting temperatures (T_{m1} and T_{m2}) with respective melting enthalpy (ΔH_{m1} and ΔH_{m2}), and glass transition temperature (T_g). A representative cooling curve and the second heating curve per analysed material for the respective material group (PE, PP, PS, PO, and P) are shown in Appendix B for better illustration.

Table 1. Results of the DSC measurements: crystallisation temperature (T_C), crystallisation enthalpy (ΔH_c), melting temperatures (T_{m1} and T_{m2}), melting enthalpy (ΔH_{m1} and ΔH_{m2}), and glass transition temperature (T_g).

Parameters	T_C	ΔH_c	T_{m1}	ΔH_{m1}	T_{m2}	ΔH_{m2}	T_g
Material	**(°C)**	**(J/g)**	**(°C)**	**(J/g)**	**(°C)**	**(J/g)**	**(°C)**
P_PE	110.3 ± 2.2	115.8 ± 18.6	129.3 ± 2.8	94.4 ± 18.6	162.8 ± 1.2	4.8 ± 4	–
P_W,PE	105.1 ± 1.8	118.9 ± 8.2	125.4 ± 0.7	97.1 ± 10.4	161.5 ± 0.6	4 ± 1.4	–
P_C,PE	107.6 ± 0.3	109.7 ± 4.8	127.6 ± 0.2	80.9 ± 2.3	162.7 ± 0.1	4.5 ± 0.2	–
P_W,C,PE	108.8 ± 1.3	128.3 ± 3	127.1 ± 0.8	98.7 ± 1.8	–	–	–
P_PP	116 ± 2.9	86.7 ± 8.8	165.3 ± 0.8	74.2 ± 11.2	–	–	–
P_W,PP	115.5 ± 2.5	91.8 ± 2.7	166.3 ± 1	79.6 ± 6.9	–	–	–
P_C,PP	119.4 ± 1.6	83.5 ± 4.1	164 ± 1	47.6 ± 18.3	128.1 ± 0.6	6.1±0.2	–
P_W,C,PP	119 ± 0.8	83.5 ± 2.1	163.8 ± 0.7	63.6 ± 0.5	–	–	–
P_PS	119.6 ± 3.9	10.4 ± 8.9	163.5 ± 1.4	7.7 ± 9.5	–	–	99.5 ± 0.9
P_W,PS	113.4 ± 3.5	5.2 ± 2.4	162.2 ± 0.9	2.8 ± 2.2	–	–	98.9 ± 1.6
P_C,PS	114 ± 0.3	7.7 ± 0.9	161.5 ± 0.1	4.5 ± 0.3	–	–	98.3 ± 0.2
P_W,C,PS	–	–	161.9 ± 0.1	3.6 ± 0.2	–	–	98.9 ± 0.4
PO_A	108.7 ± 4.6	74.1 ± 18.9	124.2 ± 1.2	46.1 ± 14.9	163.1 ± 1.1	13.7 ± 4.2	–
PO_A,W	107.9 ± 2.4	81.1 ± 4.6	125.4 ± 0.8	50.8 ± 4.8	163.5 ± 1.3	15 ± 4.6	–
PO_A,C	108.3 ± 1.1	83.8 ± 0.3	125.4 ± 0.3	50.2 ± 2.9	162 ± 0.5	15.1 ± 0.2	–
PO_A,W,C	107.8 ± 1.5	86.6 ± 3.2	125.4 ± 0.6	51 ± 0.5	162 ± 0.7	17.5 ± 1.4	–
PO_B	110.4 ± 3.9	105 ± 10.3	129 ± 4.9	54.6 ± 12.4	163.7 ± 1	18.8 ± 3.9	–
PO_B,C	110.4 ± 1.4	110 ± 1.5	126.7 ± 0.3	61.9 ± 3.1	162 ± 0.6	22.1 ± 0.9	–
P	111.2 ± 1.8	52.2 ± 10.6	128.2 ± 6.9	31.5 ± 9.4	164.2 ± 1.2	12 ± 7.1	–
P_C	110.6 ± 0.5	67.3 ± 2.4	126.4 ± 0.3	39.6 ± 3.1	161.1 ± 0.4	13.1 ± 0.3	–

The measured T_C for the investigated PE materials is, on average, 108 °C. The calculation of the crystallinity for the PE materials according to [13,14] with 293 J/g for totally crystalline PE resulted in values between 36% and 38% for a cooling rate of 20 K/min. This is a comparatively low crystallinity for PE and corresponds to that for virgin (v)LLDPE (10–50%) [23]. vLDPE typically has a crystallinity in the range of 45–55% and vHDPE in the range of 70–80% [23].

Two melting temperatures were determined for the PE materials. The primary melting point (T_{m1}) is that most of the material melts are between 125 and 129 °C. The measured secondary melting point T_{m2} is about 162 °C and is due to contained impurities (higher melting foreign plastics such as PP, for example). Only P_W,PE shows a more distinct secondary melting point at approx. 110 °C. In the literature, melting temperature ranges for different vPE types are given as follows: 120–130 °C for LLDPE, 105–115 °C for LDPE, and 128–136 °C for HDPE [24]. It is interesting to note that the DSC curves are very similar, especially for the heterogeneous PE materials. As was to be expected, these become even more similar through homogenisation, which is evident in the smaller fluctuation margins.

The measured T_C for the investigated PP materials is 117 °C on average. According to [13,14], the calculation of the crystallinity with 207 J/g for totally crystalline PP yields values between 55% and 58% for a cooling rate of 20 K/min. This is a relatively high crystallinity for PP. Isotactic vPP has a crystallinity of 70–80%, syndiotactic PP of 30–40%, and atactic PP is amorphous and has no crystallinity [23,25]. The T_{m1} at approx. 165 °C was determined for the PP materials. Only P_PP and P_C,PP show a distinct T_{m2} at about 128 °C, which is due to contamination with foreign material, which can be removed by washing. In the literature, melting temperature ranges for vPP types are given between 161 and 186 °C [26]. Likewise, the DSC curves of the heterogeneous PP materials are very similar and, after homogenisation, even closer to each other.

Both heating curves of all investigated PS materials show a continuous decrease over the measured temperature range. This corresponds to the literature, as PS has low heat resistance, and from 55 °C onwards, an acceleration of ageing starts, which is why PS is usually only used up to 70 °C [27]. The measured T_g is about 99 °C on average, which corresponds to the literature value of about 80–100 °C for vPS [24,25]. The vPS types predominantly used are atactic and are, thus, in amorphous form and, therefore, have neither a T_C nor a T_m [24]. Therefore, it is remarkable that both a T_C (113–120 °C) and a T_{m1} (161–164 °C) were measured for the PS materials. The melting temperature is 240°C [28] for isotactic vPS and 270 °C [28] for syndiotactic vPS. The heterogeneous PS materials' curves are much more heterogeneous compared to those of PE and PP and show more fluctuations and deviations from each other. Due to the homogenisation, these are smoothed considerably and are more similar to each other.

For the PO materials, a T_C at approx. 108 °C, a distinct T_{m1} at approx. 125 °C (ΔH_m = 50 J/g), and a T_{m2} at approx. 163 °C (ΔH_m = 15 J/g) are measured. Furthermore, a further secondary melting temperature is measured at approx. 110 °C. This has already been observed with P_W,PE. With PO_B,C, it is evident compared to the other PO materials that T_{m1} is more distinct and the secondary melting temperature at 110 °C is hardly present. Additionally, with PO_B,C, a second crystallisation peak at approx. 120 °C becomes clear from the HDPE content [24]. The comparison of the curves of the PO_A materials shows major deviations only for the cooling curves. The other curves are very similar, especially those of the homogeneous PO_A materials. For PO_B, the 2nd heating curves also show major deviations from each other.

The **mixed plastic fraction** (**P**) curves are surprisingly similar and show a high degree of similarity with those of PO materials. This is especially true for P_C and PO_B,C.

3.3. Melt Mass Flow Rate

Figure 2 shows a comparison of the mean MFR values of all materials investigated. The MFR results of all investigated materials are given in Appendix D.

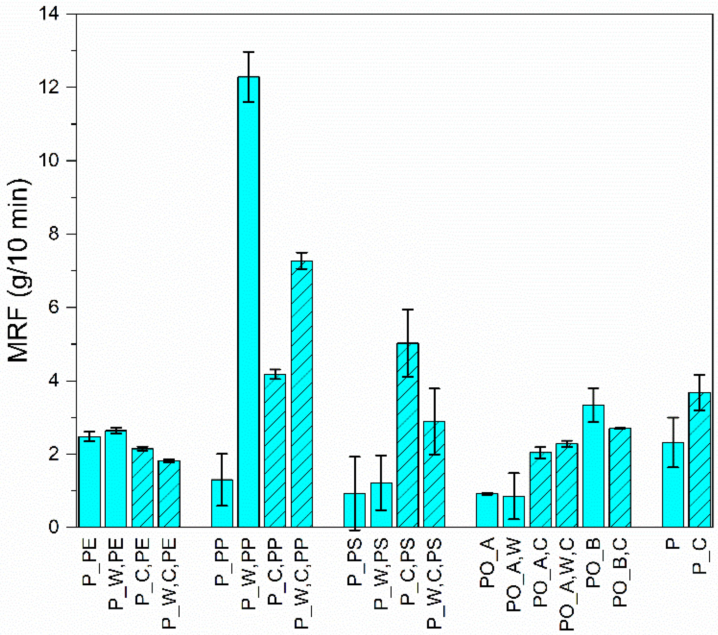

Figure 2. Averaged mass flow rate (MFR) values with standard deviation of all materials investigated.

3.4. Mechanical Material Properties

The measured MFR for the PE materials is between 1.8 and 2.6 g/10min. These are very low values. In the literature, MFR values between 0.5 and 25 g/10 min (test conditions: 190/2.16) are given for vLDPE and 0.35–17 g/10 min for vHDPE [24]. These are surprisingly good values, which indicate low material damage and, thus, good processability. No influence of the washing process can be seen.

PP materials show a significant increase in MFR due to washing. Thus, the MFR of P_PP is increased by a factor of 12 for P_W,PP. The MFR for P_C,PP is higher by a factor of three than for P_PP. The homogenised PP materials also show that a 40% higher MFR is achieved by washing. During all PP sample measurements, outgassing of volatile components was observed, which pushed the sample upwards [29,30]. This leads to certain measurement uncertainties. The reasons for this have not been further investigated in this paper. In the literature, MFR values of 0.5–65 (test conditions: 190/5) are found for vPP [24].

The large fluctuation ranges of all PS materials can be explained by the measurement uncertainties caused by clogging of the nozzle after a certain time. This was observed in all PS samples and can be explained by contaminants with a higher melting temperature [29]. The two heterogeneous PS materials show low MFR values compared to the homogenised PS materials. P_W,C,PS shows a lower MFR than P_C,PS. In the literature, MFR values between 1.5 and 18 g/10 min (test conditions: 200/5) are achieved for vPS [24]. Thus, the heterogeneous PS materials can be classified as very easy flowing and the homogeneous materials as normal flowing.

The heterogeneous PO_A materials show the lowest MFR values (below 1 g/10 min). There is no influence of washing on the MFR of the PO_A materials seen. Due to the homogenisation, the MFR rises to the MFR level of the PE materials. PO_B has a mean MFR of 3.3, which is reduced to 2.7 by homogenisation.

P has a mean MFR of 2.3, which is increased to 3.7 by homogenisation. The fluctuation ranges of the mean values can be explained by the measurement uncertainty caused by the outgassing of volatile components after a certain time [29,30]. The reasons for this have not been further investigated in this paper.

The tensile parameters, the Charpy impact strength (a_{cU}), and the Charpy notched impact strength (a_{cN}) are reported in Figure 3 for all materials. The results of the impact tests of all investigated materials are given in Appendix E, and the results of the tensile tests are given in Appendix F.

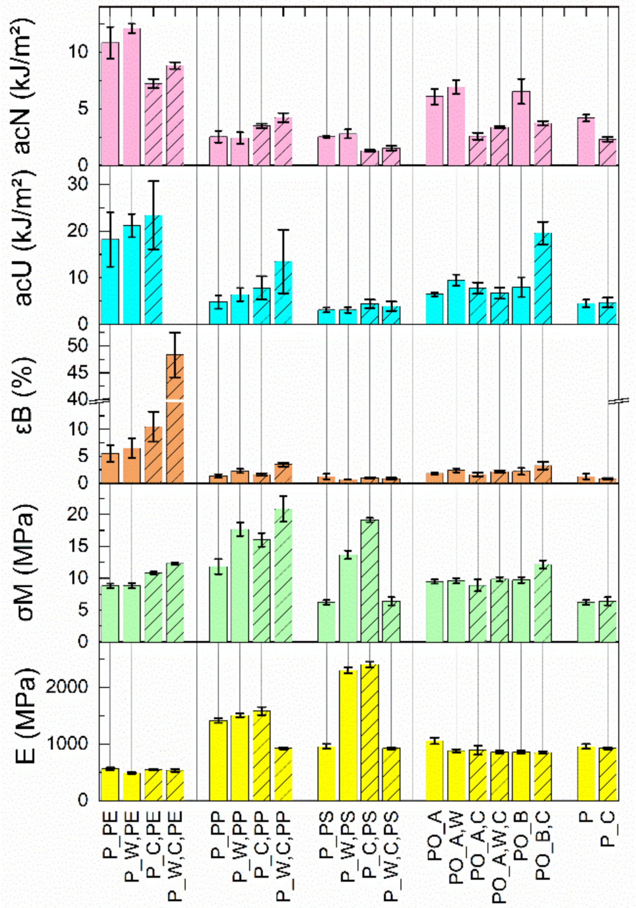

Figure 3. The results of the tensile tests (E, σ_M, ε_B), the Charpy impact strength (a_{cU}), and the Charpy notched impact strength (a_{cN}) for all materials investigated.

Only P_W,C,PE displays plastic deformation with a well-defined yield point in the stress–strain curves [31]. P_PS, P_W,C,PP, P_PE, PO_A, and PO_A,C showed this behaviour only with single test specimens. The other materials showed mainly brittle behaviour [31].

The Young's modulus (E) is for all PE materials in a similar range around 530 ± 40 MPa, and no significant influences due to washing or homogenisation can be detected. Comparison with data from the literature (vLDPE: ~200 MPa; vHDPE: ~1000 MPa) [24,31] shows that the achievable values are acceptable. According to the literature, vPE has the following tensile strengths (σ_M) and elongations at the yield point (ε_M): vLDPE—8–15 MPa at ~20%; and vHDPE—20–30 MPa at ~12% [24,31]. The literature gives elongations at break (ε_B) of 400–800% [24]. The measured values for σ_M correspond to those for vLDPE. However, both ε_M and ε_B are far below the literature values. The notched impact strength for all PE materials is in the range between 6 and 15 kJ/m^2. In the literature, values of about 6 kN/m^2 or without a break are given for vPE [24,31]. For the impact strength, the literature predominantly states "no break". The examined PE materials are mostly only partially broken, and P_W,C,PE is not broken at all (see notes in Tables A6–A25 in Appendix E) [32].

The PP materials have Young's moduli (~1500 MPa) almost three times higher than PE. Interestingly, P_W,C,PP is the lowest value of this material series at 923 ± 19 MPa. Again, a comparison with the literature values (E: 1300–1800 MPa) [23,33] shows that these values are acceptable. For vPP, σ_M between 25 and 40 MPa at $\varepsilon_{M,}$ around 20% [24], depending on the type, can be found in the literature. Depending on the vPP type, ε_B of 200–900% is possible [24]. The measured σ_M for PP materials is below 25 MPa, and only an ε_B of 2.5 ± 0.4% was measured. As with the PE materials, this indicates significant material embrittlement. The impact strength determined for the PP materials is below 20 kJ/m^2, which corresponds to the literature values [24]. The a_{cN} determined is between 2 and 5 kJ/m^2, which is slightly below the literature's values (vPP: 4–12 kJ/m^2) [24].

The Young's modulus of P_PS (~955 MPa) shows a sharp increase to ~2300 MPa for P_W,PS and about 2400 MPa for P_C,PS and thus, are the highest values of all materials examined. However, the combination of washing and homogenisation causes E (~923 MPa) to drop even below the initial value of P_PS. In the literature, values between 2200 and 3300 MPa [24] are given for vPS. For vPS, σ_B between 45 and 65 MPa/mm^2 and 3 and 4% for ε_B are found in the literature [24,33]. The measured a_{cU} of the PS materials is below 5 kJ/m^2 and below the values found in the literature (5–20 kJ/mm^2) for vPS [31,33]. The a_{cN} of the PS materials are between 1 and 2.5 kJ/m^2, and this is in the field of the literature values (vPS: ~2.0 kJ/m^2) [24].

Except for PO_A (1,053 ± 56 MPa), the PO materials have very similar Young's moduli between 830 and 900 MPa. Significant influences due to washing or homogenisation are not recognisable. The Young's moduli of the P and P_C material (~940 MPa) are also very similar, and no influence of homogenisation can be seen.

The values of σ_M and ε_B increases due to the homogenisation of PE, PP, and PO_B materials. With PS, a significant increase is measured of σ_M and ε_M by washing or compounding, but in combination, no significant change to P_PS is observed. The PO_A materials all show very similar values for σ_M and $\varepsilon_{M,}$ with the higher values for PO_A,W,C being achieved.

3.5. Ash Content

Figure 4 shows the ash contents (AC) of all investigated materials. The results of the ash content measurements of all investigated materials are given in Appendix H.

The AC for the PE materials decreases for both the heterogeneous and the homogeneous fraction from about 4% to 2.4% by about 40% due to the washing process. For the two heterogeneous PP materials, no influence of the washing on the AC of about 2.4% was observed. In the homogenised PP fraction, the AC decreases by approx. 40% from 2.7% to 1.7% due to washing. The AC of the PS and PO_A materials has been reduced by approx. 30% for both the heterogeneous and the homogeneous fraction by washing. The unwashed PO_A materials have the second-highest AC of all investigated materials. The average AC for the PO_B is 2.2%, and for PO_B,C 2.5%. The lower contents compared to PO_A can be explained by the cleaner input materials (e.g., pre-sorted mixed plastic fraction) used for PO_B production. As expected, the unwashed, unsorted mixed plastic fraction (P) has the highest AC (approx. 8.4% for P and 6.2% for P_C) since there was no surface cleaning by washing or losing fine material, e.g., by sorting.

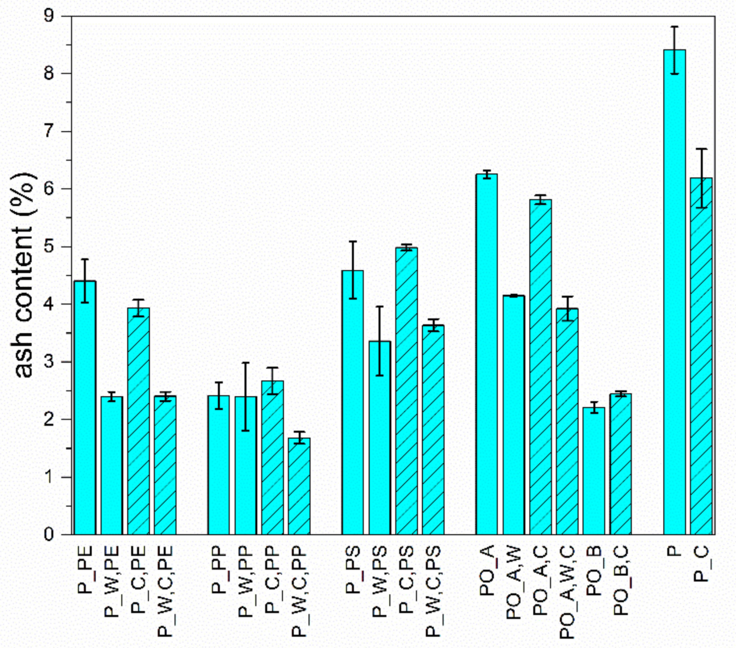

Figure 4. Calculated ash contents of all investigated materials.

3.6. Bulk Densities

The determined bulk densities of all materials are shown in Figure 5 before (flakes <4 mm) and after homogenisation (granulates). The results of the bulk densities of all investigated materials are given in Appendix G. Exemplary photos of the produced flakes (Figure A5), and granulates (Figure A6) are given in Appendix I.

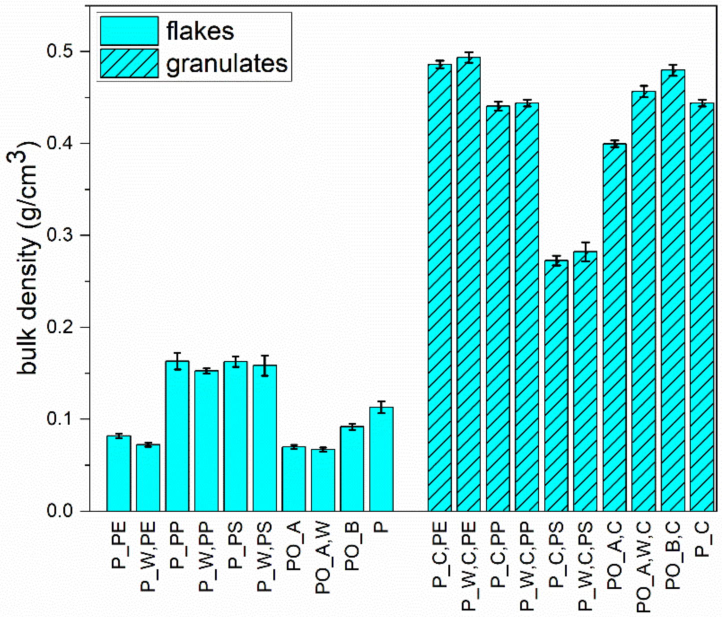

Figure 5. Determined bulk densities of all investigated materials before (flakes <4 mm) and after homogenisation (granulates).

3.6.1. Flakes

As expected, the bulk densities of all flakes are lower than those of the granules. The PE flakes have a bulk density of 0.082 ± 0.0023 g/cm^3 (P_PE) and 0.072 ± 0.0022 g/cm^3 (P_W,PE). The PP and PS flakes have a bulk density of approx. 0.16 g/cm^3, almost twice as high. For PP, this can be explained by the higher proportion of compacted, three-dimensional particles, although vPP (0.895–0.91 g/cm^3) is in the same material density range as vPE (0.87–0.97 g/cm^3) [24]. The PE flakes consist mainly of flat, thin, two-dimensional particles, although vPS has a higher material density (0.104–0.109 g/cm^3) [24] than vPE or vPP, and 2D particles are less common. Nevertheless, PS can occur in an expanded form (EPS: 0.0015–0.009 g/cm^3) [31], which would significantly reduce the bulk density. The PO_A flakes have a bulk density of about 0.07 g/cm^3. This suggests that the flakes contain a high proportion of mainly PE films. The bulk density of PO_B is 0.092 g/cm^3 and of P is 0.113 g/cm^3. No feeding problems (e.g., bridge formation) were observed for the flakes of all materials.

3.6.2. Granulates

The homogeneous PE granulates have the highest bulk density with 0.49 g/cm^3. The PP granulates have a bulk density of 0.44 g/cm^3. The PS granulates have the lowest bulk density of the homogeneous materials with approx. 0.27 g/cm^3. This can be explained by the fact that degradation processes caused increased outgassing during extrusion, which could not be sufficiently removed (see Figure A6 in Appendix I). Additionally, the different bulk densities of PO_A,C (0.4 g/cm^3) and PO_A,W,C (0.46 g/cm^3) can be explained in this way. The bulk density of PO_B,C was the second highest with 0.48 g/cm^3. P_C had a bulk density of 0.44 g/cm^3. Commercially available plastic granulates have a bulk density between 0.5 and 0.9 g/cm^3 [32]. No feeding problems (e.g., bridge formation) were observed for the granulates produced from all materials.

4. Discussion

The degree of crystallinity of polymers is directly related to their material properties: the more crystalline a polymer is, the harder and more brittle it is, and dimensional stability and melting point or softening point increase because intermolecular forces can act more effectively due to the more uniform arrangement of the molecules [13,22]. Despite the low crystallinity (36–38%), the PE materials examined, except for P_W,C,PE, show predominantly brittle material behaviour. Since a washing process somewhat improves the mechanical properties, it can be concluded that these are mainly impurities that negatively influence the material properties and that material ageing plays a subordinate role. Likewise, the distinct, second melting temperature at about 128 °C for P_PP and P_C,PP can be explained by the presence of organic impurities (e.g., other plastics with a density >1 g/cm^3), which can also be removed by washing. Therefore, T_C and T_{m1} of the PS materials can only be explained by contained organic impurities, e.g., PP.

The DSC curve progressions of the investigated PO materials as well as the determined values of T_C and a distinct T_{m1} at approx. 125 °C and a T_{m2} at approx. 163 °C indicate a higher PE than PP content of the PO materials. The melting temperature at approx. 110 °C of some PO materials and P_W,PE can be attributed to organic impurities or a higher LDPE content. A second crystallisation peak at approx. 120 °C for PO_B,C becomes clear from the HDPE content [34]. This and the higher ΔH_m of T_{m2} allow the assumption of a somewhat higher PP content than in PO_A. The similar DSC curves of mixed plastics (P) to the investigated PO materials lead to the hypothesis that most investigated P materials consist of PO. This indicates that a separation, and separate PE, PP, and PO processing is not necessary since the thermal properties do not change significantly.

The MFR results are surprisingly good for almost all materials examined, which indicate low material damage and thus, good processability. Depending on the material (high or low viscosity), suitable processing methods must be selected. The investigated PO and P materials have similar MRF values to the investigated PE materials. From this, it can be concluded for the MFR that a separation of the PE materials out of mixed plastics is not mandatory.

Except for the very brittle PS materials, all other materials investigated have surprisingly good mechanical properties. The mechanical characteristics show that wet processing, combined with a homogenisation step, does not necessarily lead to an improvement in mechanical properties. Most of the investigated materials show a clear decrease in mechanical properties compared to virgin homopolymers known from the literature. This indicates the existence of organic and inorganic impurities as well as material degradation due to ageing [35].

The investigations on the ash content of the materials show high inorganic contents, which are mostly significantly reduced by washing. These inorganic impurities are a plausible explanation for the observed deviations between the washed and unwashed materials. Additionally, a short service life (<1 year) is to be expected for the plastics in the wastes examined. It is therefore assumed that material ageing plays only a minor role. A part of the AC is due to inorganic fillers (e.g., glass fibres, silicates, oxides, and hydroxides) in the polymer matrix. Thus, despite the comparatively high ash contents (3–8%), the PO and P materials investigated show a good mechanical property profile. This suggests that the inorganic impurities contained act to a certain extent as a reinforcing material.

Knowledge of the bulk density of free-flowing materials is an essential parameter for the design of storage, transport, and dosing equipment. The bulk density is also essential for the material feed behaviour and the pressure build-up in solid conveying areas of extruders or injection moulding machines [36]. It should be noted that the pelletising system's settings and the melt strand temperature have a significant influence on the pellet geometry and, thus, on the bulk density [31]. Commercially available plastic granulates have a bulk density between 0.5 and 0.9 g/cm^3 [33]. As the granulate bulk densities determined are only slightly lower, with the exception of P_C,PS, and P_W,C,PS, it is assumed that these materials have good conveying and feeding properties. No feeding problems (e.g., bridging) occurred with the flakes and granulates produced from all materials.

5. Conclusions

The investigations have shown that all waste materials could be processed into plastic-rich fractions with a grain size < 4 mm using simple waste treatment without any significant problems. The processing of the different plastic fractions with simple compression moulding showed that all PE, PP, PO, and P materials could be processed without any major problems. This, together with the low MFR values, suggests that conventional extrusion into semi-finished products such as pipes or plates could be technically possible. A list of potential products for the materials investigated is given in Appendix J. The injection moulding process must be tested, and investigations must be carried out with a high-pressure capillary rheometer. Furthermore, thermogravimetric (TGA) and Fourier-transform infrared (FTIR) analysis to determine chemical structure changes possible for polymeric waste during the technological process of the materials is recommended for future investigations. The PS materials emitted gas in both processing variants, and several test runs were necessary to find a stable processing method. Therefore, an evaluation of volatile organic compound emissions from the materials is necessary if they would be implemented in industrial processes. The PET materials could neither be homogenised nor compression moulded due to excessive contamination.

In some cases, the material properties determined are (Young's modulus, impact strength) clearly below those of virgin polymers. This limits the product range that can be manufactured and its range of applications. The results also show that an upstream washing process improves the achievable properties, but homogenisation does not necessarily improve properties. It was also found that a higher treatment depth (recovery of plastic types) from mixed wastes is not necessary since the PO and mixed plastics fractions showed similarly good material data with good processability.

In summary, the investigations show that the recovery and simple treatment of plastics from mixed, contaminated wastes into at least downcycling products seems to be possible. The transfer of used plastics from thermal recovery to recycling could make an important contribution to achieving additional recycling targets, resource conservation, and CO_2 and waste reduction.

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Abbreviations

Abbreviation	Description
ΔH_C	crystallisation enthalpy
ΔH_m	melting enthalpy
ε_B	elongation at break
ε_M	maximum elongation at the yield point
σ_B	tensile strength at break
σ_M	maximum tensile strength
AC	ash content
a_{cN}	notched impact strength
a_{cU}	impact strength
C	homogenised
CO_2	carbon dioxide—greenhouse gas
D	screw diameter
DS	dry substance
DSC	differential scanning calorimetry
E	Young's modulus
e.g.,	for example
EPS	expanded polystyrene
EU	European Union
FTIR	Fourier-transform infrared
HDPE	high-density polyethylene
LDPE	low-density polyethylene
LLDPE	linear low-density polyethylene
min	minutes
MFR	melt (mass) flow rate
Mt	million tonnes
NIR	near-infrared

Abbreviation	**Description**
OS	original substance
P	plastics
P&C	paper and cardboard
PO	polyolefins
(v)PE	(virgin) polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride
rpm	revolutions per minute
SRF	solid recovered fuel
T_C	crystallisation temperature
Tg	glass transition temperature
T_m	melting temperature
TSE	twin-screw extruder
v	virgin
W	washed

Appendix A. Total Composition of SRF and Plastic Type Content

Table A1. Total composition of SRF determined by manual sorting analysis (Note: fine fraction <20 (8.5%) mm was separated and is not considered in the table).

Fraction	Mass (kg)	Mass (%)
Plastics	150.4	86.5
Metals	1.01	0.6
P&C [1]	10.03	5.8
Inert	1.04	0.6
Wood	0.17	0.1
Other	11.27	6.5
Total	173.92	100

[1] P&C: paper and cardboard.

Table A2. Plastic type content of P determined by sensor-based sorting with near-infrared.

Fraction	Mass (kg)	Mass (%)
PE	44.64	36.42
PP	19.19	15.66
PET	25.34	20.67
PS	7.41	6.04
Other	26	21.21
Total	122.58	100

Appendix B. DSC Measurements

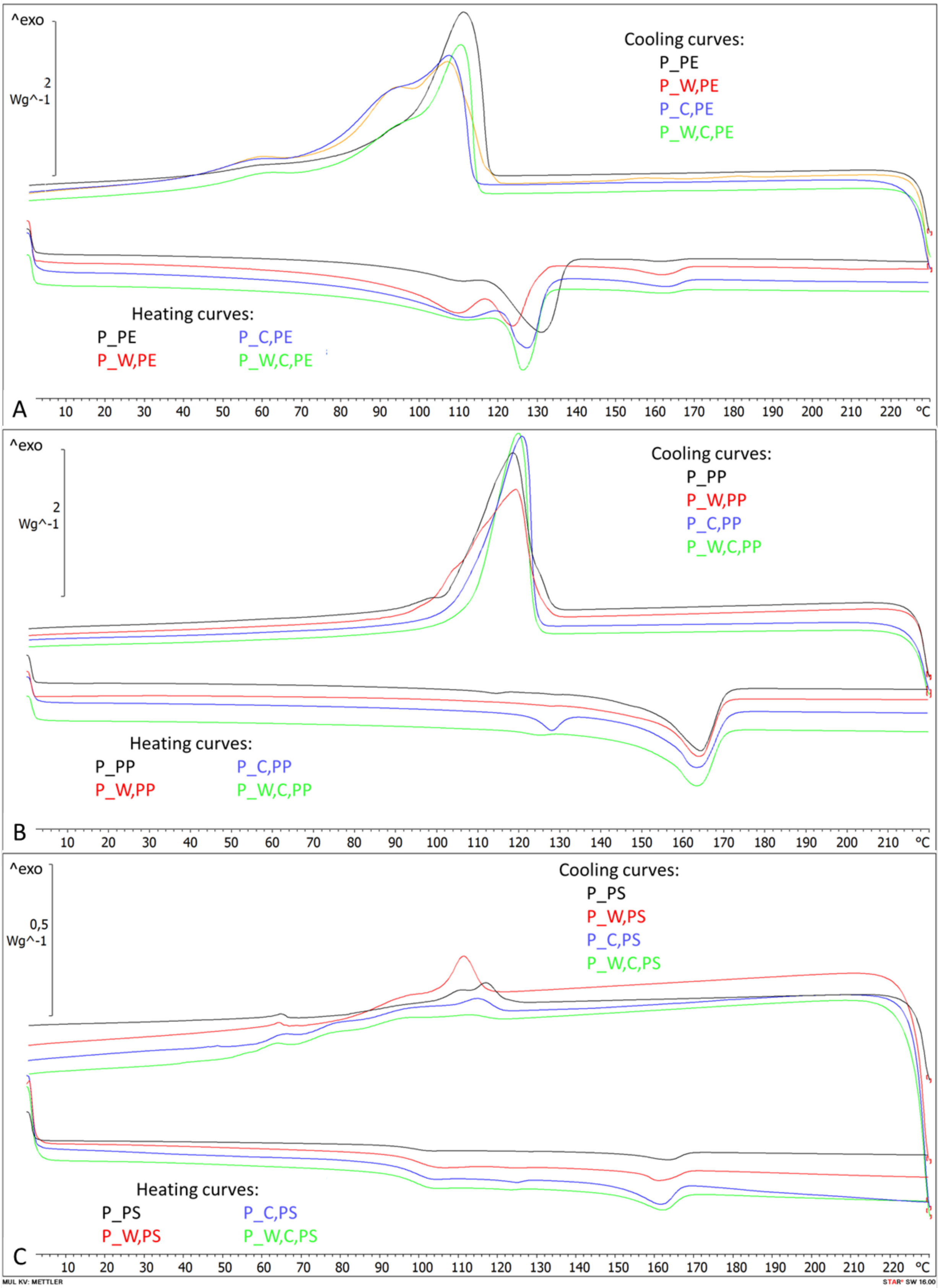

Figure A1. *Cont.*

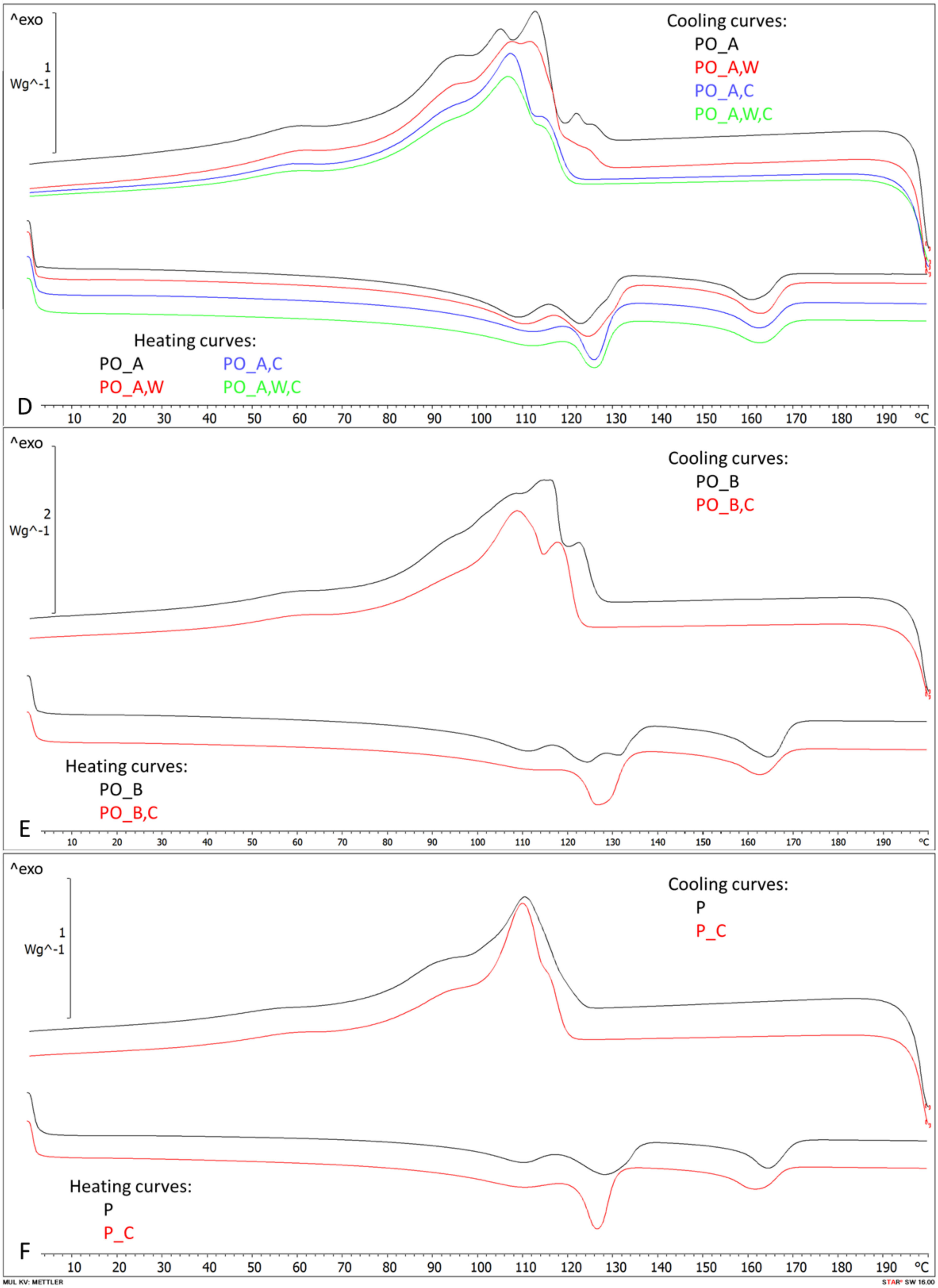

Figure A1. Representative DSC measurement results for (**A**) PE, (**B**) PP, (**C**) PS materials. Note: cooling with 20 K/min on top and second heating with 10 K/min at the bottom of each diagram, (**D**) PO_A, (**E**) PO_B, and (**F**) P materials. Note: cooling with 20 K/min on top and second heating with 10 K/min at the bottom of each diagram.

Appendix C. Processing Conditions

Table A3. Extrusion conditions for homogenization of all investigated materials.

Materials:	**P_PE; P_W,PE; P_PP; P_W,PP; P_PS; P_W,PS**			
Zones	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Temperature (°C)	150	170	170	170
Materials:	PO_A; PO_A,W; PO_B			
	Zone 1	Zone 2	Zone 3	Zone 4
Temperature (°C)	150	180	200	205

Table A4. Compression moulding conditions of all investigated materials.

Materials:	**P_PE**	**P_W,PE**			
Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Temperature (°C)	210	210	210	210	30
Pressure (bar)	1	10	50	100	100
Time (min)	8	5	4	4	15
Materials:	P_C,PE	P_W,C,PE			
Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Temperature (°C)	200	200	200	200	30
Pressure (bar)	1	10	50	100	100
Time (min)	10	5	4	4	15
Materials:	P_PP	P_W,PP	P_C,PP	P_W,C,PP	
Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Temperature (°C)	200	200	200	200	30
Pressure (bar)	1	10	50	100	100
Time (min)	14	5	4	4	15
Materials:	P_PS	P_W,PS	P_C,PS	P_W,C,PS	
Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Temperature (°C)	207	205	205	205	30
Pressure (bar)	5	10	50	100	100
Time (min)	10	5	4	4	15
Materials: PO_A	PO_A,W	PO_A,C	PO_A,W,C	PO_B	PO_B,C
Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Temperature (°C)	210	210	210	210	30
Pressure (bar)	1	10	50	100	100
Time (min)	8	5	4	4	15
Materials:	P	P_C			
Phases	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Temperature (°C)	210	210	210	210	30
Pressure (bar)	1	10	50	100	100
Time (min)	8	5	4	4	15

Appendix D. MFR Measurements

Table A5. MFR measurement results.

Sample Identification	Sample Number	Total Mass (g)	Time Interval (min)	MFR (g/10 min)	Mean Value (g/10 min)	Standard Deviation (g/10 min)
P_PE	P1	2.10	10	2.571	2.479	0.130
P_PE	P2	2.09	10	2.387		
P_W,PE	P1	2.71	10	2.586	2.641	0.078
P_W,PE	P2	3.08	10	2.696		
P_C,PE	P1	2.38	10	2.184	2.147	0.053
P_C,PE	P2	2.31	15	2.110		
P_W,C,PE	P1	2.41	20	1.794	1.820	0.037
P_W,C,PE	P2	2.40	20	1.846		
P_PP	P1	2.20	5	1.805	1.304	0.708
P_PP	P2	2.18	10	0.803		
P_W,PP	P1	2.78	10	11.801	12.286	0.687
P_W,PP	P2	3.35	5	12.772		
P_C,PP	P1	2.53	10	3.932	4.178	0.130
P_C,PP	P2	2.62	10	4.029		
P_W,C,PP	P1	2.31	10	7.114	7.273	0.225
P_W,C,PP	P2	3.19	10	7.432		
P_PS	P1	2.82	20	0.218	0.927	1.003
P_PS	P2	2.56	10	1.636		
P_W,PS	P1	3.21	20	1.744	1.217	0.746
P_W,PS	P2	2.94	20	0.689		
P_C,PS	P1	2.00	10	5.673	5.026	0.914
P_C,PS	P2	2.00	10	4.380		
P_W,C,PS	P1	2.78	10	3.526	2.891	0.898
P_W,C,PS	P2	2.73	10	2.255		
PO_A	P1	2.67	20	0.936	0.920	0.023
PO_A	P2	2.72	20	0.904		
PO_A,W	P1	2.56	20	0.410	0.855	0.630
PO_A,W	P2	2.50	20	1.301		
PO_A,C	P1	2.23	20	1.934	2.042	0.153
PO_A,C	P2	2.56	20	2.150		
PO_A,W,C	P1	2.34	15	2.220	2.280	0.085
PO_A,W,C	P2	2.71	15	2.341		
PO_B	P1	2.40	10	3.012	3.338	0.460
PO_B	P2	2.44	10	3.663		
PO_B,C	P1	2.64	10	2.690	2.700	0.013
PO_B,C	P2	2.39	10	2.709		
P	P1	2.32	10	2.798	2.319	0.677
P	P2	2.94	10	1.840		
P_C	P1	2.35	10	3.333	3.676	0.485
P_C	P2	2.50	10	4.019		

Appendix E. Impact Tests

Table A6. Results of the notched impact tests and unnotched impact tests of P_PE.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.54	10.10	3.51	0.000035	0.988	0.004	0.000984	27.8	partially broken
P2	78.35	10.09	3.40	0.000034	0.500	0.004	0.000496	14.5	partially broken
P3	78.50	10.07	3.42	0.000034	0.596	0.004	0.000592	17.2	partially broken
P4	78.62	10.09	3.42	0.000035	0.452	0.004	0.000448	13.0	
P5	78.26	10.08	3.48	0.000035	0.660	0.004	0.000656	18.7	
P6	78.62	8.12	3.51	0.000029	0.322	0.007	0.000315	11.1	
P7	78.64	8.15	3.51	0.000029	0.298	0.007	0.000291	10.2	
P8	78.72	7.89	3.48	0.000027	0.357	0.007	0.000350	12.7	
P9	78.55	8.00	3.53	0.000028	0.324	0.007	0.000317	11.2	
P10	78.71	7.95	3.49	0.000028	0.255	0.007	0.000248	8.9	

Table A7. Results of the notched impact tests and unnotched impact tests of P_W,PE.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.94	10.08	3.50	0.000035	0.808	0.004	0.000804	22.8	partially broken
P2	79.04	10.04	3.52	0.000035	0.732	0.004	0.000728	20.6	partially broken
P3	79.03	9.95	3.49	0.000035	0.604	0.004	0.000600	17.3	partially broken
P4	78.58	10.03	3.51	0.000035	0.844	0.004	0.000840	23.9	partially broken
P5	79.10	10.15	3.51	0.000036	0.772	0.004	0.000768	21.6	partially broken
P6	77.55	7.90	3.70	0.000029	0.348	0.007	0.000341	11.7	
P7	78.45	7.94	3.53	0.000028	0.337	0.007	0.000330	11.8	
P8	78.46	7.84	3.54	0.000028	0.345	0.007	0.000338	12.2	partially broken
P9	78.30	8.03	3.49	0.000028	0.348	0.007	0.000341	12.2	
P10	77.60	7.79	3.60	0.000028	0.364	0.007	0.000357	12.7	partially broken

Table A8. Results of the notched impact tests and unnotched impact tests of P_C,PE.

Scheme Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.17	10.14	3.69	0.000037	0.764	0.004	0.000760	20.3	
P2	79.06	10.15	3.72	0.000038	1.068	0.004	0.001064	28.2	
P3	79.17	10.18	3.75	0.000038	0.604	0.004	0.000600	15.7	
P4	79.03	10.17	3.65	0.000037	0.716	0.004	0.000712	19.2	
P5	78.08	10.14	3.64	0.000037	1.240	0.004	0.001236	33.5	
P6	78.13	7.96	3.58	0.000028	0.213	0.007	0.000206	7.2	
P7	78.04	7.95	3.55	0.000028	0.213	0.007	0.000206	7.3	
P8	78.03	8.01	3.56	0.000029	0.230	0.007	0.000223	7.8	
P9	78.10	8.00	3.68	0.000029	0.206	0.007	0.000199	6.8	
P10	78.10	8.01	3.61	0.000029	0.214	0.007	0.000207	7.2	

Table A9. Results of the notched impact tests and unnotched impact tests of P_W,C,PE.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.52	10.18	3.59	0.000037	2.080	0.030	0.002050	56.1	not broken
P2	78.18	10.16	3.54	0.000036	1.260	0.030	0.001230	34.2	not broken
P3	78.37	10.19	3.53	0.000036	3.250	0.030	0.003220	89.5	not broken
P4	78.25	10.22	3.55	0.000036	2.770	0.030	0.002740	75.5	not broken
P5	78.49	10.15	3.53	0.000036	3.000	0.030	0.002970	82.9	not broken
P6	78.67	8.00	3.57	0.000029	0.270	0.007	0.000263	9.2	
P7	78.72	7.90	3.58	0.000028	0.251	0.007	0.000244	8.6	
P8	78.77	7.82	3.56	0.000028	0.255	0.007	0.000248	8.9	
P9	78.74	8.05	3.60	0.000029	0.267	0.007	0.000260	9.0	
P10	78.79	8.06	3.59	0.000029	0.252	0.007	0.000245	8.5	

Table A10. Results of the notched impact tests and unnotched impact tests of P_PP.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.60	10.24	3.81	0.000039	0.188	0.008	0.000180	4.6	
P2	77.92	10.25	3.62	0.000037	0.258	0.008	0.000250	6.7	
P3	77.94	10.25	3.62	0.000037	0.126	0.008	0.000118	3.2	
P4	77.92	10.25	3.63	0.000037	0.152	0.008	0.000144	3.9	
P5	77.91	10.25	3.62	0.000037	0.213	0.008	0.000205	5.5	
P6	78.80	8.37	3.59	0.000030	0.084	0.007	0.000077	2.6	
P7	79.26	8.29	3.63	0.000030	0.073	0.007	0.000066	2.2	
P8	78.20	8.20	3.60	0.000030	0.097	0.007	0.000090	3.0	
P9	78.06	8.13	3.63	0.000030	0.095	0.007	0.000088	3.0	
P10	77.68	8.57	3.67	0.000031	0.069	0.007	0.000062	2.0	

Table A11. Results of the notched impact tests and unnotched impact tests of P_W,PP.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	77.24	10.25	3.65	0.000037	0.220	0.004	0.000216	5.8	
P2	77.65	10.30	3.60	0.000037	0.180	0.004	0.000176	4.7	
P3	77.40	10.24	3.58	0.000037	0.312	0.004	0.000308	8.4	
P4	77.88	10.18	3.60	0.000037	0.216	0.004	0.000212	5.8	
P5	77.59	10.20	3.55	0.000036	0.264	0.004	0.000260	7.2	
P6	79.02	7.96	3.65	0.000029	0.068	0.007	0.000061	2.1	
P7	77.68	7.96	3.80	0.000030	0.064	0.007	0.000057	1.9	
P8	77.86	8.38	3.76	0.000032	0.106	0.007	0.000099	3.1	
P9	77.92	8.01	3.77	0.000030	0.072	0.007	0.000065	2.2	
P10	79.02	8.22	3.80	0.000031	0.096	0.007	0.000089	2.8	

Table A12. Results of the notched impact tests and unnotched impact tests of P_C,PP.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	77.61	10.35	3.88	0.000040	0.197	0.008	0.000189	4.7	
P2	78.07	10.25	3.70	0.000038	0.221	0.008	0.000213	5.6	
P3	77.84	10.10	3.70	0.000037	0.357	0.008	0.000349	9.3	
P4	78.05	10.22	3.73	0.000038	0.363	0.008	0.000355	9.3	
P5	77.47	10.02	3.69	0.000037	0.382	0.008	0.000374	10.1	
P6	77.77	8.06	3.68	0.000030	0.121	0.007	0.000114	3.8	
P7	78.08	8.24	3.64	0.000030	0.116	0.007	0.000109	3.6	
P8	77.89	8.37	3.66	0.000031	0.106	0.007	0.000099	3.2	
P9	77.85	8.14	3.69	0.000030	0.108	0.007	0.000101	3.4	
P10	77.94	8.43	3.92	0.000033	0.119	0.007	0.000112	3.4	

Table A13. Results of the notched impact tests and unnotched impact tests of P_W,C,PP.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	77.87	10.25	3.70	0.000038	0.948	0.004	0.000944	24.9	
P2	77.85	10.20	3.71	0.000038	0.464	0.004	0.000460	12.2	
P3	77.49	10.25	3.80	0.000039	0.508	0.004	0.000504	12.9	
P4	77.50	10.25	3.63	0.000037	0.244	0.004	0.000240	6.5	
P5	77.47	10.00	3.65	0.000037	0.412	0.004	0.000408	11.2	
P6	77.74	8.14	3.65	0.000030	0.131	0.007	0.000124	4.2	
P7	77.68	8.02	3.65	0.000029	0.133	0.007	0.000126	4.3	
P8	77.74	8.22	3.65	0.000030	0.113	0.007	0.000106	3.5	
P9	77.78	7.99	3.67	0.000029	0.139	0.007	0.000132	4.5	
P10	77.63	8.28	3.61	0.000030	0.147	0.007	0.000140	4.7	

Table A14. Results of the notched impact tests and unnotched impact tests of P_PS.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.32	10.30	3.88	0.000040	0.121	0.006	0.000115	2.9	
P2	79.54	10.30	3.86	0.000040	0.098	0.006	0.000092	2.3	
P3	79.24	10.30	3.85	0.000040	0.129	0.006	0.000123	3.1	
P4	79.75	10.30	3.91	0.000040	0.143	0.006	0.000137	3.4	
P5	79.59	10.10	3.90	0.000039	0.149	0.006	0.000143	3.6	
P6	79.10	8.03	3.93	0.000032	0.091	0.006	0.000085	2.7	
P7	78.58	7.93	3.98	0.000032	0.085	0.006	0.000079	2.5	
P8	78.46	7.83	3.96	0.000031	0.083	0.006	0.000077	2.5	
P9	78.62	7.95	3.98	0.000032	0.085	0.006	0.000079	2.5	
P10	78.78	8.01	3.95	0.000032	0.088	0.006	0.000082	2.6	

Table A15. Results of the notched impact tests and unnotched impact tests of P_W,PS.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.61	10.29	3.89	0.000040	0.101	0.008	0.000093	2.3	
P2	79.39	10.18	3.88	0.000039	0.152	0.008	0.000144	3.6	
P3	80.18	10.21	3.85	0.000039	0.109	0.008	0.000101	2.6	
P4	79.55	10.27	3.95	0.000041	0.145	0.008	0.000137	3.4	
P5	79.47	10.35	3.87	0.000040	0.157	0.008	0.000149	3.7	
P6	78.44	7.88	3.89	0.000031	0.110	0.007	0.000103	3.4	
P7	78.31	8.17	3.93	0.000032	0.109	0.007	0.000102	3.2	
P8	79.49	8.39	3.84	0.000032	0.092	0.007	0.000085	2.6	
P9	79.65	8.18	3.85	0.000031	0.079	0.007	0.000072	2.3	
P10	79.74	8.50	3.86	0.000033	0.091	0.007	0.000084	2.6	

Table A16. Results of the notched impact tests and unnotched impact tests of P_C,PS.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.92	10.40	3.99	0.000041	0.157	0.008	0.000149	3.6	
P2	79.79	10.40	4.03	0.000042	0.230	0.008	0.000222	5.3	
P3	78.26	10.36	3.95	0.000041	0.175	0.008	0.000167	4.1	
P4	79.78	10.40	4.02	0.000042	0.157	0.008	0.000149	3.6	
P5	79.92	10.14	3.99	0.000040	0.222	0.008	0.000214	5.3	
P6	78.64	8.26	3.97	0.000033	0.050	0.007	0.000043	1.3	
P7	78.68	8.12	3.96	0.000032	0.048	0.007	0.000041	1.3	
P8	78.73	8.07	3.98	0.000032	0.047	0.007	0.000040	1.2	
P9	78.72	8.01	3.99	0.000032	0.052	0.007	0.000045	1.4	
P10	78.85	7.95	4.02	0.000032	0.047	0.007	0.000040	1.3	

Table A17. Results of the notched impact tests and unnotched impact tests of P_W,C,PS.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.42	10.30	4.04	0.000042	0.155	0.008	0.000147	3.5	
P2	79.09	10.25	4.00	0.000041	0.114	0.008	0.000106	2.6	
P3	79.28	10.35	3.95	0.000041	0.163	0.008	0.000155	3.8	
P4	79.44	10.30	3.91	0.000040	0.179	0.008	0.000171	4.2	
P5	79.45	10.31	3.90	0.000040	0.217	0.008	0.000209	5.2	
P6	79.08	8.02	3.94	0.000032	0.067	0.007	0.000060	1.9	
P7	79.12	8.04	3.87	0.000031	0.055	0.007	0.000048	1.5	
P8	79.36	8.08	3.99	0.000032	0.054	0.007	0.000047	1.5	
P9	79.29	7.88	3.98	0.000031	0.049	0.007	0.000042	1.3	
P10	79.37	8.20	3.89	0.000032	0.055	0.007	0.000048	1.5	

Table A18. Results of the notched impact tests and unnotched impact tests of PO_A.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.36	10.03	3.76	0.000038	0.276	0.008	0.000268	7.1	partially broken
P2	79.57	10.06	3.73	0.000038	0.245	0.008	0.000237	6.3	partially broken
P3	79.46	10.13	3.76	0.000038	0.252	0.008	0.000244	6.4	partially broken
P4	79.66	10.06	3.75	0.000038	0.242	0.008	0.000234	6.2	partially broken
P5	79.38	10.03	3.80	0.000038	0.247	0.008	0.000239	6.3	partially broken
P6	78.64	8.13	3.79	0.000031	0.200	0.007	0.000193	6.3	
P7	78.57	8.00	3.80	0.000030	0.203	0.007	0.000196	6.4	partially broken
P8	78.63	8.08	3.78	0.000031	0.159	0.007	0.000152	5.0	
P9	78.61	8.15	3.83	0.000031	0.193	0.007	0.000186	6.0	partially broken
P10	78.59	8.13	3.78	0.000031	0.215	0.007	0.000208	6.8	

Table A19. Results of the notched impact tests and unnotched impact tests of PO_A,W.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.52	10.11	3.68	0.000037	0.316	0.004	0.000312	8.4	
P2	78.98	10.11	3.82	0.000039	0.388	0.004	0.000384	9.9	partially broken
P3	78.64	10.10	3.70	0.000037	0.308	0.004	0.000304	8.1	partially broken
P4	78.66	10.20	3.68	0.000038	0.396	0.004	0.000392	10.4	partially broken
P5	78.70	10.15	3.65	0.000037	0.396	0.004	0.000392	10.6	partially broken
P6	78.85	8.01	3.67	0.000029	0.234	0.007	0.000227	7.7	
P7	78.86	8.30	3.61	0.000030	0.219	0.007	0.000212	7.1	
P8	78.85	8.13	3.62	0.000029	0.191	0.007	0.000184	6.3	
P9	78.75	8.15	3.65	0.000030	0.217	0.007	0.000210	7.1	
P10	78.70	8.09	3.64	0.000029	0.200	0.007	0.000193	6.6	

Table A20. Results of the notched impact tests and unnotched impact tests of PO_A,C.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.55	10.05	3.87	0.000039	0.234	0.008	0.000226	5.8	
P2	78.61	10.03	3.61	0.000036	0.289	0.008	0.000281	7.8	
P3	78.66	9.96	3.75	0.000037	0.311	0.008	0.000303	8.1	
P4	78.37	9.95	3.63	0.000036	0.318	0.008	0.000310	8.6	
P5	78.59	9.81	3.65	0.000036	0.325	0.008	0.000317	8.9	
P6	78.56	8.35	3.65	0.000030	0.073	0.007	0.000066	2.2	
P7	78.51	8.21	3.65	0.000030	0.097	0.007	0.000090	3.0	
P8	78.75	8.62	3.59	0.000031	0.084	0.007	0.000077	2.5	
P9	78.21	8.35	3.68	0.000031	0.086	0.007	0.000079	2.6	
P10	78.60	8.18	3.63	0.000030	0.088	0.007	0.000081	2.7	

Table A21. Results of the notched impact tests and unnotched impact tests of PO_A,W,C.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.96	9.90	3.61	0.000036	0.232	0.007	0.000225	6.3	
P2	79.11	9.89	3.85	0.000038	0.245	0.007	0.000238	6.3	
P3	78.71	9.97	3.59	0.000036	0.231	0.007	0.000224	6.3	
P4	78.62	9.98	3.61	0.000036	0.214	0.007	0.000207	5.7	
P5	78.48	10.04	3.57	0.000036	0.321	0.007	0.000314	8.8	
P6	79.21	7.94	3.54	0.000028	0.105	0.007	0.000098	3.5	
P7	79.15	8.14	3.53	0.000029	0.106	0.007	0.000099	3.4	
P8	79.42	8.02	3.88	0.000031	0.106	0.007	0.000099	3.2	
P9	79.10	8.00	3.57	0.000029	0.105	0.007	0.000098	3.4	
P10	79.20	8.08	3.57	0.000029	0.105	0.007	0.000098	3.4	

Table A22. Results of the notched impact tests and unnotched impact tests of PO_B.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.79	9.96	3.61	0.000036	0.202	0.008	0.000194	5.4	partially broken
P2	78.55	9.96	3.57	0.000036	0.342	0.008	0.000334	9.4	partially broken
P3	78.90	9.92	3.56	0.000035	0.284	0.008	0.000276	7.8	partially broken
P4	78.42	9.97	3.61	0.000036	0.390	0.008	0.000382	10.6	
P5	78.49	10.02	3.53	0.000035	0.245	0.008	0.000237	6.7	partially broken
P6	78.46	8.08	3.69	0.000030	0.206	0.007	0.000199	6.7	
P7	78.41	7.95	3.50	0.000028	0.183	0.007	0.000176	6.3	partially broken
P8	78.55	7.92	3.59	0.000028	0.147	0.007	0.000140	4.9	partially broken
P9	78.53	7.94	3.52	0.000028	0.195	0.007	0.000188	6.7	
P10	78.39	7.85	3.77	0.000030	0.245	0.007	0.000238	8.0	

Table A23. Results of the notched impact tests and unnotched impact tests of PO_B,C.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.64	9.99	3.51	0.000035	0.708	0.004	0.000704	20.1	
P2	78.58	9.93	3.52	0.000035	0.820	0.004	0.000816	23.3	
P3	78.72	10.00	3.56	0.000036	0.676	0.004	0.000672	18.9	
P4	78.72	9.95	3.60	0.000036	0.680	0.004	0.000676	18.9	
P5	78.61	9.99	3.54	0.000035	0.596	0.004	0.000592	16.7	
P6	78.68	8.08	3.56	0.000029	0.121	0.007	0.000114	4.0	
P7	78.70	7.95	3.58	0.000028	0.111	0.007	0.000104	3.7	
P8	78.72	7.92	3.57	0.000028	0.106	0.007	0.000099	3.5	
P9	78.70	7.94	3.55	0.000028	0.113	0.007	0.000106	3.8	
P10	78.81	7.85	3.56	0.000028	0.112	0.007	0.000105	3.8	

Table A24. Results of the notched impact tests and unnotched impact tests of P.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{leer} (J)	W_{empty} (kJ)	a_{cN} (kJ/m^2)	Note
P1	78.72	10.07	4.08	0.000041	0.162	0.008	0.000154	3.7	parcially broken
P2	79.23	10.16	3.87	0.000039	0.214	0.008	0.000206	5.2	parcially broken
P3	79.14	10.32	3.88	0.000040	0.189	0.008	0.000181	4.5	parcially broken
P4	79.20	10.15	3.87	0.000039	0.151	0.008	0.000143	3.6	parcially broken
P5	79.10	10.17	4.15	0.000042	0.231	0.008	0.000223	5.3	parcially broken
P6	79.00	8.43	3.88	0.000033	0.129	0.007	0.000122	3.7	
P7	79.17	8.05	3.95	0.000032	0.155	0.007	0.000148	4.7	
P8	79.28	8.01	3.93	0.000031	0.135	0.007	0.000128	4.1	
P9	79.24	8.02	3.89	0.000031	0.143	0.007	0.000136	4.4	
P10	79.20	8.01	3.97	0.000032	0.138	0.007	0.000131	4.1	

Table A25. Results of the notched impact tests and unnotched impact tests of P_C.

Sample Number	l (mm)	b_B (mm)	d (mm)	A (m^2)	W (J)	W_{empty} (J)	W_{corr} (kJ)	a_{cN} (kJ/m^2)	Note
P1	79.23	9.92	3.65	0.000036	0.184	0.008	0.000176	4.9	
P2	78.38	10.05	3.72	0.000037	0.132	0.008	0.000124	3.3	
P3	78.42	10.01	3.69	0.000037	0.235	0.008	0.000227	6.1	
P4	78.42	9.97	3.65	0.000036	0.169	0.008	0.000161	4.4	
P5	78.19	9.95	3.66	0.000036	0.188	0.008	0.000180	4.9	
P6	79.47	7.98	3.70	0.000030	0.077	0.007	0.000070	2.4	
P7	78.38	8.00	3.67	0.000029	0.074	0.007	0.000067	2.3	
P8	79.41	7.97	3.69	0.000029	0.078	0.007	0.000071	2.4	
P9	79.55	7.96	3.70	0.000029	0.066	0.007	0.000059	2.0	
P10	79.35	8.06	3.67	0.000030	0.083	0.007	0.000076	2.6	

Appendix F. Tensile Tests

Table A26. Results of the tensile tests of P_PE.

Sample Number	Curve Type	E_t (MPa)	s_y (MPa)	F_y (N)	e_y (%)	e_Y (mm)	s_m (MPa)	s_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	c	532.0	9.12	325.6	6.06	3.028	9.12	325.6	6.06	3.028	8.227	293.7	7.08	3.54	9.89	3.61	35.70
P2	a	560.6	–	–	–	–	8.67	320.9	4.44	2.219	8.393	310.6	4.93	2.47	10	3.7	37.00
P3	c	579.0	9.19	329.4	5.43	2.714	9.19	329.4	5.43	2.714	1.836	65.9	7.36	3.68	9.88	3.63	35.86
P4	a	550.6	–	–	–	–	8.30	292.5	3.48	1.738	7.969	281.0	3.81	1.90	9.85	3.58	35.26
P5	c	593.3	–	–	–	–	8.61	315.9	3.79	1.897	8.404	308.4	3.93	1.96	9.89	3.71	36.69
P6	c	551.5	9.01	321.2	5.17	2.586	9.01	321.2	5.17	2.586	8.320	296.5	6.13	3.07	9.9	3.6	35.64
Mean value		561.2	9.11	325.4	5.55	2.776	8.82	317.6	4.73	2.363	7.192	259.3	5.54	2.77			
Standard deviation		21.9	0.09	4.1	0.45	0.227	0.35	13.1	1.00	0.499	2.628	95.4	1.55	0.77			
Relative deviation [%]		3.91	0.97	1.27	8.18	8.18	3.93	4.13	21.10	21.10	36.55	36.78	27.94	27.95			

Table A27. Results of the tensile tests of P_W,PE.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	c	486.5	9.04	321.2	7.21	3.604	6.472	230.0	9.75	4.87	10.04	3.54	35.54
P2	c	498.6	9.13	324.5	5.68	2.842	8.884	315.7	6.00	3.00	10.01	3.55	35.54
P3	c	459.6	9.16	330.1	6.70	3.352	9.163	330.1	6.70	3.35	9.98	3.61	36.03
P4	c	494.7	8.82	314.8	6.63	3.316	8.824	314.8	6.63	3.32	10.05	3.55	35.68
P5	c	483.5	8.12	291.8	3.95	1.973	7.898	284.0	4.16	2.08	10.1	3.56	35.96
P6	c	497.0	8.75	306.7	5.94	2.970	8.753	306.7	5.94	2.97	10.04	3.49	35.04
Mean value		486.6	8.84	314.9	6.02	3.010	8.33	296.9	6.53	3.265			
Standard deviation		14.5	0.39	13.9	1.16	0.578	1.01	36.1	1.82	0.912			
Relative deviation [%]		2.98	4.42	4.41	19.20	19.20	12.08	12.16	27.93	27.93			

Table A28. Results of the tensile tests of P_C,PE.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	540.2	10.89	389.8	9.03	4.513	10.621	380.0	10.30	5.15	9.94	3.6	35.78
P2	a	537.2	11.10	397.3	11.82	5.911	10.593	379.3	15.06	7.53	9.89	3.62	35.80
P3	a	574.2	10.71	388.4	8.67	4.337	10.406	377.4	9.42	4.71	9.91	3.66	36.27
P4	a	557.6	10.58	378.8	6.22	3.111	10.481	375.2	6.41	3.21	9.89	3.62	35.80
P5	a	533.2	10.90	390.8	9.78	4.890	10.517	377.0	11.20	5.60	9.93	3.61	35.85
P6	a	540.8	10.91	391.0	9.70	4.850	10.611	380.3	10.73	5.36	10.01	3.58	35.84
Mean value		547.2	10.85	389.4	9.20	4.602	10.538	378.2	10.52	5.26			
Standard deviation		15.6	0.18	6.0	1.82	0.912	0.085	2.0	2.80	1.40			
Relative deviation [%]		2.86	1.66	1.54	19.82	19.82	0.81	0.52	26.64	26.64			

Table A29. Results of the tensile tests of P_W,C,PE.

Sample Number	Curve Type	E_t (MPa)	s_y (MPa)	F_y (N)	e_y (%)	e_Y (mm)	s_m (MPa)	s_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	c	499.2	12.14	429.7	11.45	5.727	12.14	429.7	11.45	5.727	9.511	336.8	44.26	22.13	9.89	3.58	35.41
P2	c	533.9	12.26	435.7	11.56	5.781	12.26	435.7	11.56	5.781	8.435	299.7	49.63	24.82	9.87	3.6	35.53
P3	c	526.4	12.23	435.4	12.30	6.150	12.23	435.4	12.30	6.150	5.915	210.6	53.86	26.93	9.86	3.61	35.59
P4	c	539.7	12.36	436.6	12.39	6.193	12.36	436.6	12.39	6.193	4.356	153.9	43.94	21.97	9.84	3.59	35.33
P5	c	535.3	12.34	431.0	11.57	5.784	12.34	431.0	11.57	5.784	3.918	136.9	46.26	23.13	9.84	3.55	34.93
P6	c	578.9	12.56	449.8	12.31	6.154	12.56	449.8	12.31	6.154	4.634	166.0	52.04	26.02	9.87	3.63	35.83
Mean value		535.6	12.31	436.4	11.93	5.965	12.31	436.4	11.93	5.965	6.128	217.3	48.33	24.17	–	–	–
Standard deviation		25.7	0.14	7.2	0.44	0.221	0.14	7.2	0.44	0.221	2.327	82.7	4.15	2.08	–	–	–
Relative deviation [%]		4.80	1.16	1.64	3.71	3.71	1.16	1.64	3.71	3.71	37.97	38.07	8.59	8.59	–	–	–

Table A30. Results of the tensile tests of P_PP.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	1373.1	13.09	469.8	1.69	0.843	12.596	452.2	1.84	0.92	10	3.59	35.90
P2	a	1435.4	13.19	473.4	1.64	0.820	13.186	473.4	1.64	0.82	10	3.59	35.90
P3	a	1399.6	11.65	418.2	1.30	0.648	11.648	418.2	1.30	0.65	10	3.59	35.90
P4	a	1414.2	11.88	426.7	1.24	0.620	11.884	426.7	1.24	0.62	10	3.59	35.90
P5	a	1380.5	10.16	364.8	0.97	0.487	10.035	360.3	0.99	0.50	10	3.59	35.90
P6	a	1467.9	11.01	395.4	1.02	0.508	11.014	395.4	1.02	0.51	10	3.59	35.90
Mean value		1411.8	11.83	424.7	1.31	0.655	11.727	421.0	1.34	0.67	-	-	-
Standard deviation		35.6	1.17	42.2	0.30	0.151	1.121	40.3	0.34	0.17	-	-	-
Relative deviation [%]		2.52	9.93	9.93	23.01	23.01	9.56	9.56	25.35	25.35	-	-	-

Table A31. Results of the tensile tests of P_W,PP.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	1509.3	15.69	555.8	1.50	0.748	15.690	555.8	1.50	0.75	10.15	3.49	35.42
P2	a	1517.7	18.16	657.4	2.50	1.250	18.160	657.4	2.50	1.25	10.14	3.57	36.20
P3	a	1508.4	18.65	678.4	2.48	1.242	18.654	678.4	2.48	1.24	10.13	3.59	36.37
P4	a	1552.9	17.90	644.2	2.30	1.150	17.897	644.2	2.30	1.15	10.14	3.55	36.00
P5	a	1452.3	17.58	642.2	2.30	1.150	17.579	642.2	2.30	1.15	10.29	3.55	36.53
P6	a	1502.7	18.21	652.6	2.58	1.292	18.213	652.6	2.58	1.29	10.18	3.52	35.83
Mean value		1507.2	17.70	638.4	2.28	1.139	17.699	638.4	2.28	1.14	-	-	-
Standard deviation		32.4	1.05	42.5	0.40	0.200	1.047	42.5	0.40	0.20	-	-	-
Relative deviation [%]		2.15	5.92	6.66	17.54	17.54	5.92	6.66	17.54	17.54	-	-	-

Table A32. Results of the tensile tests of P_C,PP.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	1697.3	14.46	525.1	1.24	0.620	14.455	525.1	1.24	0.62	9.98	3.64	36.33
P2	a	1573.2	16.34	592.8	1.74	0.872	16.345	592.8	1.74	0.87	9.91	3.66	36.27
P3	a	1599.2	17.61	618.4	1.99	0.995	17.614	618.4	1.99	1.00	9.78	3.59	35.11
P4	a	1481.3	16.23	576.5	1.59	0.794	16.137	573.3	1.59	0.79	9.68	3.67	35.53
P5	a	1589.4	15.35	551.9	1.44	0.720	15.352	551.9	1.44	0.72	9.69	3.71	35.95
P6	a	1549.7	16.31	599.0	1.60	0.798	16.276	597.6	1.60	0.80	9.87	3.72	36.72
Mean value		1581.7	16.05	577.3	1.60	0.800	16.030	576.5	1.60	0.80	-	-	-
Standard deviation		70.6	1.06	34.0	0.26	0.128	1.060	33.8	0.26	0.13	-	-	-
Relative deviation [%]		4.46	6.63	5.89	16.01	16.01	6.61	5.87	16.01	16.01	-	-	-

Table A33. Results of the tensile tests of P_W,C,PP.

Sample Number	Curve Type	E_t (MPa)	s_y (MPa)	F_y (N)	e_y (%)	e_Y (mm)	s_m (MPa)	s_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	1484.0	-	-	-	-	23.88	869.9	3.88	1.942	23.880	869.9	3.88	1.94	9.98	3.65	36.43
P2	a	1556.5	-	-	-	-	21.07	765.5	3.28	1.638	21.069	765.5	3.28	1.64	9.9	3.67	36.33
P3	c	1542.1	17.54	638.0	2.14	1.071	17.54	638.0	2.14	1.071	10.456	380.3	2.89	1.45	9.91	3.67	36.37
P4	a	1282.4	-	-	-	-	21.20	778.5	3.57	1.783	21.202	778.5	3.57	1.78	9.87	3.72	36.72
P5	a	2039.3	-	-	-	-	20.64	746.1	3.50	1.749	19.999	722.9	3.72	1.86	9.93	3.64	36.15
P6	a	1616.8	-	-	-	-	20.87	758.9	3.55	1.776	20.867	758.9	3.55	1.78	9.91	3.67	36.37
Mean value		1586.9	17.54	638.0	2.14	1.071	20.87	759.5	3.32	1.660	19.579	712.7	3.48	1.74	-	-	-
Standard deviation		249.7	-	-	-	-	2.02	74.2	0.61	0.304	4.657	170.0	0.35	0.18	-	-	-
Relative deviation [%]		15.74	-	-	-	-	9.66	9.77	18.34	18.34	23.78	23.86	10.09	10.07	-	-	-

Table A34. Results of the tensile tests of P_PS.

Sample Number	**Curve Type**	**E_t (MPa)**	**s_y (MPa)**	**F_y (N)**	**e_y (%)**	**e_Y (mm)**	**s_m (MPa)**	**s_M (N)**	**e_m (%)**	**e_M (mm)**	**s_b (MPa)**	**s_B (N)**	**e_b (%)**	**e_B (mm)**	**b (mm)**	**h (mm)**	**A_0 (mm^2)**
P1	a	924.8	-	-	-	-	5.83	216.3	0.78	0.391	5.664	210.1	0.79	0.40	10	3.71	37.10
P2	a	914.5	-	-	-	-	6.01	223.4	0.93	0.464	5.663	210.3	1.01	0.50	10.01	3.71	37.14
P3	c	1005.8	6.24	227.9	0.86	0.429	6.24	227.9	0.86	0.429	1.246	45.5	1.82	0.91	9.95	3.67	36.52
P4	c	909.4	6.25	229.0	1.02	0.510	6.25	229.0	1.02	0.510	1.248	45.8	1.90	0.95	9.91	3.7	36.67
P5	a	983.7	-	-	-	-	6.89	259.1	1.13	0.565	6.647	249.9	1.19	0.60	10	3.76	37.60
P6	a	990.5	-	-	-	-	6.12	219.6	0.78	0.389	5.959	213.8	0.80	0.40	9.91	3.62	35.87
Mean value		954.8	6.24	228.5	0.94	0.469	6.22	229.2	0.92	0.458	4.404	162.6	1.25	0.63	-	-	-
Standard deviation		43.1	0.00	0.8	0.11	0.057	0.36	15.4	0.14	0.070	2.472	91.8	0.50	0.25	-	-	-
Relative deviation [%]		4.52	0.06	0.35	12.11	12.11	5.80	6.71	15.19	15.19	56.13	56.48	39.55	39.55	-	-	-

Table A35. Results of the tensile tests of P_W,PS.

Sample Number	**Curve Type**	**E_t (MPa)**	**s_m (MPa)**	**F_M (N)**	**e_m (%)**	**e_M (mm)**	**s_b (MPa)**	**s_B (N)**	**e_b (%)**	**e_B (mm)**	**b (mm)**	**h (mm)**	**A_0 (mm^2)**
P1	a	2265.6	12.65	483.4	0.64	0.318	12.545	479.2	0.64	0.32	10	3.82	38.20
P2	a	2336.9	13.34	511.0	0.69	0.346	12.800	490.4	0.72	0.36	10.03	3.82	38.31
P3	a	2309.6	14.40	547.8	0.74	0.370	14.402	547.8	0.74	0.37	10.01	3.8	38.04
P4	a	2244.1	13.65	527.9	0.69	0.343	13.436	519.6	0.68	0.34	10.07	3.84	38.67
P5	a	2267.7	14.25	559.5	0.78	0.391	14.246	559.5	0.78	0.39	10.2	3.85	39.27
P6	a	2379.6	13.81	536.7	0.65	0.323	13.785	535.5	0.65	0.32	10.09	3.85	38.85
Mean value		2300.6	13.68	527.7	0.70	0.348	13.536	522.0	0.70	0.35	-	-	-
Standard deviation		51.3	0.64	27.3	0.06	0.028	0.755	31.9	0.06	0.03	-	-	-
Relative deviation [%]		2.23	4.66	5.18	8.05	8.05	5.58	6.11	8.04	8.04	-	-	-

Table A36. Results of the tensile tests of P_C,PS.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	2453.1	19.15	771.9	0.95	0.474	18.830	759.1	1.03	0.51	10.18	3.96	40.31
P2	a	2438.1	19.44	773.0	0.96	0.480	19.041	757.2	1.08	0.54	10.17	3.91	39.76
P3	a	2374.3	19.21	786.4	0.95	0.474	17.708	725.1	1.19	0.59	10.16	4.03	40.94
P4	a	2351.4	18.78	769.8	0.90	0.451	18.776	769.8	0.90	0.45	10.25	4	41.00
P5	a	2446.2	19.51	782.2	0.93	0.467	19.461	780.2	0.95	0.48	10.15	3.95	40.09
P6	a	2363.5	18.75	755.2	0.86	0.429	18.751	755.2	0.86	0.43	10.17	3.96	40.27
Mean value		2404.4	19.14	773.1	0.92	0.462	18.761	757.8	1.00	0.50	-	-	-
Standard deviation		46.1	0.32	10.9	0.04	0.019	0.580	18.6	0.12	0.06	-	-	-
Relative deviation [%]		1.92	1.67	1.41	4.12	4.12	3.09	2.45	12.23	12.23	-	-	-

Table A37. Results of the tensile tests of P_W,C,PS.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	930.4	6.80	248.6	0.86	0.432	6.729	245.9	0.87	0.43	9.85	3.71	36.54
P2	a	923.3	7.33	266.0	1.04	0.519	6.714	243.8	1.09	0.55	9.84	3.69	36.31
P3	a	936.5	5.46	196.1	0.67	0.334	4.349	156.1	0.64	0.32	9.78	3.67	35.89
P4	a	896.6	6.33	227.0	0.85	0.425	6.333	227.0	0.85	0.42	9.82	3.65	35.84
P5	a	945.8	6.12	222.7	0.76	0.381	6.119	222.7	0.76	0.38	9.89	3.68	36.40
P6	a	904.8	6.38	229.3	0.88	0.438	6.378	229.3	0.88	0.44	9.85	3.65	35.95
Mean value		922.9	6.40	231.6	0.84	0.422	6.104	220.8	0.85	0.42	-	-	-
Standard deviation		18.9	0.63	23.8	0.12	0.062	0.891	33.0	0.15	0.08	-	-	-
Relative deviation [%]		2.05	9.83	10.28	14.71	14.71	14.60	14.96	17.72	17.72	-	-	-

Table A38. Results of the tensile tests of PO_A.

Sample Number	**Curve Type**	**E_t (MPa)**	**s_m (MPa)**	**F_M (N)**	**e_m (%)**	**e_M (mm)**	**s_b (MPa)**	**s_B (N)**	**e_b (%)**	**e_B (mm)**	**b (mm)**	**h (mm)**	**A_0 (mm^2)**
P1	a	994.1	8.87	352.3	1.74	0.872	8.847	351.4	1.81	0.91	10.03	3.96	39.72
P2	a	1043.2	9.59	360.6	1.68	0.838	8.960	337.1	1.82	0.91	10.06	3.74	37.62
P3	a	1113.7	9.44	356.1	1.70	0.852	9.283	350.2	1.79	0.89	9.98	3.78	37.72
P4	a	1115.3	9.50	359.0	1.47	0.733	9.368	354.0	1.50	0.75	9.97	3.79	37.79
P5	a	986.5	9.79	371.1	1.80	0.901	9.449	358.3	1.97	0.99	9.98	3.8	37.92
P6	a	1066.1	9.67	361.7	1.78	0.889	9.241	345.5	1.95	0.98	9.97	3.75	37.39
Mean value		1053.2	9.48	360.2	1.70	0.848	9.191	349.4	1.81	0.90	-	-	-
Standard deviation		56.1	0.32	6.4	0.12	0.061	0.237	7.4	0.17	0.09	-	-	-
Relative deviation [%]		5.32	3.39	1.76	7.14	7.14	2.58	2.11	9.43	9.43	-	-	-

Table A39. Results of the tensile tests of PO_A,W.

Sample Number	**Curve Type**	**E_t (MPa)**	**s_m (MPa)**	**F_M (N)**	**e_m (%)**	**e_M (mm)**	**s_b (MPa)**	**s_B (N)**	**e_b (%)**	**e_B (mm)**	**b (mm)**	**h (mm)**	**A_0 (mm^2)**
P1	a	845.8	9.29	341.8	2.19	1.096	8.707	320.4			9.92	3.71	36.80
P2	a	896.9	10.07	358.5	2.66	1.331	9.856	351.0	2.83	1.41	9.92	3.59	35.61
P3	a	855.9	9.77	350.7	2.11	1.054	9.581	343.9	2.17	1.09	9.97	3.6	35.89
P4	a	908.6	9.98	358.3	2.54	1.268	9.763	350.4	2.76	1.38	9.97	3.6	35.89
P5	a	905.5	9.55	342.7	1.87	0.934	9.289	333.1	1.99	0.99	9.99	3.59	35.86
P6	a	860.9	8.95	325.2	2.04	1.018	8.746	317.7	2.20	1.10	9.98	3.64	36.33
Mean value		878.9	9.60	346.2	2.23	1.117	9.324	336.1	2.39	1.19	-	-	-
Standard deviation		27.8	0.43	12.5	0.31	0.153	0.502	14.7	0.38	0.19	-	-	-
Relative deviation [%]		3.16	4.44	3.62	13.65	13.65	5.38	4.37	15.86	15.86	-	-	-

Table A40. Results of the tensile tests of PO_A,C.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	1037.3	10.16	350.1	1.96	0.980	10.158	350.1	1.96	0.98	9.82	3.51	34.47
P2	a	920.6	8.65	306.6	1.43	0.713	8.555	303.2	1.42	0.71	9.9	3.58	35.44
P3	a	835.9	9.37	344.9	2.06	1.029	9.366	344.9	2.06	1.03	9.82	3.75	36.83
P4	a	873.2	9.16	322.3	1.56	0.779	9.161	322.3	1.56	0.78	9.8	3.59	35.18
P5	a	825.4	7.34	258.4	1.11	0.556	7.224	254.3	1.12	0.56	9.78	3.6	35.21
P6	a	840.7	8.70	307.7	1.52	0.760	8.541	302.0	1.53	0.77	9.85	3.59	35.36
Mean value		888.9	8.90	315.0	1.61	0.803	8.834	312.8	1.61	0.80	-	-	-
Standard deviation		80.5	0.94	33.2	0.35	0.175	0.990	35.1	0.35	0.17	-	-	-
Relative deviation [%]		9.06	10.55	10.54	21.85	21.85	11.21	11.20	21.68	21.68	-	-	-

Table A41. Results of the tensile tests of PO_A,W,C.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	814.3	9.52	338.5	1.85	0.925	9.351	332.6	1.87	0.93	9.88	3.6	35.57
P2	a	884.0	10.31	367.3	2.43	1.217	10.310	367.3	2.43	1.22	9.84	3.62	35.62
P3	a	876.0	9.93	352.6	2.05	1.027	9.499	337.4	2.12	1.06	9.84	3.61	35.52
P4	a	860.8	10.19	364.3	2.35	1.174	10.037	358.8	2.40	1.20	9.82	3.64	35.74
P5	a	855.1	9.66	343.3	1.97	0.983	9.663	343.3	1.97	0.98	9.95	3.57	35.52
P6	a	840.7	9.58	338.5	2.03	1.015	9.449	333.7	2.08	1.04	9.92	3.56	35.32
Mean value		855.1	9.87	350.7	2.11	1.057	9.718	345.5	2.15	1.07	-	-	-
Standard deviation		25.2	0.33	12.8	0.23	0.114	0.377	14.3	0.23	0.11	-	-	-
Relative deviation [%]		2.95	3.36	3.64	10.77	10.77	3.88	4.15	10.61	10.61	-	-	-

Table A42. Results of the tensile tests of PO_B.

Sample Number	Curve Type	E_t (MPa)	s_y (MPa)	F_y (N)	e_y (%)	e_Y (mm)	s_m (MPa)	s_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	c	830.6	-	-	-	-	9.47	332.6	1.85	0.925	9.368	329.0	1.86	0.93	10.15	3.46	35.12
P2	c	830.7	-	-	-	-	10.35	384.5	2.52	1.260	10.120	375.8	2.67	1.34	10.2	3.64	37.13
P3	c	877.0	-	-	-	-	9.48	333.7	1.81	0.903	9.302	327.6	1.85	0.92	10.18	3.46	35.22
P4	c	837.6	-	-	-	-	9.35	338.8	1.82	0.910	9.174	332.5	1.85	0.93	10.21	3.55	36.25
P5	c	847.8	10.21	369.3	2.53	1.263	10.21	369.3	2.53	1.263	7.597	274.7	3.20	1.60	10.3	3.51	36.15
P6	c	904.5	-	-	-	-	9.47	350.5	1.58	0.788	9.347	345.9	1.62	0.81	10.25	3.61	37.00
Mean value		854.7	10.21	369.3	2.53	1.263	9.72	351.6	2.02	1.008	9.151	330.9	2.18	1.09	-	-	-
Standard deviation		29.9	-	-	-	-	0.44	21.2	0.40	0.202	0.832	32.9	0.62	0.31	-	-	-
Relative deviation [%]		3.50	-	-	-	-	4.53	6.02	20.05	20.05	9.09	9.95	28.47	28.47	-	-	-

Table A43. Results of the tensile tests of PO_B,C.

Sample Number	Curve Type	E_t (MPa)	s_y (MPa)	F_y (N)	e_y (%)	e_Y (mm)	s_m (MPa)	s_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	836.5	-	-	-	-	12.51	435.6	3.64	1.818	12.512	435.6	3.64	1.82	9.89	3.52	34.81
P2	a	845.2	-	-	-	-	11.75	415.5	2.79	1.393	11.689	413.3	2.82	1.41	9.96	3.55	35.36
P3	a	845.3	-	-	-	-	12.43	428.7	3.20	1.600	12.178	419.9	3.34	1.67	9.88	3.49	34.48
P4	c	864.0	12.92	447.9	3.66	1.829	12.92	447.9	3.66	1.829	12.453	431.8	4.27	2.13	9.85	3.52	34.67
P5	a	814.7	-	-	-	-	11.07	384.1	2.23	1.113	11.066	384.1	2.23	1.11	9.86	3.52	34.71
P6	a	870.5	-	-	-	-	12.35	432.6	3.27	1.636	12.043	421.7	3.35	1.68	9.92	3.53	35.02
Mean value		846.0	12.92	447.9	3.66	1.829	12.17	424.0	3.13	1.565	11.990	417.7	3.27	1.64	-	-	-
Standard deviation		20.0	-	-	-	-	0.66	22.2	0.55	0.273	0.542	18.4	0.70	0.35	-	-	-
Relative deviation [%]		2.36	-	-	-	-	5.42	5.24	17.48	17.48	4.52	4.40	21.31	21.31	-	-	-

Table A44. Results of the tensile tests of P.

Sample Number	Curve Type	E_t (MPa)	s_y (MPa)	F_y (N)	e_y (%)	e_Y (mm)	s_m (MPa)	s_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	924.8	-	-	-	-	5.83	216.3	0.78	0.391	5.664	210.1	0.79	0.40	10	3.71	37.10
P2	a	914.5	-	-	-	-	6.01	223.4	0.93	0.464	5.663	210.3	1.01	0.50	10.01	3.71	37.14
P3	c	1005.8	6.24	227.9	0.86	0.429	6.24	227.9	0.86	0.429	1.246	45.5	1.82	0.91	9.95	3.67	36.52
P4	c	909.4	6.25	229.0	1.02	0.510	6.25	229.0	1.02	0.510	1.248	45.8	1.90	0.95	9.91	3.7	36.67
P5	c	983.7	-	-	-	-	6.89	259.1	1.13	0.565	6.647	249.9	1.19	0.60	10	3.76	37.60
P6	a	990.5	—	-	-	-	6.12	219.6	0.78	0.389	5.959	213.8	0.80	0.40	9.91	3.62	35.87
Mean value		954.8	6.24	228.5	0.94	0.469	6.22	229.2	0.92	0.458	4.404	162.6	1.25	0.63	—	—	—
Standard deviation		43.1	0.00	0.8	0.11	0.057	0.36	15.4	0.14	0.070	2.472	91.8	0.50	0.25	—	—	—
Relative deviation [%]		4.52	0.06	0.35	12.11	12.11	5.80	6.71	15.19	15.19	56.13	56.48	39.55	39.55	—	—	—

Table A45. Results of the tensile tests of P_C.

Sample Number	Curve Type	E_t (MPa)	s_m (MPa)	F_M (N)	e_m (%)	e_M (mm)	s_b (MPa)	s_B (N)	e_b (%)	e_B (mm)	b (mm)	h (mm)	A_0 (mm^2)
P1	a	930.4	6.80	248.6	0.86	0.432	6.803	248.6	0.86	0.43	9.85	3.71	36.54
P2	a	923.3	7.33	266.0	1.04	0.519	7.327	266.0	1.04	0.52	9.84	3.69	36.31
P3	a	936.5	5.46	196.1	0.67	0.334	5.465	196.1	0.67	0.33	9.78	3.67	35.89
P4	a	896.6	6.33	227.0	0.85	0.425	6.333	227.0	0.85	0.42	9.82	3.65	35.84
P5	a	945.8	6.12	222.7	0.76	0.381	6.119	222.7	0.76	0.38	9.89	3.68	36.40
P6	a	904.8	6.38	229.3	0.88	0.438	6.378	229.3	0.88	0.44	9.85	3.65	35.95
Mean value		922.9	6.40	231.6	0.84	0.422	6.404	231.6	0.84	0.42	—	—	—
Standard deviation		18.9	0.63	23.8	0.12	0.062	0.629	23.8	0.12	0.06	—	—	—
Relative deviation [%]		2.05	9.83	10.28	14.71	14.71	9.83	10.28	14.71	14.71	—	—	—

Appendix G. Bulk Densities

Table A46. Results of bulk density tests of P_PE; P_C,PE; P_W,PE; and P_W,C,PE.

Material	**P_PE**		**P_C,PE**		**P_W,PE**		**P_W,C,PE**	
Sample Number	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**
P1	8.486	0.0849	48.996	0.4900	7.272	0.0727	48.983	0.4898
P2	8.237	0.0824	48.538	0.4854	7.373	0.0737	48.992	0.4899
P3	8.178	0.0818	49.016	0.4902	7.466	0.0747	49.069	0.4907
P4	8.211	0.0821	48.050	0.4805	7.192	0.0719	50.302	0.5030
P5	7.854	0.0785	48.420	0.4842	6.891	0.0689	49.531	0.4953

Table A47. Results of bulk density tests of P_PP; P_C,PP; P_W,PP; and P_W,C,PP.

Material	**P_PP**		**P_C,PP**		**P_W,PP**		**P_W,C,PP**	
Sample Number	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**
P1	16.825	0.1683	43.877	0.4388	15.463	0.1546	46.074	0.4607
P2	16.368	0.1637	44.926	0.4493	15.625	0.1563	47.104	0.4710
P3	17.537	0.1754	43.697	0.4370	15.075	0.1508	46.296	0.4630
P4	15.492	0.1549	44.057	0.4406	15.196	0.1520	47.222	0.4722
P5	15.415	0.1542	43.769	0.4377	14.955	0.1496	46.712	0.4671

Table A48. Results of bulk density tests of P_PS; P_C,PS; P_W,PS; and P_W,C,PS.

Material	**P_PS**		**P_W,PS**		**P_W,PS**		**PS_W,C,PS**	
Sample Number	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**
P1	16.986	0.1699	26.825	0.2683	16.369	0.1637	28.51	0.2851
P2	16.08	0.1608	27.184	0.2718	17.167	0.1717	28.062	0.2806
P3	16.506	0.1651	26.986	0.2699	14.616	0.1462	27.355	0.2736
P4	15.464	0.1546	27.859	0.2786	16.297	0.1630	27.326	0.2733
P5	16.216	0.1622	27.357	0.2736	14.762	0.1476	28.576	0.2858

Table A49. Results of bulk density tests of PO_A; PO_A,C; PO_A,W; and PO_A,W,C.

Material	**PO_A**		**PO_A,C**		**PO_A,W**		**PO_A,W,C**	
Sample Number	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**
P1	6.955	0.0696	40.454	0.4045	7.046	0.0705	46.537	0.4654
P2	7.202	0.0720	39.489	0.3949	6.758	0.0676	45.656	0.4566
P3	7.133	0.0713	40.002	0.4000	6.483	0.0648	45.822	0.4582
P4	6.671	0.0667	39.872	0.3987	6.574	0.0657	45.478	0.4548
P5	7.091	0.0709	40.090	0.4009	6.640	0.0664	44.83	0.4483

Table A50. Results of bulk density tests of PO_B; PO_B,C; P; and P_C.

Material	**PO_B**		**PO_B,C**		**P**		**P_C**	
Sample Number	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**
P1	8.944	0.0894	47.328	0.4733	10.362	0.1036	44.022	0.4402
P2	8.805	0.0881	48.663	0.4866	11.124	0.1112	44.705	0.4471
P3	9.143	0.0914	48.607	0.4861	11.679	0.1168	44.073	0.4407
P4	9.586	0.0959	47.541	0.4754	12.066	0.1207	44.469	0.4447
P5	9.452	0.0945	47.759	0.4776	11.326	0.1133	44.847	0.4485

Table A51. Results of bulk density tests of P_PET and P_W,PET.

Material	**P_PET**		**P_W,PET**	
Sample Number	**Net Mass (g)**	**Bulk Density (g/cm^3)**	**Net Mass (g)**	**Bulk Density (g/cm^3)**
P1	24.481	0.2448	18.762	0.1876
P2	24.018	0.2402	16.966	0.1697
P3	23.101	0.2310	19.372	0.1937
P4	24.342	0.2434	18.594	0.1859
P5	24.587	0.2459	17.674	0.1767
Mean value		0.2411		0.1827
Standard deviation		0.0060		0.0095

Appendix H. Ash Contents

Table A52. Results of ash content tests of P_PET and P_W,PET.

Sample Identification	Crucible Empty (g)	Crucible and Sample (g)	Crucible Containing Ash (g)	Ignition Residue (g)	Ash Content (AC) (%)	Mean Value AC (%)	Relative Deviation (%)
P_PE	36.81	38.90	36.89	0.086	4.08	4.40	0.37
P_PE	38.59	40.46	38.67	0.081	4.32		
P_PE	36.51	38.92	36.62	0.116	4.81		
P_W,PE	34.33	36.30	34.37	0.046	2.31	2.40	0.08
P_W,PE	38.15	40.07	38.19	0.048	2.48		
P_W,PE	33.20	34.84	33.24	0.039	2.40		
P_C,PE	32.97	34.58	33.03	0.063	3.89	3.93	0.14
P_C,PE	38.04	39.99	38.12	0.080	4.09		
P_C,PE	36.40	38.01	36.46	0.061	3.81		
P_W,C,PE	32.72	34.60	32.77	0.044	2.32	2.40	0.08
P_W,C,PE	39.22	40.96	39.26	0.043	2.47		
P_W,C,PE	34.45	36.01	34.48	0.038	2.43		
P_PP	34.92	37.02	34.96	0.045	2.16	2.41	0.23
P_PP	34.89	36.85	34.94	0.051	2.60		
P_PP	35.70	38.24	35.76	0.063	2.48		
P_W,PP	32.67	34.59	32.72	0.045	2.37	2.39	0.59
P_W,PP	35.33	37.33	35.39	0.060	3.00		
P_W,PP	37.50	39.66	37.53	0.040	1.82		
P_C,PP	34.98	37.00	35.04	0.059	2.91	2.67	0.23
P_C,PP	39.22	41.00	39.26	0.044	2.46		
P_C,PP	31.23	32.67	31.27	0.038	2.63		
P_W,C,PP	34.86	36.70	34.89	0.032	1.72	1.68	0.10
P_W,C,PP	34.98	36.63	35.01	0.026	1.57		
P_W,C,PP	35.64	37.28	35.67	0.029	1.77		
P_PS	39.17	41.17	39.25	0.083	4.17	4.59	0.50
P_PS	32.72	34.65	32.81	0.086	4.46		
P_PS	39.48	40.96	39.55	0.076	5.14		
P_W,PS	33.10	35.11	33.17	0.071	3.53	3.36	0.60
P_W,PS	39.98	40.94	40.01	0.026	2.69		
P_W,PS	37.68	39.95	37.77	0.088	3.85		
P_C,PS	39.48	41.24	39.56	0.088	4.97	4.98	0.05
P_C,PS	39.04	41.02	39.14	0.100	5.04		
P_C,PS	31.23	33.28	31.33	0.101	4.94		
P_W,C,PS	38.81	40.94	38.88	0.078	3.63	3.63	0.11
P_W,C,PS	39.81	41.94	39.88	0.075	3.53		
P_W,C,PS	33.64	35.25	33.70	0.060	3.74		
PO_A	34.55	36.60	34.67	0.127	6.18	6.25	0.07
PO_A	33.56	35.43	33.68	0.118	6.32		
PO_A	39.06	41.03	39.18	0.124	6.27		
PO_A,W	36.39	38.37	36.47	0.082	4.13	4.15	0.01
PO_A,W	34.48	36.53	34.56	0.085	4.16		
PO_A,W	32.13	34.51	32.23	0.099	4.15		

Table A52. *Cont.*

Sample Identification	Crucible Empty (g)	Crucible and Sample (g)	Crucible Containing Ash (g)	Ignition Residue (g)	Ash Content (AC) (%)	Mean Value AC (%)	Relative Deviation (%)
PO_A,C	33.17	35.05	33.28	0.110	5.90	5.81	0.08
PO_A,C	34.10	35.73	34.19	0.094	5.76		
PO_A,C	39.17	40.54	39.25	0.079	5.78		
PO_A,W,C	37.67	39.67	37.76	0.082	4.12	3.92	0.21
PO_A,W,C	40.03	41.28	40.08	0.050	3.96		
PO_A,W,C	33.37	34.51	33.42	0.042	3.70		
PO_B	38.58	40.23	38.62	0.036	2.20	2.21	0.10
PO_B	33.44	35.33	33.48	0.040	2.12		
PO_B	37.67	39.87	37.72	0.051	2.31		
PO_B,C	39.04	40.77	39.08	0.043	2.46	2.45	0.05
PO_B,C	34.44	36.07	34.48	0.040	2.48		
PO_B,C	35.64	36.95	35.67	0.031	2.40		
P	33.41	35.43	33.59	0.176	8.71	8.41	0.41
P	34.53	36.85	34.72	0.184	7.95		
P	33.53	36.45	33.78	0.251	8.57		
P_C	36.54	38.42	36.67	0.122	6.47	6.19	0.51
P_C	38.43	40.20	38.54	0.115	6.48		
P_C	38.59	39.76	38.66	0.065	5.60		

Appendix I. Exemplary Material Photos

Figure A2. Exemplary photos of the input materials: SRF in (**A**) and (**B**), PO_A in (**C**), and PO_B in (**D**).

Figure A3. Exemplary photos of the manually sorted material fractions: wood—**A**; P&C—**B**; plastics—**C**; inert—**D**; metals—**E**; others—**F**.

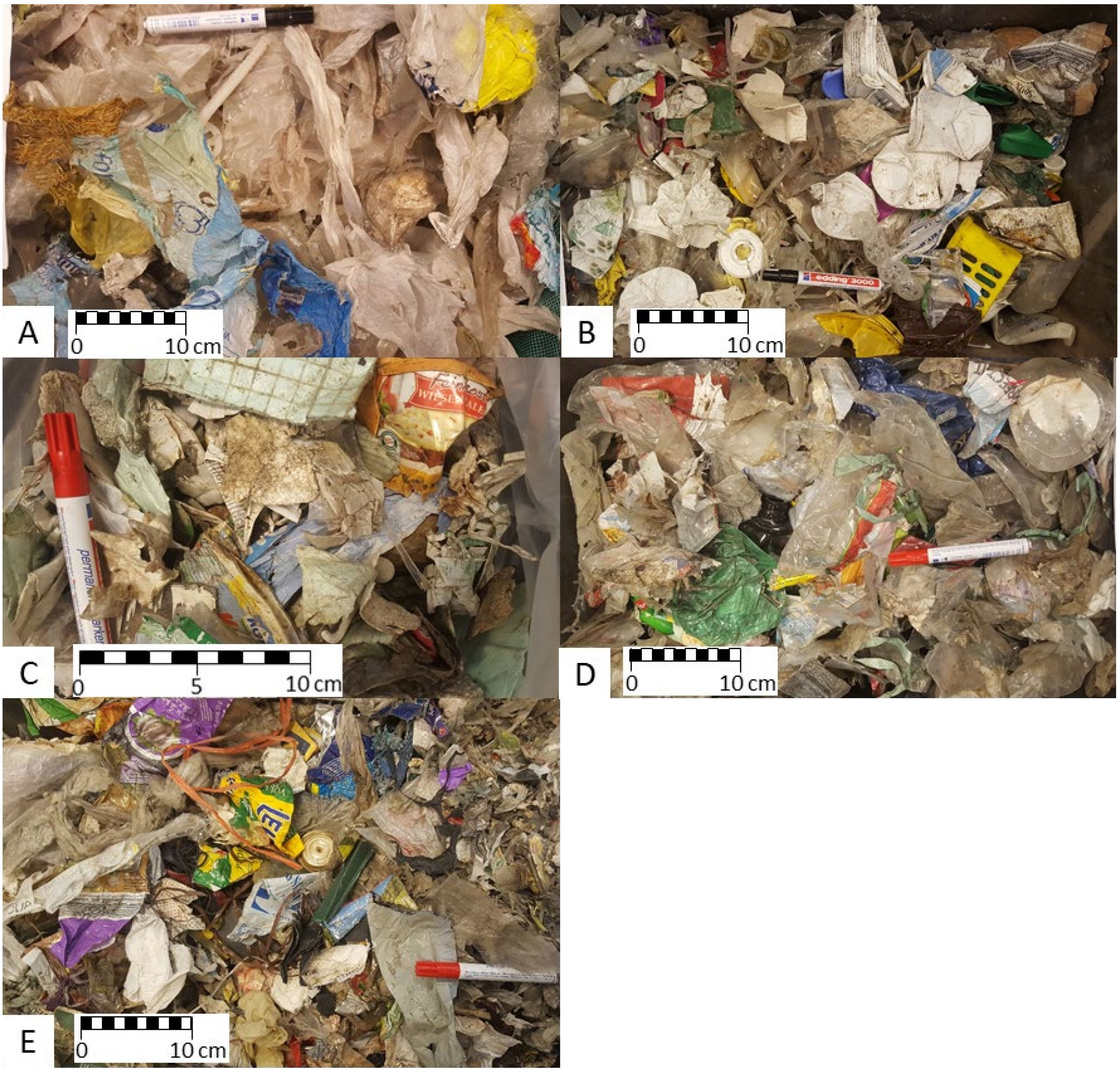

Figure A4. Exemplary photos of plastic types sorted with NIR: PE—**A**; PP—**B**; PET—**C**; PS—**D**; and others—**E**.

Figure A5. Exemplary photos of the flakes of all investigated materials after shredding to <4 mm: P_PE—**A**; P_W,PE—**B**; P_PP—**C**; P_W,PP—**D**; P_PS—**E**; P_W,PS—**F**; PO_A—**G**; PO_W,**A–H**; PO_B—**I**; and P—**J**.

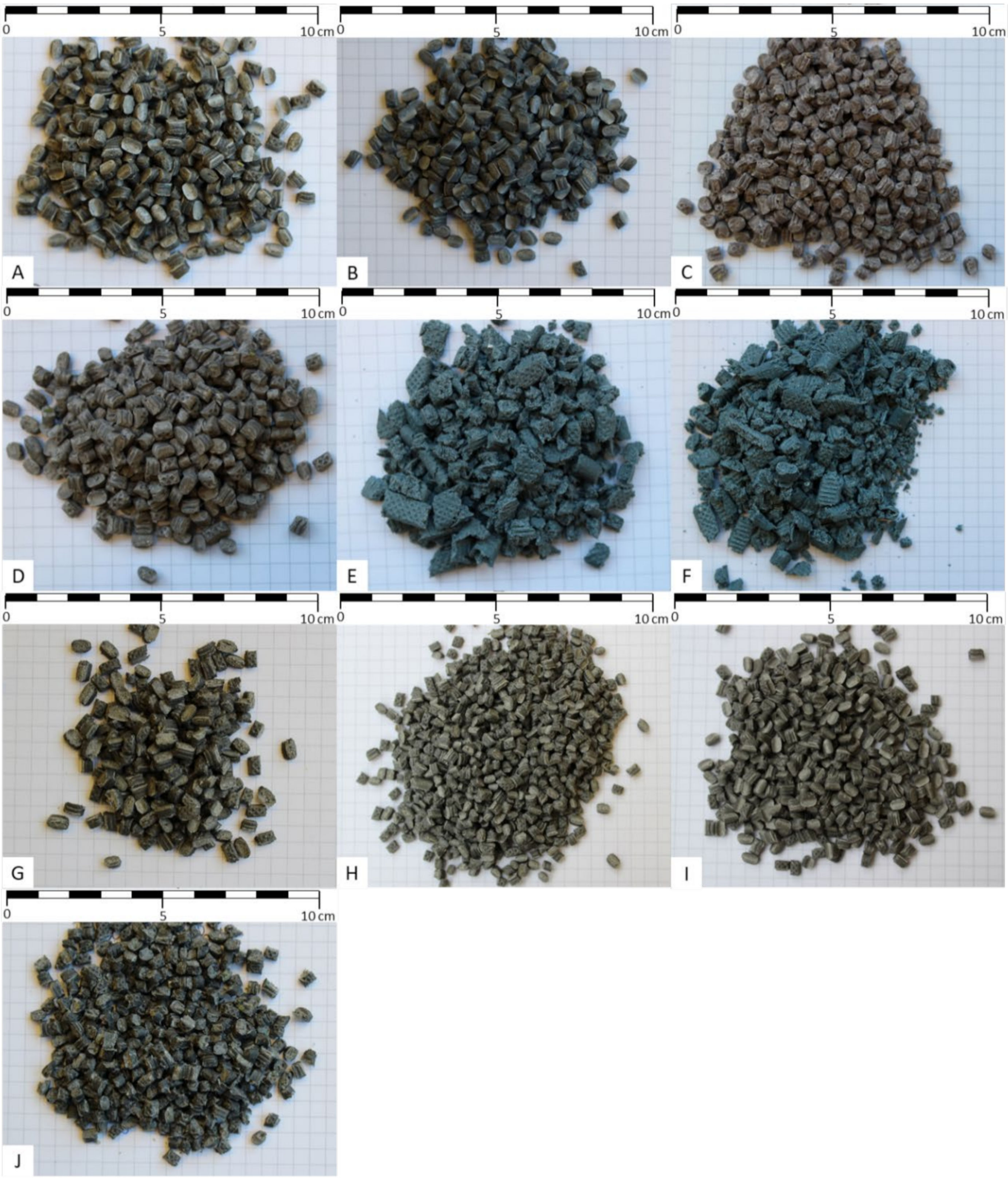

Figure A6. Exemplary photos of the granulates of all investigated materials after homogenisation and pelletising: P_C,PE—**A**; P_W,C,PE—**B**; P_PP_C—**C**; P_W,C,PP—**D**; P_C,PS—**E**; P_W,C,PS—**F**; PO_A,C—**G**; PO_W,**C**,**A–H**; PO_B,**C—I**; and P_C—**J**.

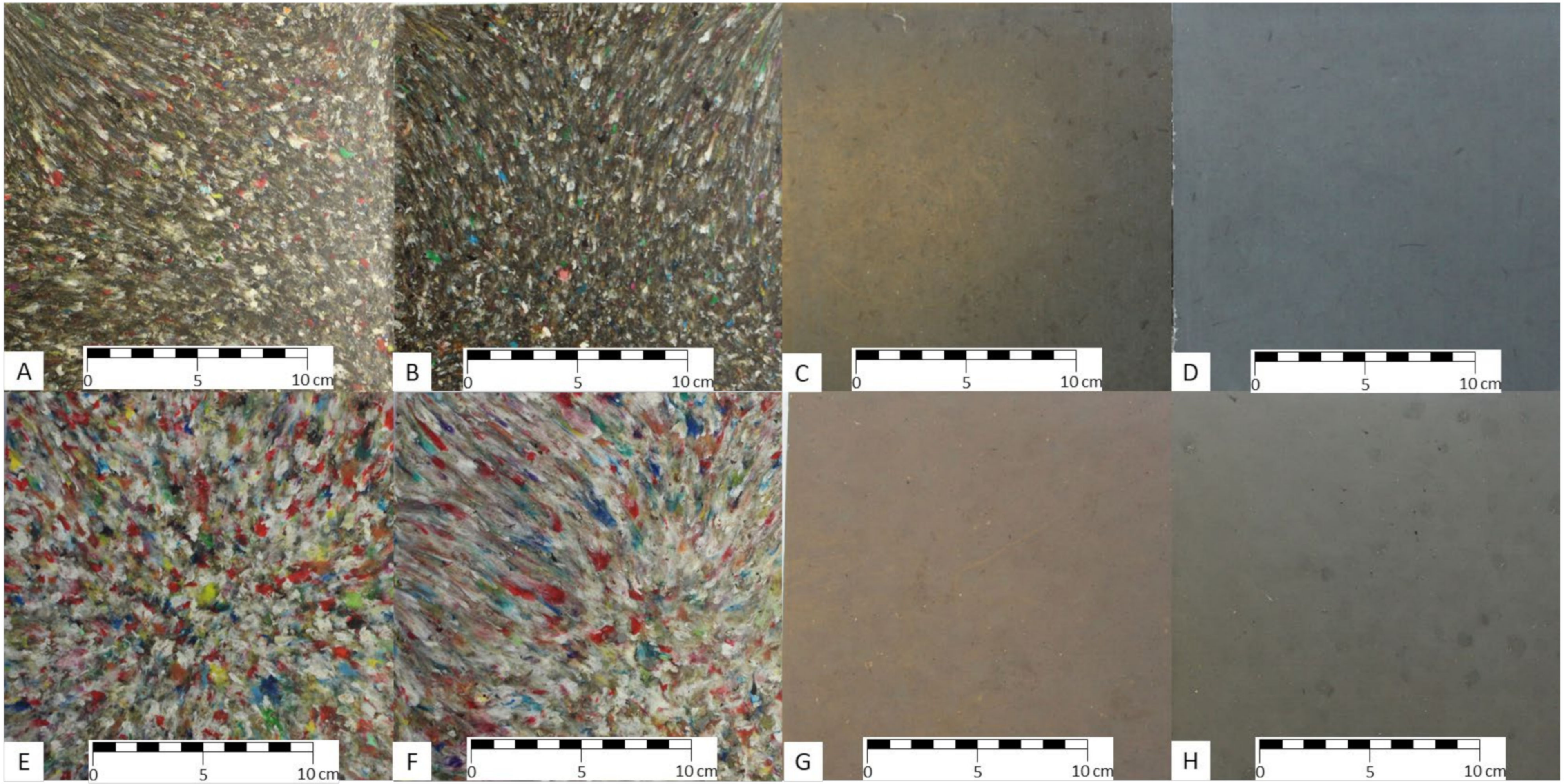

Figure A7. Exemplary photos of vacuum compression moulded plates: P_PE—**A**; P_W,PE—**B**; P_C,PE—**C**; P_W,C,PE—**D**; P_PP—**E**; P_W,PP—**F**; P_C,PP—**G**; and P_W,C,PP—**H**.

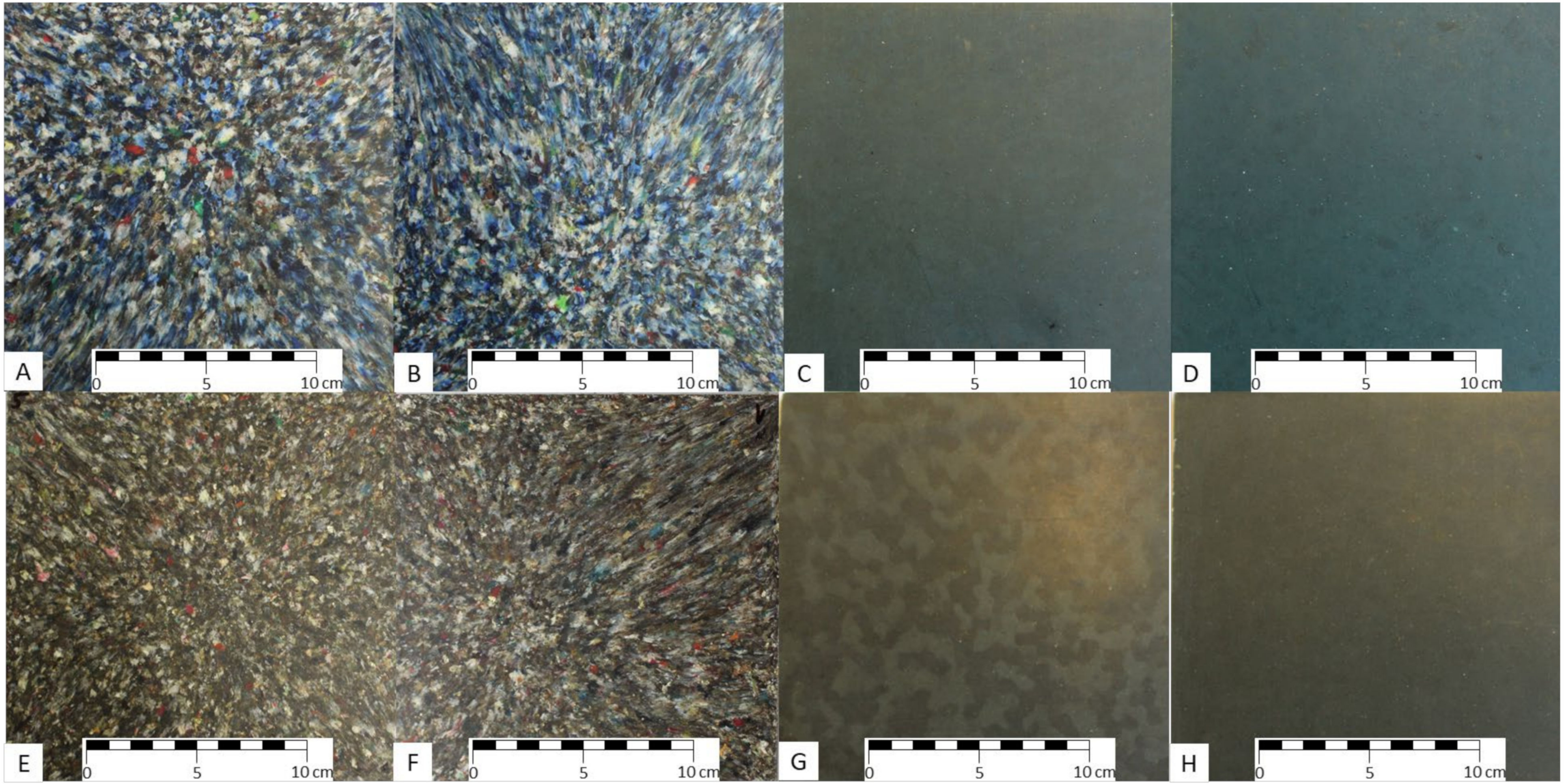

Figure A8. Exemplary photos of vacuum compression moulded plates: P_PS—**A**; P_W,PS—**B**; P_C,PS—**C**; P_W,C,PS—**D;** PO_A—**E**; PO_A,W—**F**; PO_A,**C**–**G**; and PO_A,W,**C**–**H**.

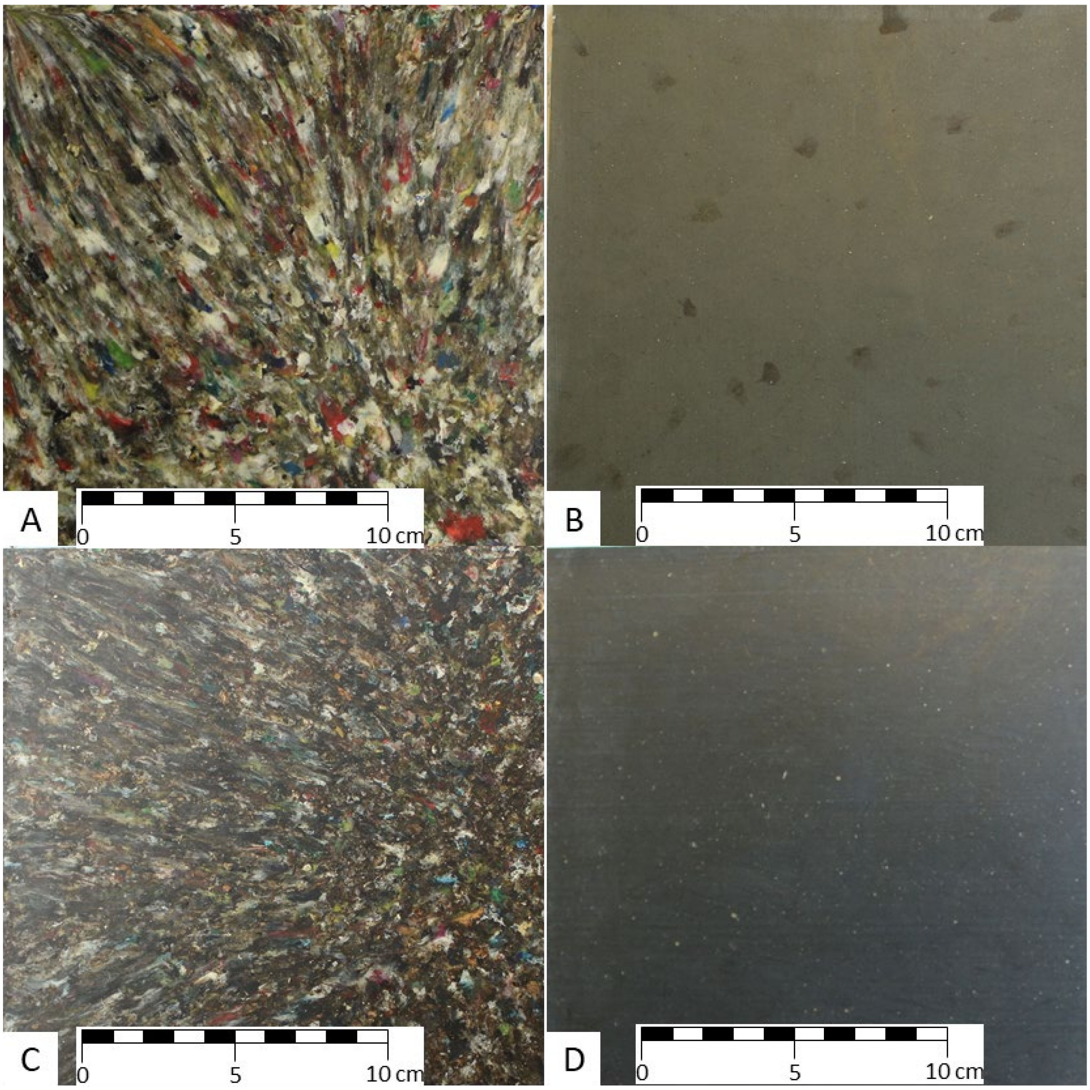

Figure A9. Exemplary photos of vacuum compression moulded plates: PO_B—**A**; PO_B,W—**B**; P—**C**; and P_C—**D**.

Appendix J. Application Options

Table A53. Possible applications for the materials investigated.

Material	Processability	Potential Products for Application
P_PE	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
P_W,PE	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
P_C,PE	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications
P_W,C,PE	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications
P_PP	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
P_W,PP	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
P_C,PP	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications
P_W,C,PP	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications

Table A53. *Cont.*

Material	Processability	Potential Products for Application
P_PET	No processing possible	No application
P_W,PET	No processing possible	No application
P_C,PET	No processing possible	No application
P_W,C,PET	No processing possible	No application
P_PS	compression moulding	roofing and fencing sheets, plates for thermal insulation, office equipment, cases, plant pots, desk items [39]
P_W,PS	compression moulding	roofing and fencing sheets, plates for thermal insulation, office equipment, cases, plant pots, desk items [39]
P_C,PS	extrusion	Round, square and flat profiles [38], sheets, plates for in and outdoor applications
P_W,C,PS	extrusion	Round, square and flat profiles [38], sheets, plates for in and outdoor applications
PO_A	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
PO_A,W	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
PO_A,C	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications
PO_A,W,C	extrusion	Round, square and flat profiles [38], sheets, plates for in- and outdoor applications
PO_B	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
PO_B,C	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications
P	compression moulding	distribution pallets [33], bins, pails, roofing [36] and fencing [35] sheets [37], plates for impact sound and thermal insulation, lawn stones
P_C	extrusion	Round, square and flat profiles [38], sheets, plates for in-and outdoor applications

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4.3.2 Publication 6

Benchmark Analysis for Plastic Recyclates in Austrian Waste Management

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MS: Conceptualisation, Methodology, Investigation, Data Curation, Writing – original draft (section 2.2., 3.3.), Writing – review and editing, Visualisation, Project Administration.

HS: Investigation, Data Curation, Writing – review, and editing.

PR: Resources, Supervision, Funding acquisition.

VD: Writing – review and editing, Supervision.

SR: Writing – review and editing, Supervision, Funding acquisition.

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BENCHMARK ANALYSIS FOR PLASTIC RECYCLATES IN AUSTRIAN WASTE MANAGEMENT

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ABSTRACT

Plastic recyclates are granulates which are produced by the processing of plastic wastes. The circular economy package of the EU, especially the amendment of the Waste Framework Directive, sets a new goal for the use of different types of these recyclates. Corresponding primary raw materials can assure reliable qualities with respect to stable physical and chemical properties. Besides, the production of recyclates is often even more expensive than the production of primary raw material granulates. Several quality assurance measures are carried out along the value chain from plastic waste to final plastic products. Recyclates are evidently priced based on the price of primary raw material granulate. Pricing also correlates with different quality parameters, however, such as degree of mixing, degree of degradation and presence of impurities. This paper examines the correlation between different quality features and how they affect the pricing policy for recyclates. Experts and Stakeholders along the value chain of plastic recycling in Austria and Germany have been interviewed about the most important quality assurance parameters and how they (would) affect prices of recyclates. Therefore, quality parameters for the sorted plastic waste as an input for plastic waste recycling companies and manufactured recyclates are included in this paper. Experts from the plastic waste recycling industry confirmed that there is a profound correlation between price and quality that is presented and discussed in the paper: The higher the quality of the recyclates, the lower the level of impurities and the purer the recyclates, the higher the price.

1. INTRODUCTION

The European plastic strategy presented by the European Commission, to be implemented in the Recycling Sector Package, poses an enormous challenge for the European waste management and the plastics processing industry. The circular economy package sets a recycling rate of 55 wt.% by 2030 for plastic packaging waste (European Union, 2018). The European Commission has not stipulated a compulsory percentage of recycled plastics in the manufacturing process of new consuming products, i.e. substitution rate on a primary raw material level. Moreover, the Commission appeals to the responsibility of manufacturers to achieve its objectives regarding circular economy.

Currently, recyclates are applied with a content lower than 10% in new plastic packaging products (Reitz, 2019). This suggests that recyclates are either too expensive or of too low quality. Although scientific studies (Klumpp & Su, 2018; Martel, 2018; Pauwels & D'Aveni, 2014; Voros, 2019; Zhe Gin & Kato, 2010) have already focused on the correlation of quality and price for other goods, this paper does not only examine such correlations but also includes quality parameters for the sorted plastic waste and recyclates to provide a practical guideline for quality assurance. In the course of the applied survey for this paper, experts gave a comprehensive overview of how quality is assessed in the field and which parameters are significant for high quality material. Furthermore, this data will support assessing the economic feasibility of certain stages of plastic packaging waste treatment (European Committee, 2019).

Wide range of composited materials and problematic additives can lead to sales difficulties for recyclates too, since recycled materials from "older" waste plastics may still contain substances that are no longer permitted in new plastics due to their negative effects on the environment and health (Wilts et. al., 2014). Plastic recycling is also limited by a lack of quality and constant supply of raw materials required by the industry (Vilaplana & Karlsson, 2008). Quality criteria for recyclates for the final plastic processing companies are not standardised but defined individu-

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ally by the recycling and processing companies. Criteria include exceptionally pure colour and low content of contaminations (Vilaplana & Karlsson, 2008). Besides the lack of quality, the poor image of recycled plastics in the public also impairs plastic recycling (Moser et. al., 2016). As a result, recyclates are not used in new plastic products to the desired extent or not at all.

Despite the number of obstacles, however, recyclates are increasingly applied by the industry to pursue a sustainable strategy (Polymer Comply Europe, 2017). The market for primary raw plastics is characterized by:

- A close correlation with the price of crude oil, resulting in comparatively high volatility of prices. As a result, when the price of primary raw plastic significantly decreases, recyclates will be increasingly substituted by primary raw material granulate, as well as
- Easy substitutability of products of different suppliers and also by oligopolistic market structures, inspiring strategic behaviour of suppliers (Rothgang et. al., 2017).

The main question raised by this paper is based on these two findings and seeks to establish a correlation between the price and the quality of plastic recyclates. In addition, the quality requirements for sorted plastic waste and produced recyclates are examined. The importance of quality assurance and its practical implementation are treated in a separate section. Furthermore, the market for primary raw plastics and recyclates is examined in detail and pricing developments are analyzed.

2. MATERIALS AND METHODS

2.1 Materials

The following plastic types are being investigated in the study as they represent 57% of the demand for the plastic packaging waste processing industry in Austria (Stoifl et. al., 2017):

- High-density polyethylene (HDPE) foils and hollow bodies (emptied);
- Low-density polyethylene (LDPE) foils and hollow bodies (emptied);
- Polypropylene (PP) foils and dimensionally stable PP (bucket, canister, emptied);
- Polyethylene terephthalate (PET) bottles (emptied);
- Polystyrene (PS) foils (thermoforming film).

This paper mainly discusses recyclates since regrind materials do not undergo extensive quality assurance and, frequently, only the impurity content is of importance.

2.2 Methods

All relevant stakeholders along the value chain from plastic wastes to the finished products are shown in Figure 1. This figure also shows all the terms used in this paper along the presented value chain.

A market analysis of secondary plastic granulates was conducted to identify the quality benchmark in plastic recyclates, performed by observing the development of pricing, identifying drivers to the increase or decrease of value and verifying whether the value depends on recyclate quality or on other economic features.

To analyse the correlation between price and quality, several packaging plastic waste processing companies and plastic waste recycling companies were provided with a specially designed assessment guide. In addition to personal discussion with plastic waste recyclers and the plastic waste processing industry in Austria, the plastics recyclers and the plastics processing industry in Germany was approached with short and targeted e-mail questions. Altogether, 19 different stakeholders responded. Six phone calls were made, reaching two plastic recyclers, three plastics processing companies and one association. In addition, about 80 e-mails were sent to plastic waste collectors, plastics recyclers and plastics processing companies, resulting in a return rate of approximately 20%. Four plastics recyclers, five plastic processing companies and four other stakeholders responded. Figure 2 shows the distribution of the consulted companies by industry. 32% of plastic re-

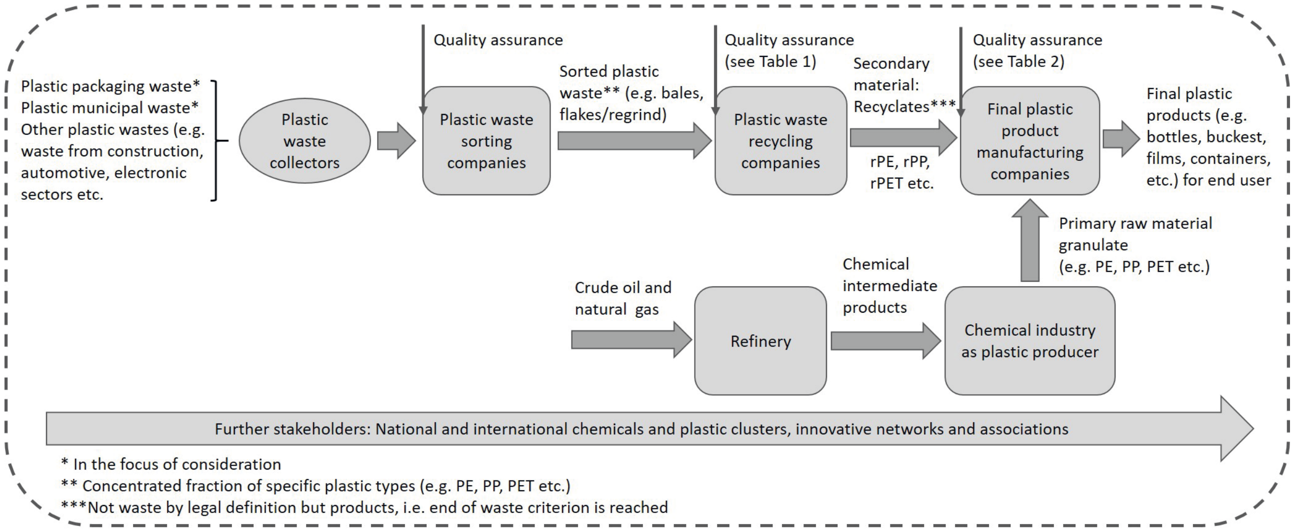

FIGURE 1: Stakeholders along the value chain from plastic waste to final plastic products.

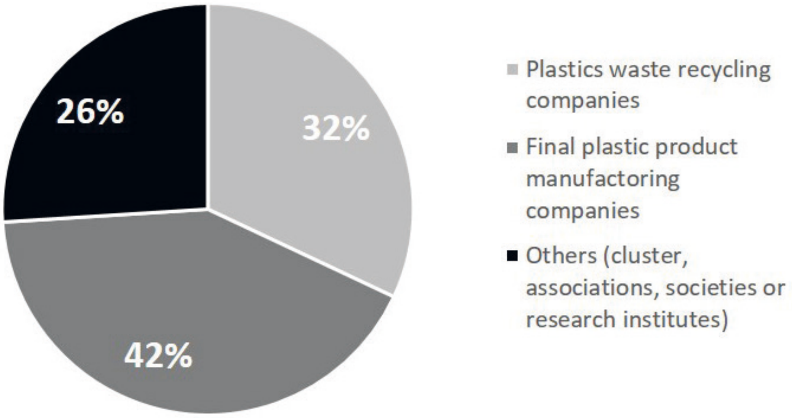

FIGURE 2: Distribution of the consulted companies by industry.

cyclers, 42% of plastic processing companies and 26% of other stakeholders along the plastic value chain participated the survey. The other stakeholders are cluster, associations, societies or research institutions operating in the field of plastics processing.

3. RESULTS AND DISCUSSION

The following section is divided into five subsections. First, the quality requirements for the sorted plastic waste and the plastic recyclates are shown. Second, the section "Quality Control" is describing, which parameters are significant for reliable quality control for the sorted plastic waste and manufactured recyclates. Additionally, price development for the polymer types mentioned above has been done. Furthermore, the most relevant questions of this study are answered in a separate section. Finally, to fulfil the titles of this paper, the quality benchmark in plastics recyclates are described.

3.1 Quality Requirements

Requirements for sorted plastic waste qualities:

In Germany, quality standards for sorted plastic waste applied in the plastic waste recycling companies have evolved within the plastic industry (Grüner Punkt, 2019), summarized in Table 1.

Quality requirements for produced recyclates:

Provided specification sheets or datasheets of produced recyclates include limit ranges (see Table 2) for the following properties:

- The density of non-cellular plastics (DIN EN ISO 1183-1)
- Melt volume-flow rate (MVR), melt-mass flow rate (MFR) and flow rate ratio (DIN EN ISO 1133-1)
- Tensile properties, in particular, modulus of elasticity (E-Modul) (DIN EN ISO 527-1)
- Notch impact strength (DIN EN ISO 179/1eA)

3.2 Quality assurance

3.2.1 Quality assurance of plastic waste

The key competence in the quality assurance process of the delivered mixed plastic waste material to the plastic waste sorting plant is found with the material acceptance staff. Based on their experience, the quality of supplied plastic waste bales can be assessed by visual inspection. Attention is paid to coarse impurities. The collective experience of the stuff is decisive. An essential part of the input control is the colour distribution of the bale because a majority of pure plastics is a requirement for the production of high-quality recyclates and their use in new products.

Furthermore, the origin of waste affects the assessment of the sorted plastic waste quality. Hence, the materi-

TABLE 1: Quality standards for sorted plastic wastes for recycling (Grüner Punkt, 2019).

Sorted plastic wastes	Metal items [wt.%]	Other plastic particles [wt.%]	Other residues [1] [wt.%]	Dimensionally stable PE articles [wt.%]	Foamed plastics incl. EPS* [wt.%]	Plastic Foils [wt.%]	PVC [wt.%]	Dimensionally stable PP [wt.%]
Plastic Foils (mostly LDPE)	< 0.5	< 4.0	< 4.0	-	-	-	-	-
Plastic hollow body (mostly HDPE)	< 0.5	< 3.0	< 3.0	-	-	-	-	-
PP	< 0.5	-	< 3.0	< 1.0	< 0.5	< 2	-	-
PET bottles	< 0.5	< 2.0	< 2.0	-	-	-	< 0.1	-
PE	< 0.5	-	< 3.0	-	< 0.5	< 5.0	-	< 3.0
PS	< 0.5	< 4.0	< 2.0	-	< 1.0	-	-	-

*Compostable waste (foods, garden rubbish). * EPS: expanded polystyrene*

TABLE 2: Physical, chemical and rheological properties of the investigated recyclates (Grüner Punkt, 2019).

Properties	LDPE	HDPE	PP	PET	PS
Density [g/cm^3]	0.920 - 0.945	0.940 - 0.970	0.895 - 0.920	1.360 - 1.390	1.050 - 1.290
Melt-mass flow rate (MFR) [g/10 min]	0.5 – 0.9(1)	0.1 - 30.0(1)	0.1 - 30.0(2)	20.0 - 30.0(3)	2.3 - 8.2(4)
Tensile properties (modulus of elasticity) [MPa]	220 - 380	1 170 - 1 350	850 - 1 450	3 400 - 3 700	3 000 - 3 400
Notch impact strength [kJ/m^2]	8.00 - 15.00	4.85 - 5.15	3.00 - 5.50	2.00 - 4.00	8.0 - 12.0

(1) 190°C | 2,16 kg (2) 230°C | 2,16 kg (3) 280°C | 5,00 kg (4) 200°C | 5,00 kg

al flow can be assessed using empirical values depending on the origin.

There are interesting arguments why deliveries of sorted plastic waste bales are rejected. Cartridges for sealing compounds repeatedly lead to rejection. The moisture of bales is another argument. Increased moisture can affect the surface of the particles and foaming processes during injection moulding may occur. Basically, however, non-conformity with quality requirements usually leads to a price reduction. If the content of contaminants is too high, the processing is impaired (material variations).

3.2.2 Quality control of recyclates

The quality of random samples of recyclates is controlled in a laboratory. The physical, rheological and mechanical properties of the recyclates are of great interest. The following characteristics are analysed in the course of a random sample inspection:

1. Physical properties
   a. density determination (DIN EN ISO 1183-1)
2. Rheological properties
   a. melt-mass flow rate (MFR) (DIN EN ISO 1133-1)
3. Mechanical properties
   a. tensile properties, especially modulus of elasticity (DIN EN ISO 527-1)
   b. notch impact strength DIN EN ISO 179/1eA

Frequently, further parameters of the recyclates are determined. These include:

- Melting temperature
- Colour distribution and colour composition
- Size and form of the granulated material (e.g. lenses, cylinder)
- Moisture content
- Filtration fineness
- Ash content
- Heavy metal content

In addition, there is often a continuous control of recyclates and an inspection for any specks, gas emissions, mechanical values and the colour of the recyclates.

The hardness of recyclates allows initial prediction of the foreign plastic content, the shape of the granulates and the bulk density indicating potential gas inclusions or vacuoles. The colour and odour of granulates may indicate previous thermal degradation of the material. The following devices or test methods are frequently used in quality assurance refers to the previously mentioned standard specifications: Melt index testers, differential scanning calorimetry (DSC), ash furnaces, residual moisture scales, density analysers, capillary rheometers, tensile testing and notched-bar impact test machine.

3.3 Price Development

The plastic trading market is currently shifting and, as mentioned before, increasingly developing into a buyer's market. A high dollar exchange rate (1,1008 $/€ on 24-Sept-2019) (Wallstreet-online, 2019) and weak crude oil prices (62.90 $/barrel on 24-Sept-2019) (Tecson, 2019) result in a preference for primary raw material over recyclates. Moreover, the European plastic market has changed due to the ban of exports to China that has previously been one of the largest importers of European plastic waste.56% of all plastic waste worldwide and 87% of all European plastic waste has been sent to China in recent years (Uken, 2018). The plastic waste streams, which are heavily contaminated and poorly sorted are most seriously affected. As a result, there is an oversupply of this plastic wastes in the European plastic recycling market. It follows that the plastics processing industry will favour high quality of plastics available.

Plastic wastes with low extraneous and pollutant contents and lower humidity are demanded. This oversupply of polluted plastic waste enables customers to select highest-quality plastic waste, ultimately affecting the pricing. Low-quality plastic waste losing market shares used to a great extent for thermal treatment or recovery (Sarc et. al., 2019).

3.3.1 Price development for sorted plastic waste

The price developments for HDPE and LDPE (A), PP (B), PET (C) and PS (D) regrinds and bales over the last years are shown in Figure 3. The average selling price for regrinds of commodity plastics (e.g. PE, PP, PET, PS) is about 538 €/t, varying by 92 €/t (Plasticker, 2019).

For the PE types, it is stated that the average regrind price is very similar for HDPE and LDPE with approximately 0.6 €/kg (Plasticker, 2019). The HDPE regrind price fluctuated significantly more than LDPE in the years 2014 to 2017. The LDPE regrind price is on average three times higher than the prices for the LDPE bales. This can also be observed for PP and PET. At 0.56 €/kg, the average regrind price for PP is 2.5 times higher than for PP bales, and at 0.37 €/kg, the average regrind price for PET is 1.9 times higher (Plasticker, 2019). The reason for this is the higher processing depth and the associated higher costs for the production of regrinds compared to bales. The different

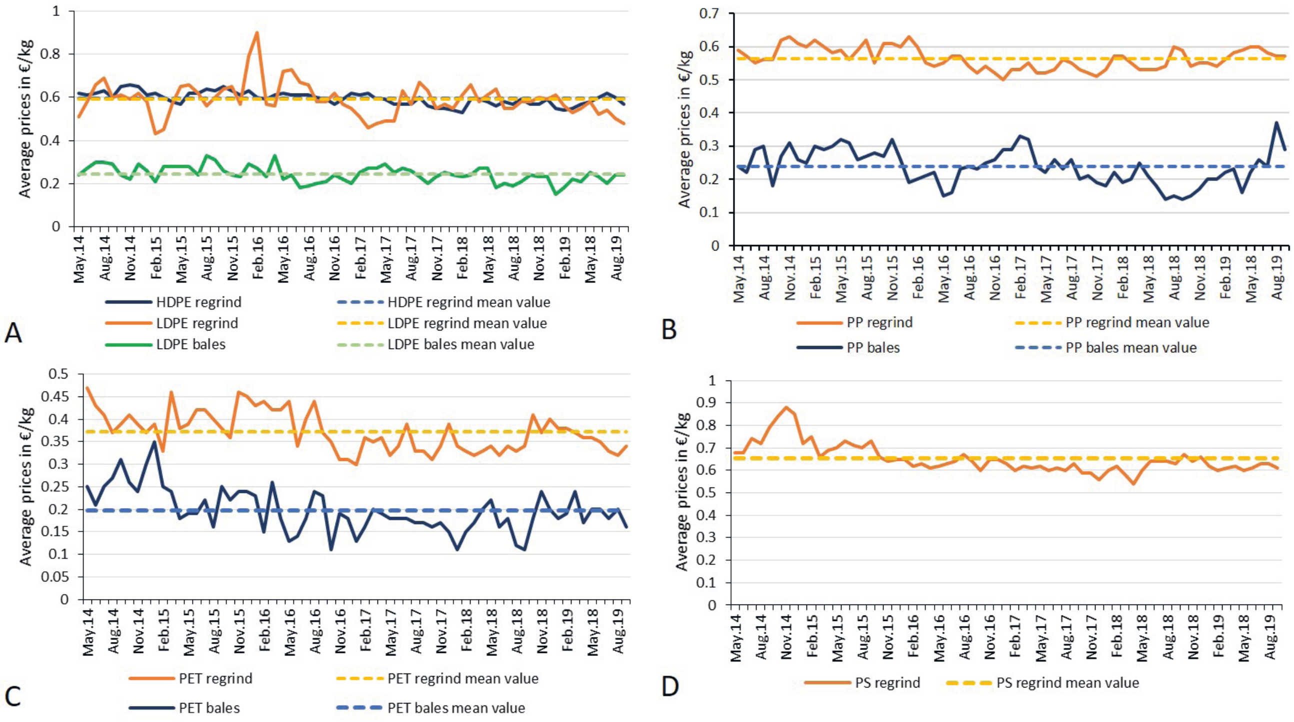

FIGURE 3: Price development for regrinds and bales of PE types (A), PP (B), PET (C) and PS (D) (Plasticker, 2019).

price differences between regrinds and bales of the plastic types can be explained by the different processing costs.

3.3.2 Price development for recyclates

The price developments for LDPE (A), HDPE (B), PP (C) and PS (D) granulates of primary raw materials and recyclates are shown in figure 4. No reliable price development could be collected for PET. The average selling price in July 2019 of primary raw material granulates of standard plastics (e.g. PE, PP, PS, PET) was around 1.17 €/t and 0.537 €/t (Plasticker, 2019) was the average selling price of recyclates of standard plastics. This means that granulates produced of primary raw material are on average twice as expensive as recyclates.

A comparison of the price developments of the primary raw materials with those of recyclates shows that there is a certain dependency between both price developments. If the price of a primary raw material rises or falls, the recyclate price of this plastic type also reacts with a price rise or fall. This fact can be seen for example well for LDPE in Figure 4 (A).

3.4 Market Study

The following section provides a summary of the most important statements:

Is there a correlation between price and quality of the sorted plastic waste?

First, the general market balance of supply and demand is pointed out. This provides the basis for any pricing. Where supply and demand meet, a corresponding market for goods develops.

The respondents 'affirm' the question, though. There is indeed a strong correlation between the quality and price of the sorted plastic waste. In addition, better application options are made accessible by purer sorted plastic waste, higher-priced. Surveyed plastic processing companies also reported the dependence of co-payments, i.e. a negative price for recyclates. If the sorted plastic waste can be purchased for a higher additional price, then the recyclates may be offered for less. When co-payments decline, however, the prices in sales have to rise. Additional payments depend primarily on the quality of the sorted plastic waste. If the material is dirty and includes high amounts of extraneous plastic, additional payments are higher. It the material is clean, on the other hand, and has a low level of extraneous plastics, additional payments will be lower.

It was also mentioned that the quality of the sorted plastic waste is primarily defined by its colour. The higher its purity, the higher the price that can be achieved on the plastic trade market. This is mainly due to its broader application range, say, in subsequent colouring, foil thickness and mechanical properties.

As mentioned above, the staff is crucial for sorted plastic waste price. They ultimately control the quality and their wealth of experience facilitates a reliable quality level and, accordingly, adequate pricing.

Is there a correlation between price and quality of the recyclates?

Regarding this question, there is again a general agreement on a higher quality of recyclates leading to higher prices. It is backed by the argument that higher quality of the recyclate reduces the risk of failures or bad batches from contamination for final plastic processing companies. Furthermore, it was mentioned that the quality of the

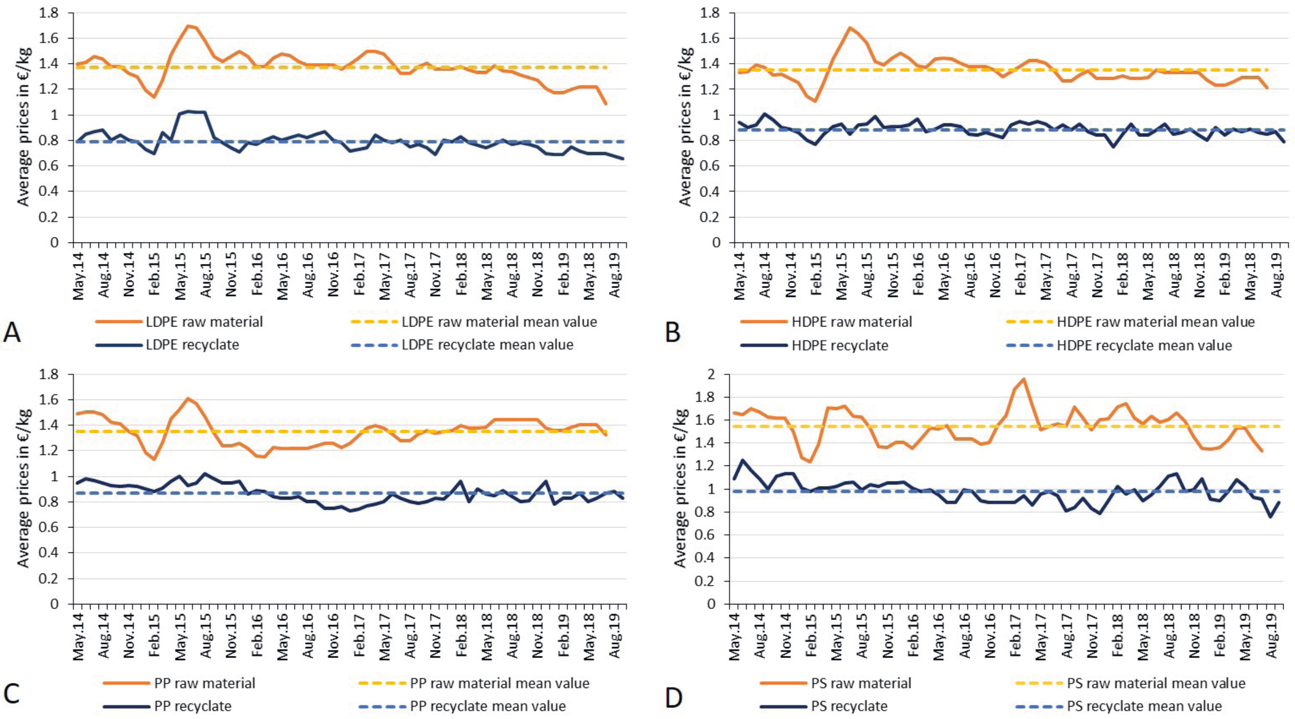

FIGURE 4: Price development for primary raw material and recyclates of LDPE (A), HDPE (B), PP (C) and PS (C) (Plasticker, 2019).

sorted plastic waste strangely affects the quality of the produced recyclates.

Pricing of recyclates

Basically, the market mechanisms of supply and demand apply. In addition, the following criteria were identified for pricing recyclates:

- Purity: the purer a material, the broader its range of application and the higher the price potentially achieved;
- Colour purity: the purer the colour of recycled material, the broader its range of application and the higher the price potentially achieved;
- A function of the primary raw material prices: Pricing polymer types is a function of the respective commodity price. If the price of primary raw material decreases, the price of polymers will drop as well. Recyclate prices are usually following the trend.

Other pricing contributors are melt filtration in the context the lower the melt filtration (measured in µm), the higher the quality and cost supplement for masterbatches. When plastic is dyed, a certain amount will be charged for this procedure, raising the price.

3.5 Quality benchmark in plastics recyclates

Market analysis has not produced any evidence for plastics recyclate benchmark. Therefore, producers of recyclates were asked to give one.

The surveys indicated that the quality standards for recyclates from Grüner Punkt (2019) are considered as a benchmark in the industry. For the recyclate quality, two levels are distinguished: mean quality for standard products like flower pots or buckets in 'standard plants' and high quality surpassing defined threshold values from Grüner Punkt (2019).

The demand for plastic recyclates is higher now than the recycling market is able to provide. For this reason, primary raw plastic granulates are mostly about 40 to 60% (see Figure 4) more expensive than plastic recyclates compared by the market data. The quality of recyclates is below that of primary raw plastic granulates regarding material properties but the consumers would tolerate it for the sake of sustainability. Better recyclability of plastics might reduce the market value of plastic recyclates. As best plastic recyclate quality, i.e. the benchmark, is met by plastic recyclates applied to food packaging like 'cap-to-cap' or 'bottle-to-bottle' production referring to the surveyed plastic processing companies.

4. CONCLUSIONS

The essential question was whether a correlation between price and quality of plastics recyclates is perceived. Experts from the plastics product manufacturing companies and plastics recyclers confirmed it unequivocally: The higher the quality of the material, the lower the impurities and the purer the material, the more applications for the material exist.

For sorted plastic waste, the plastic waste recycling companies quality standards defined by Grüner Punkt (2019) are considered a benchmark while recyclates applicable as food packaging (like cap-to-cap or bottle-to-bottle) constitute a benchmark for plastic recyclates.

In addition to the general market mechanisms of supply and demand, the pricing of secondary plastics is mainly a function of the purity of the recyclate, the purity of the colour and the respective price of raw materials. The purer and the cleaner the material, the higher the price that can be achieved on the market. The impact of respective commodity prices is also linked to the crude oil price and the dollar exchange rate.

Furthermore, the key competence of the staff in terms of quality control must be underlined. Their experience allows fast and reliable control, essential for successful further processing. For the quality control of recycled material, physical, rheological and mechanical properties are identified. In addition to density and melt flow rate, tensile properties and impact strength are identified to assure the required quality.

Plastic waste recycling companies would very much welcome a stipulation of minimum requirements for sorted plastic waste and recyclates by legislation.

Finally, it can be stated that, although the use of recyclates is facing some obstacles, many plastic product manufacturing companies are using plastic recyclates in their spite. There is a need for further changes at the political level (note: very positive example is “plastic strategy” of the EU) to help achieve a breakthrough. Many stakeholders along the plastic value chain would favour the further international introduction of quality standards. In addition, raising public awareness of the value of plastic waste is of key importance for further developments in the use of recycled plastic. Therefore, a package of measures and tools is needed to reduce obstacles and to promote high-quality plastics recycling as well as the use of recyclates.

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5 SUMMARY AND DISCUSSION

This doctoral thesis contains six research papers, subdivided into four subject areas with three research areas that build on one another (see Figure 9). The six research questions, defined in the three research areas of chapter 3.1 (see Figure 8), are answered based on the results from these peer-reviewed papers.

5.1 Potential of Plastics

This chapter presents a summary of publication 1, which forms the basis for further research.

Publication 1

This research paper aimed to determine the plastic content in the pre-shredded waste MCW and MMW as a function of the particle size. The following six screen cuts were created for the analysis after shredding for both wastes: 20-40 mm, 40-60 mm, 60-80 mm, 80-100 mm, 100-200 mm, and 200-400 mm. Since the particle shape of the plastic particles is also essential for specific recycling processes, each of the six screen fractions of both wastes was additionally sorted manually into two-dimensional and three-dimensional plastic particles. To determine the distribution of individual plastic types, each of the 12 particle size fractions generated per waste type was manually sorted into the seven plastic types LDPE_n, LDPE_c, HDPE_n, HDPE_c, PP, PVC, PUR, PET, PS, and EPS, using sensor-based sorting. Other sorting fractions were other plastics, composites, no plastics, unidentified, and residue.

With this publication, it could be shown that it is essential for an initial concentration of certain types of plastics of a particle shape to know their distribution after shredding and screening. These data will be important in the planning of future mixed waste treatment plants for the concentration and recovery of plastics for recycling in order to be able to operate the plants efficiently at high capacity levels.

Research question 1:

Which quantities of different plastic types can be found in non-hazardous, mixed, solid commercial, and municipal waste in which dimensionality (2D/3D) and grain size?

The results of publication 1 show that the plastics content in MCW (23%) is higher than in MMW (15%). Both wastes have a similar proportion of 2D-plastics (8-9%), whereas the content of plastics-3D in MCW is twice as high (14%). The most representative fraction with about one-third of the total mass of both wastes is the fine fraction <20 mm. Due to the higher total plastic content, MCW seems to be more suitable for recovering plastics for recycling.

The investigation of the particle size-dependent plastic distribution showed for both wastes that the proportion of 2D-plastic increases with the particle size, and the maximum is reached in the largest particle size (MCW: ~46%; MMW: ~23%). The results of MCW showed that significantly more 3D-plastics (20-30%) are contained in the particle size classes smaller than 100 mm. For MMW, no grain size dependence could be found for the 3D-plastic content.

The composition of investigated plastic fractions in both wastes by plastic types shows that the majority (70-85%) of both plastic-2D fractions is composed of polyolefins, with PP being relatively low at ~10%. The two plastic-3D fractions, however, show higher contents of PP (20-30%), PET (~18%), PVC (7-11%), and PS+EPS (8-11%). Higher quantities of PC, PA, and PUR plastics were only observed in the plastics-3D fraction of the MCW. A particularly high proportion of unidentifiable objects (15-20%) was found in the plastics-3D fraction for both wastes. In summary, this means that an initial concentration of certain plastic types can be achieved by splitting the material flow during both waste processing, e.g., using air separation technology or ballistic separator. Through further processing using screening, it was determined for both wastes that the largest proportion of material for the plastic-2D fractions falls into the particle size class 100-200 mm and for the plastic-3D fraction into the particle size classes 40-60 mm and 60-80 mm. Furthermore, it was found that specific types of plastics are increasingly present in certain particle size classes. For example, for the plastic-2D fractions, it was observed that the examined PE-types are predominantly present in the particle size 80-100 mm. In contrast, PP, PVC, PUR, PET, and PS are rather represented in the smaller particle sizes.

Of course, these results cannot be transferred to other wastes. They must be collected for each waste with the respective shredding technology used in order to be able to guarantee a correct aggregate selection and sequence for the concentration of plastics and certain plastic types from mixed wastes through shredding, material flow separation, and screening.

5.2 Processing and Concentration of Plastics

This section summarises and discusses the key results of research publications 2, 3, and 4.

Publication 2

As publication 1 showed, screening is a key element in processing mixed wastes for valuable material enrichment. The influence of pre-screening on the down-stream processing of the mixed wastes MCW and MMW to produce plastics-enriched fractions for recycling was investigated in more detail in publication 2.

Large-scale processing experiments were carried out for these investigations. The investigated wastes MCW and MMW were shredded, optionally screened (<80 mm) in two test setups (with and without pre-screening), and divided into the three material streams, 2D-, 3D-fraction and fines (<80 mm) using a ballistic separator. Samples of the 3D-fractions were then NIR-sorted for plastic (eject) separation, and the two output fractions (eject and reject) were sorted manually for quality assessment. Samples of the 2D-fractions were only sorted manually for quality assessment. The two resulting fines from the screen and the ballistic separator were screened into four particle size classes and visually assessed to their remaining plastic content.

Research question 2:

How can plastics from mixed wastes be concentrated and discharged as easily as possible, and what influence does pre-screening have on down-stream processing and output quality?

The large-scale experiments have shown that this simple processing through shredding, pre-screening with a drum screen, and ballistic separation (with screen paddles) is well suited to generate plastics-rich 2D- and 3D-fractions from mixed waste that are suitable for further processing in, e.g., plastic recycling plants. For example, the plastics from the 3D-fraction separated by NIR-sorting could be used, post-shredded and screened, as a substitute reducing agent in the blast furnace process. The 2D-fraction could be directly fed into a wet-mechanical treatment aggregate for polyolefin separation after post-shredding (see publication 3). These would then be suitable as feedstock for thermochemical conversion to produce petrochemical intermediates (see the ReOil process of OMV) for the chemical industry.

By pre-screening with a drum screen, approx. 12% more fines could be separated from both types of waste. This improved the screening and separation performance of the ballistic separator, leading to a lower 2D-output with higher quality at the same or slightly increased 3D-output of the same quality as without pre-screening. It was shown that screening efficiency and separation quality of the ballistic separator can be improved by pre-screening. Pre-screening resulted in ~5% more 2D-plastics in the 2D-fraction and a reduction in fines and inert. The pre-screening also resulted in an improved classification of the plastic particles of the 3D-fraction via NIR-sensor, which improved the SBS performance (e.g., increased yield). Based on the screening results, the visual assessment of the fines, and the results of Viczek et al. (2020), it is assumed that significantly higher pollutant concentrations occur in the fines from the screen than in the fines from the ballistic separator, which can potentially be used for further recovery of plastics or as RDF.

Due to pre-screening, the negative effect of tail-formation was observed for MCW, which can lead to clogging, plant downtime, material losses, and performance reduction of down-stream processing machinery.

Publication 3

Three different plant tests (real waste treatment plant, test plant, and sensor-based sorting unit tests) were carried out to identify mass and volume flow fluctuations, assign their causes and assess their effects.

Research question 3:

How do the mass and volume flow fluctuations influence the process and material quality?

Through investigations at a real waste treatment plant, three different temporal fluctuations of occupation density with different causes were identified: the varying discharge of material causes short-term fluctuations (~3-4 s) from upstream processing machinery (e.g., drum screen), mid-term fluctuations (~30 s) are resulting from the discontinuous feed of the processing line or braid formations, etc. and the long-term fluctuations (some minutes or longer) are the throughput variations that occur due to plant downtimes or changes in the cutting gap of a pre-shredder. The different input materials showed different shredding (selective shredding) and conveying behaviours, resulting in the short- and mid-term fluctuations. This is particularly relevant as the performance of different downstream processing machines may be affected differently, depending on the type of fluctuation occurring. The detection of mass and volume flow fluctuations can contribute to the early recognition of plant problems (e.g., signs of wear, calibration deviations in aggregates, often reversing of the shredder) and material-induced disruptions (e.g., braid formation, bridging effects, etc.).

Data from the test series with a sensor-based sorting machine can be used to quantify the relevance of fluctuations for the performance of a processing chain. The sorting performance of an SBS-machine, being affected by realistic fluctuations (six-second intervals) resulting from an up-stream drum screen, compared to a steady throughput rate.

The almost twice as high incorrect particle discharge by the fluctuating feed can be attributed to the temporarily higher occupancy densities on the acceleration belt. This led to more overlapping particles and thus misclassified particles from the residual fraction, leading to a decrease in purity with increasing occupancy density (Küppers et al., 2020). The focus of the sorting recipe was set to yield and not to purity. Therefore, the fluctuating feed hardly changed the yield, but the purity of the discharge fraction deteriorated by ~6 %. In sorting plants, mass and volume flow fluctuations can massively deteriorate the machine-made plastic concentrates quality. To achieve the required purity of a valuable material fraction, impurities must be removed in additional sensor-based sorting stages or manually.

Publication 4

Samples from the 2D-fraction obtained in the experiments described in publication 2 were used for the wet-mechanical tests. The aim was to separate the polyolefins contained in the MCW and MMW, which had been pre-treated with a drum screen and ballistic separator and then shredded (<20 mm), with the highest possible throughput and high separation selectivity using the wet-mechanical separation unit - centrifugal force separator. To produce a light fraction with high purity, a cascade configuration of two CFSs was simulated by feeding the light material again after the first pass. To assess the quality of the fractions produced, samples of the input materials and all output fractions produced (heavy and light material) and the process water were subjected to a detailed physical-chemical analysis.

Research question 4:

Is wet-mechanical processing suitable for the recovery of polyolefins from mixed wastes (MCW/MMW) for material or chemical recycling?

The CFS test plant results showed that a single-cascade connection of two CFSs achieves a purity of the light fraction (predominantly PO) of approx. 95% for both wastes. Throughputs between 31 and 37 kg/h were achieved. The heavy fraction still contained 20-30% light fraction, which was not separated. The minor sediment fraction of ~1% was almost completely separated in the first run. The sediment does not meet HP[1] criteria and can therefore be treated in a waste incineration plant or sewage sludge mono-incineration plant. The density of the process waters, which plays an essential role in efficient separation, was only slightly changed by the increasing impurities so that no impairment of the separation process in the CFS was expected. The results of the process water investigations show that a water treatment (mechanical biological or chemical biological cleaning) has to be carried out before discharge into a watercourse or sewage treatment plant to limit the discharge of toxic substances and their concentration, as prescribed by law. Summarised, the cascaded CFS process appears to be suitable for further processing of already pre-treated waste to recover a PO-fraction for chemical and mechanical recycling options, especially since this process efficiently combines the separation and cleaning steps.

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[1] HP (hazardous property): The Waste Framework Directive (Directive 2008/98/EC) defines fifteen hazard criteria or HP criteria. With their help, the hazardousness of waste can be determined according to limit concentrations.

5.3 Recovery and Recycling Aspects

This final subchapter summarises and discusses the research findings of both publications 5 and 6.

Publication 5

Different processed, mixed wastes were investigated concerning their necessary processing depth (e.g., washed and unwashed) and their basic processability. For this purpose, pre-treated mixed waste from SRF production and two polyolefin (PO) fractions were used. All plastics were manually sorted out and washed or unwashed and dried fed into a sensor-based sorting aggregate from the mixed waste. The sorted plastic types (PE, PP, PET, and PS) and the washed or unwashed PO fractions were shredded to <4 mm for further processing. All material streams were divided after shredding. One material stream was fed directly to a compression moulding process, and the other part to a previous homogenisation. All 20 materials produced were then extensively characterised thermally, mechanically, and rheologically.

Research question 5:

Are different plastic fractions, which have been recovered from mixed wastes, processable, and what material properties do the recycled materials then have?

The investigations have shown that all waste materials could be processed into plastic-rich fractions with a grain size <4 mm using simple waste treatment without any significant problems. The processing of the different plastic fractions with simple compression moulding showed that all PE-, PP-, PO- and P[1]-materials could be processed without any major problems. Only the PET materials could not be processed. The low MFR values in combination with the processability of the other materials, suggests that conventional extrusion into semi-finished products could be technically possible. Although the material properties determined were in some cases much lower than those of the virgin polymers, they were better than expected. The results also show that an upstream washing process improves the achievable properties, but homogenisation does not necessarily lead to an improvement in properties. Nor is it necessary to recover individual plastic types from the mixed waste since the PO- and mixed plastics fractions showed similarly good material data with good processability. In summary, the investigations show that the recovery and simple treatment of plastics from mixed, contaminated wastes into at least downcycling products seems to be possible.

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[1] P - mixed plastic fraction

Publication 6

A wide range of composited materials and problematic additives can lead to sales difficulties for plastic recyclates. The pricing of plastic recyclates also correlates with different quality parameters (e.g., presence of impurities, material properties). Besides, the production of recyclates is often even more expensive than the production of virgin material. Quality criteria for recyclates for the plastic processing companies are not standardised but defined individually by the recycling and processing companies. The correlation between different quality features and how they affect the pricing policy for recyclates is investigated in this Publication. Therefore, experts and stakeholders along the value chain of plastic recycling in Austria and Germany have been interviewed about the most essential quality assurance parameters and how they affect the prices of recyclates. The quality parameters for both the sorted plastic waste and the plastic recyclates produced from it were gathered. Furthermore, the market for virgin plastics and recyclates is examined in detail, and pricing developments were analysed. The investigations were focused on the packaging plastics HDPE, LDPE, PP, PET, and PS.

Research question 6:

How do different quality properties of plastic concentrates and recycled plastics affect the pricing policy of recycled plastics?

The market balance of supply and demand provides the basis for any pricing. The investigations confirmed that a strong correlation between the quality and price of the sorted plastic waste exists. Better application options are made accessible by purer sorted plastic waste, which is then higher-priced. There is also a dependence on co-payments, i.e., a negative price for recyclates. If the sorted plastic waste can be purchased for a higher additional price, then the recyclates may be offered for less. Additional payments depend primarily on the quality of the sorted plastic waste. If the material is highly contaminated (e.g., dirt or other plastics), additional payments are higher. It was found that its colour primarily defines the quality of the sorted plastic waste. The higher its purity, the higher the price that can be achieved on the plastic trade market. In Germany, quality standards for sorted plastic waste applied in the plastic waste recycling companies have evolved within the plastic industry (Grüner Punkt, 2019). Furthermore, the origin of waste affects the assessment of the sorted plastic waste quality (e.g., moisture).

Moreover, the European plastic market has changed due to the ban of exports to China that has previously been one of the largest importers of European plastic waste. The plastic waste streams, which are heavily contaminated and poorly sorted, are most seriously affected. This oversupply of polluted plastic waste enables customers to select highest-quality plastic waste, ultimately affecting the pricing. Low-quality plastic waste losing market shares is used to a great extent for thermal treatment or recovery (Sarc et al.,2019). It was also found out that the quality of the sorted plastic waste strongly affects the quality of the produced recyclates. The reason for higher regrind prices compared to sorted plastic bales is the higher processing depth and the associated higher costs for the production of regrinds compared to bales.

The market for primary raw plastics is characterised by a close correlation with the crude oil price, resulting in comparatively high prices volatility. As a result, when the price of primary raw plastic significantly decreases, recyclates will be increasingly substituted by primary raw material granulate. In principle, the market mechanisms of supply and demand also apply for recyclates. Other criteria for pricing recyclates are material and colour purity. The higher the quality of the recyclates, the lower the level of impurities, and the purer the recyclates, the higher the price. In Germany and Austria, material data sheets of produced recyclates, including limit ranges, are usually required from the processing company. Therefore the physical, rheological, and mechanical properties of the recyclates are of interest (see publication 5).

Granulates produced of primary raw material are on average twice as expensive as recyclates. Comparing the price developments of the primary raw materials with those of recyclates shows a certain dependency between both price developments. If the price of a primary raw material rises or falls, the recyclate price of this plastic type also reacts with a price rise or fall.

6 OUTLOOK AND FUTURE RESEARCH

The results of this doctoral thesis show that sufficient plastics are present in mixed waste such as MCW and MMW. A relatively simple concentration and recovery of these waste plastics is possible, and the potential for further processing in conventional polymer processing machines is given.

Three main topics and associated research questions with potential for further studies arose from the doctoral thesis at hand:

Although first studies have shown that knowledge about the particle size-dependent distribution of plastic types in mixed waste is essential for targeted concentration and recovery of these, large-scale test series must be carried out to create a reliable, representative database.

- What is the particle size distribution of plastic types in unshredded mixed wastes?
- What influence do various shredder types and settings have on the particle size distribution of specific plastic types?

It was found that in the concentration of plastics from mixed wastes by ballistic separation, the upstream installation of a drum screen improved the purities of the discharged 2D-fractions and the quality of the NIR-sorting. Further detailed analyses of all resulting output fractions are necessary to select suitable treatment and recycling options.

- What is the composition of the fine fraction from the screen, what contaminants does it contain, and what processes can be used to treat it further?
- How much and which types of plastics are discharged into the fine fraction of the ballistic separator, and can these be recovered by further processing steps, or can the fine fraction be used as SRF?
- What effect does the use of another screening technology instead of the drum screen have on the purity of the output fractions produced, and how is sensor-based sorting of plastics affected by this?
- Is the 3D-plastics fraction produced by NIR sorting suitable as a substitute reducing agent in the blast furnace process?

The basic processability of differently pre-treated plastic types and plastic mixtures recovered from mixed wastes was demonstrated. To clarify the processability with other polymer processing methods, further trials must be carried out and the manufactured materials and products tested.

- Is it possible to process recovered plastics from mixed wastes in extrusion and injection moulding processes, and what material or product properties are achievable?
- Can the recovered, pre-treated plastic flakes be incorporated into a virgin polymer matrix as a filler to produce a compound material?
- Which type of plastic is best suited as a matrix material?
- How do the material properties of the produced compound change when the recovered, pre-treated plastic flakes are incorporated into a virgin polymer matrix?

The investigations of this thesis show that the recovery, treatment, and processing of plastics from non-hazardous, mixed, solid wastes into at least downcycling products (mechanical recycling) or for chemical recycling is possible. By transferring these plastics from thermal recovery to recycling purposes, an important contribution is made to achieving the recycling targets, resource conservation, and reducing greenhouse gases and waste.

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LIST OF ABBREVIATIONS

Abbreviation	Description
2D	Two-dimensional
3D	Three-dimensional
CFS	Centrifugal force separator
EPS	Expanded polystyrene
EU	European union
Fe	Ferromagnetic (Iron)
HDPE	High-density polyethylene
HF	Heavy fraction
HSI	Hyperspectral imaging
LDPE	Low-density polyethylene
LF	Light fraction
MCW	Mixed commercial waste
MMW	Mixed municipal waste
Mt	million tonnes
NIR	Near-Infrared
PE	Polyethylene
PET	Polyethylene terephthalate
PO	Polyolefines
PP	Polypropylene
PRF	Plastic recycling facilities
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
RDF	Refuse Derived Fuel
SRF	Solid recovered fuels
SSP	Solid state polymerisation
VIS	Visual

APPENDIX A – PUBLICATION 1

Table A.1: Content of plastics-2D, plastics-3D, and other fractions from manual sorting analysis for all grain size classes of MCW.

Grain size (mm)	Grain width (mm)	2D	3D	Other	total
20-40	30	5.31%	29.15%	65.54%	100%
40-60	50	6.91%	19.81%	73.28%	100%
60-80	70	9.62%	19.44%	70.94%	100%
80-100	90	10.26%	20.03%	69.71%	100%
100-200	150	22.56%	16.26%	61.19%	100%
200-400	300	46.00%	11.65%	42.35%	100%
total		12.99%	20.59%	66.42%	100%

Table A.2: Content of plastics-2D, plastics-3D, and other fractions from manual sorting analysis for all grain size classes of MMW.

Grain size (mm)	Grain width (mm)	2D	3D	Other	total
20-40	30	5.88%	10.34%	83.78%	100%
40-60	50	6.48%	11.23%	82.29%	100%
60-80	70	12.44%	12.44%	75.11%	100%
80-100	90	12.68%	14.74%	72.58%	100%
100-200	150	22.35%	11.87%	65.78%	100%
200-400	300	22.56%	0.57%	76.87%	100%
total		11.99%	11.46%	76.56%	100%

Table A.3: Total composition of the plastics-2D in MCW overall grain size classes (GSC).

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	1.92%	1.07%	0.27%	0.30%	1.97%	0.05%	0.01%	0.27%	0.23%	0.05%	0.21%	0.45%	1.00%	0.50%	0.23%	8.54%
40-60	3.01%	1.79%	0.52%	0.25%	1.50%	0.00%	0.00%	0.00%	0.19%	0.01%	0.09%	0.08%	1.31%	0.25%	0.08%	9.08%
60-80	5.25%	3.35%	1.02%	1.04%	1.48%	0.06%	0.01%	0.26%	0.25%	0.00%	0.10%	0.45%	0.83%	0.64%	0.20%	14.95%
80-100	4.41%	4.26%	0.48%	0.00%	1.17%	0.00%	0.00%	0.16%	0.00%	0.00%	0.00%	0.00%	0.10%	0.48%	0.20%	11.25%
100-200	13.50%	6.22%	5.39%	5.16%	1.91%	0.08%	0.00%	0.19%	0.11%	0.00%	1.20%	1.41%	0.80%	1.71%	0.31%	37.98%
200-400	11.13%	0.91%	3.16%	1.95%	0.28%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.30%	0.37%	0.11%	18.20%
total	39.22%	17.60%	10.83%	8.69%	8.31%	0.19%	0.03%	0.88%	0.78%	0.06%	1.60%	2.40%	4.34%	3.94%	1.13%	100.00%

Table A.4: Total composition of the plastics-3D fraction in MCW overall grain size classes (GSC).

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	2.63%	0.00%	2.63%	0.83%	0.02%	0.44%	1.26%	0.91%	0.65%	0.12%	0.00%	0.25%	0.77%	3.69%	0.04%	14.24%
40-60	3.89%	0.03%	6.03%	1.59%	0.22%	3.46%	2.65%	2.40%	0.87%	0.23%	0.11%	0.97%	0.65%	6.09%	0.04%	29.23%
60-80	1.64%	0.53%	3.71%	0.23%	0.11%	5.43%	0.57%	1.26%	0.26%	0.10%	0.87%	0.96%	0.09%	4.20%	0.04%	20.02%
80-100	1.20%	0.00%	1.73%	0.65%	0.17%	4.96%	0.49%	0.53%	0.00%	0.40%	0.00%	1.24%	0.63%	2.37%	0.05%	14.43%
100-200	1.58%	0.01%	4.10%	3.57%	1.40%	3.24%	0.62%	0.16%	0.41%	0.39%	0.56%	0.00%	0.00%	3.08%	0.01%	19.12%
200-400	1.46%	0.00%	0.49%	0.00%	0.00%	0.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.65%	0.00%	2.97%
total	12.40%	0.57%	18.70%	6.87%	1.92%	17.89%	5.59%	5.26%	2.19%	1.24%	1.54%	3.42%	2.14%	20.08%	0.18%	100.00%

Table A.5: Total composition of the plastics-2D fraction in MMW overall grain size classes (GSC).

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	0.26%	0.20%	1.68%	1.06%	1.79%	0.00%	0.00%	0.25%	0.22%	0.01%	0.12%	0.65%	1.60%	0.78%	0.64%	9.25%
40-60	0.57%	0.39%	2.24%	2.72%	2.14%	0.00%	0.00%	0.08%	0.39%	0.00%	0.14%	0.66%	0.39%	1.18%	0.34%	11.23%
60-80	1.02%	0.87%	6.53%	3.53%	3.27%	0.00%	0.00%	0.35%	0.04%	0.00%	0.76%	1.06%	1.18%	2.84%	0.50%	21.94%
80-100	2.15%	1.00%	4.54%	2.96%	1.22%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.93%	0.22%	1.27%	0.24%	14.52%
100-200	5.94%	2.84%	7.75%	6.95%	2.81%	0.00%	0.00%	0.00%	0.81%	0.00%	0.48%	1.09%	1.46%	5.05%	0.23%	35.39%
200-400	0.96%	1.64%	1.51%	0.69%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.24%	0.07%	0.03%	2.21%	0.08%	7.66%
total	10.89%	6.94%	24.24%	17.91%	11.46%	0.00%	0.00%	0.68%	1.46%	0.01%	1.74%	4.46%	4.88%	13.34%	2.01%	100.00%

Table A.6: Total composition of the plastics-3D fraction in MMW overall grain size classes (GSC).

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	1.75%	0.05%	3.54%	0.36%	0.00%	0.82%	4.11%	0.49%	0.17%	0.00%	0.00%	0.73%	3.29%	3.43%	0.15%	18.90%
40-60	1.72%	0.26%	4.36%	2.52%	0.00%	1.83%	2.06%	0.32%	0.07%	0.00%	0.01%	1.19%	0.61%	6.01%	0.08%	21.05%
60-80	0.91%	0.17%	7.54%	1.47%	0.00%	6.33%	0.38%	0.21%	0.00%	0.00%	0.00%	3.47%	0.44%	2.67%	0.06%	23.65%
80-100	0.17%	0.24%	4.64%	3.87%	0.00%	5.30%	0.35%	0.00%	0.00%	0.00%	0.00%	0.76%	0.00%	1.80%	0.04%	17.19%
100-200	0.00%	0.24%	9.78%	2.77%	0.00%	5.00%	0.27%	0.00%	0.00%	0.00%	0.00%	0.43%	0.07%	0.42%	0.05%	19.03%
200-400	0.00%	0.00%	0.10%	0.00%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.18%
total	4.55%	0.97%	29.96%	11.00%	0.00%	19.36%	7.16%	1.02%	0.24%	0.00%	0.01%	6.59%	4.41%	14.33%	0.40%	100.00%

Table A.7: Cumulative grain size distribution over investigated mesh sizes for all sorting fractions of plastics-2D in MCW.

d (mm)	D-LDPE_n	D-LDPE_c	D-HDPE_n	D-HDPE_c	D-PP	D-PVC	D-PUR	D-PET	D-PS	D-EPS	D-Oth_P	D-Comp	D-No_P	D-UnID	D-Res
20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
40	4.89%	6.07%	2.53%	3.40%	23.76%	26.10%	49.95%	30.85%	28.98%	78.92%	13.26%	18.95%	23.09%	12.58%	20.56%
60	12.56%	16.24%	7.32%	6.30%	41.76%	26.10%	49.95%	30.85%	53.48%	100%	19.13%	22.42%	53.23%	18.95%	27.64%
80	25.95%	35.28%	16.71%	18.21%	59.59%	59.31%	100%	60.71%	85.48%	100%	25.19%	41.30%	72.38%	35.24%	45.04%
100	37.19%	59.48%	21.12%	18.21%	73.68%	59.31%	100%	78.53%	85.48%	100%	25.19%	41.30%	74.76%	47.32%	62.45%
200	71.62%	94.84%	70.85%	77.60%	96.67%	100%	100%	100%	100%	100%	100%	100%	93.08%	90.60%	90.12%
400	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table A.8: Cumulative grain size distribution over investigated mesh sizes for all sorting fractions of plastics-3D in MCW.

d (mm)	D-LDPE	D-HDPE	D-PP	D-PVC	D-PUR	D-PET	D-PS	D-EPS	D-PC	D-PA	D-Oth_P	D-Comp	D-No_P	D-UnID	D-Res
20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
40	21.23%	0.00%	14.08%	12.07%	1.26%	2.45%	22.61%	17.30%	29.47%	9.32%	0.00%	7.16%	35.99%	18.39%	20.20%
60	52.59%	5.83%	46.31%	35.18%	12.49%	21.76%	69.92%	62.91%	69.23%	28.14%	7.34%	35.62%	66.55%	48.70%	45.58%
80	65.83%	98.47%	66.16%	38.59%	18.43%	52.10%	80.14%	86.89%	81.31%	36.21%	63.98%	63.69%	70.61%	69.61%	67.17%
100	75.53%	98.47%	75.43%	48.05%	27.29%	79.86%	88.98%	97.00%	81.31%	68.17%	63.98%	100.00%	100%	81.40%	93.62%
200	88.25%	100.00%	97.36%	100%	100%	97.96%	100%	100%	100%	100%	100%	100%	100%	96.75%	100%
400	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table A.9: Cumulative grain size distribution over investigated mesh sizes for all sorting fractions of plastics-2D in MMW.

d (mm)	D-LDPE_n	D-LDPE_c	D-HDPE_n	D-HDPE_c	D-PP	D-PVC	D-PUR	D-PET	D-PS	D-EPS	D-Oth_P	D-Comp	D-No_P	D-UnID	D-Res
20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
40	2.41%	2.82%	6.92%	5.92%	15.61%	57.18%	-	36.95%	15.19%	100%	6.81%	14.59%	32.87%	5.88%	31.54%
60	7.61%	8.42%	16.16%	21.09%	34.31%	100%	-	48.08%	42.04%	100%	15.12%	29.50%	40.77%	14.74%	48.27%
80	16.97%	21.02%	43.08%	40.81%	62.83%	100%	-	100%	44.55%	100%	59.02%	53.21%	64.95%	36.05%	72.85%
100	36.70%	35.45%	61.82%	57.33%	73.48%	100%	-	100%	44.55%	100%	59.02%	73.99%	69.46%	45.57%	84.51%
200	91.22%	76.34%	93.77%	96.16%	97.99%	100%	-	100%	100%	100%	86.47%	98.32%	99.47%	83.43%	95.83%

400	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table A.10: Cumulative grain size distribution over investigated mesh sizes for all sorting fractions of plastics-3D in MMW.

d (mm)	D-LDPE	D-HDPE	D-PP	D-PVC	D-PUR	D-PET	D-PS	D-EPS	D-PC	D-PA	D-Oth_P	D-Comp	D-No_P	D-UnID	D-Res
20	0.00%	0.00%	0.00%	0.00%	-	0.00%	0.00%	0.00%	0.00%	-	0.00%	0.00%	0.00%	0.00%	0.00%
40	38.46%	5.42%	11.81%	3.31%	-	4.25%	57.34%	48.21%	69.10%	-	21.08%	11.05%	74.70%	23.93%	38.73%
60	76.33%	32.65%	26.36%	26.24%	-	13.70%	86.13%	79.94%	100%	-	100%	29.07%	88.45%	65.87%	59.79%
80	96.27%	50.03%	51.54%	39.57%	-	46.41%	91.37%	100%	100%	-	100%	81.81%	98.52%	84.53%	73.82%
100	100%	75.14%	67.04%	74.79%	-	73.81%	96.27%	100%	100%	-	100%	93.40%	98.52%	97.06%	84.58%
200	100%	100%	99.67%	99.96%	-	99.67%	100%	100%	100%	-	100%	100%	100%	100%	97.96%
400	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table A.11: Plastic type distribution of plastics-2D in investigated grain size classes (GSC) in MCW.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	1.92%	1.07%	0.27%	0.30%	1.97%	0.05%	0.01%	0.27%	0.23%	0.05%	0.21%	0.45%	1.00%	0.50%	0.23%	8.54%
40-60	3.01%	1.79%	0.52%	0.25%	1.50%	0.00%	0.00%	0.00%	0.19%	0.01%	0.09%	0.08%	1.31%	0.25%	0.08%	9.08%
60-80	5.25%	3.35%	1.02%	1.04%	1.48%	0.06%	0.01%	0.26%	0.25%	0.00%	0.10%	0.45%	0.83%	0.64%	0.20%	14.95%
80-100	4.41%	4.26%	0.48%	0.00%	1.17%	0.00%	0.00%	0.16%	0.00%	0.00%	0.00%	0.00%	0.10%	0.48%	0.20%	11.25%
100-200	13.50%	6.22%	5.39%	5.16%	1.91%	0.08%	0.00%	0.19%	0.11%	0.00%	1.20%	1.41%	0.80%	1.71%	0.31%	37.98%
200-400	11.13%	0.91%	3.16%	1.95%	0.28%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.30%	0.37%	0.11%	18.20%
total	39.22%	17.60%	10.83%	8.69%	8.31%	0.19%	0.03%	0.88%	0.78%	0.06%	1.60%	2.40%	4.34%	3.94%	1.13%	100.00%

Table A.12: Plastic type distribution of plastics-2D in investigated gain size classes (GSC) in MCW normalised to 100%.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	22.48%	12.51%	3.22%	3.46%	23.13%	0.57%	0.16%	3.19%	2.65%	0.54%	2.49%	5.32%	11.75%	5.81%	2.73%	100%
40-60	33.10%	19.70%	5.70%	2.78%	16.47%	0.00%	0.00%	0.00%	2.10%	0.14%	1.03%	0.92%	14.41%	2.76%	0.88%	100%
60-80	35.14%	22.42%	6.80%	6.93%	9.92%	0.41%	0.09%	1.76%	1.67%	0.00%	0.65%	3.03%	5.57%	4.30%	1.32%	100%
80-100	39.19%	37.85%	4.25%	0.00%	10.41%	0.00%	0.00%	1.40%	0.00%	0.00%	0.00%	0.00%	0.92%	4.23%	1.75%	100%
100-200	35.55%	16.38%	14.18%	13.59%	5.03%	0.20%	0.00%	0.50%	0.30%	0.00%	3.15%	3.71%	2.10%	4.49%	0.83%	100%
200-400	61.15%	4.99%	17.34%	10.70%	1.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.65%	2.04%	0.61%	100%
total	39.22%	17.60%	10.83%	8.69%	8.31%	0.19%	0.03%	0.88%	0.78%	0.06%	1.60%	2.40%	4.34%	3.94%	1.13%	100%

Table A.13: Plastic type distribution of plastics-3D in investigated gain size classes (GSC) in MCW.

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	2.63%	0.00%	2.63%	0.83%	0.02%	0.44%	1.26%	0.91%	0.65%	0.12%	0.00%	0.25%	0.77%	3.69%	0.04%	14.24%
40-60	3.89%	0.03%	6.03%	1.59%	0.22%	3.46%	2.65%	2.40%	0.87%	0.23%	0.11%	0.97%	0.65%	6.09%	0.04%	29.23%
60-80	1.64%	0.53%	3.71%	0.23%	0.11%	5.43%	0.57%	1.26%	0.26%	0.10%	0.87%	0.96%	0.09%	4.20%	0.04%	20.02%
80-100	1.20%	0.00%	1.73%	0.65%	0.17%	4.96%	0.49%	0.53%	0.00%	0.40%	0.00%	1.24%	0.63%	2.37%	0.05%	14.43%
100-200	1.58%	0.01%	4.10%	3.57%	1.40%	3.24%	0.62%	0.16%	0.41%	0.39%	0.56%	0.00%	0.00%	3.08%	0.01%	19.12%
200-400	1.46%	0.00%	0.49%	0.00%	0.00%	0.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.65%	0.00%	2.97%
total	12.40%	0.57%	18.70%	6.87%	1.92%	17.89%	5.59%	5.26%	2.19%	1.24%	1.54%	3.42%	2.14%	20.08%	0.18%	100%

Table A.14: Plastic type distribution of plastics-3D in investigated gain size classes (GSC) in MCW normalised to 100%.

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	18.49%	0.00%	18.49%	5.83%	0.17%	3.08%	8.89%	6.39%	4.54%	0.81%	0.00%	1.72%	5.40%	25.94%	0.25%	100%
40-60	13.30%	0.11%	20.62%	5.44%	0.74%	11.82%	9.05%	8.20%	2.98%	0.80%	0.39%	3.33%	2.23%	20.82%	0.15%	100%
60-80	8.20%	2.65%	18.54%	1.17%	0.57%	27.12%	2.86%	6.30%	1.32%	0.50%	4.37%	4.80%	0.43%	20.98%	0.19%	100%
80-100	8.33%	0.00%	12.02%	4.51%	1.18%	34.41%	3.43%	3.68%	0.00%	2.75%	0.00%	8.62%	4.35%	16.41%	0.32%	100%
100-200	8.25%	0.05%	21.44%	18.67%	7.32%	16.93%	3.22%	0.82%	2.14%	2.06%	2.91%	0.00%	0.00%	16.12%	0.06%	100%
200-400	49.09%	0.00%	16.63%	0.00%	0.00%	12.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	21.98%	0.00%	100%
total	12.40%	0.57%	18.70%	6.87%	1.92%	17.89%	5.59%	5.26%	2.19%	1.24%	1.54%	3.42%	2.14%	20.08%	0.18%	100%

Table A.15: Plastic type distribution of plastics-2D in investigated gain size classes (GSC) in MMW.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	0.26%	0.20%	1.68%	1.06%	1.79%	0.00%	0.00%	0.25%	0.22%	0.01%	0.12%	0.65%	1.60%	0.78%	0.64%	9.25%
40-60	0.57%	0.39%	2.24%	2.72%	2.14%	0.00%	0.00%	0.08%	0.39%	0.00%	0.14%	0.66%	0.39%	1.18%	0.34%	11.23%
60-80	1.02%	0.87%	6.53%	3.53%	3.27%	0.00%	0.00%	0.35%	0.04%	0.00%	0.76%	1.06%	1.18%	2.84%	0.50%	21.94%
80-100	2.15%	1.00%	4.54%	2.96%	1.22%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.93%	0.22%	1.27%	0.24%	14.52%
100-200	5.94%	2.84%	7.75%	6.95%	2.81%	0.00%	0.00%	0.00%	0.81%	0.00%	0.48%	1.09%	1.46%	5.05%	0.23%	35.39%
200-400	0.96%	1.64%	1.51%	0.69%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.24%	0.07%	0.03%	2.21%	0.08%	7.66%
total	10.89%	6.94%	24.24%	17.91%	11.46%	0.00%	0.00%	0.68%	1.46%	0.01%	1.74%	4.46%	4.88%	13.34%	2.01%	100%

Table A.16: Plastic type distribution of plastics-2D in investigated gain size classes (GSC) in MMW normalised to 100%.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	2.84%	2.11%	18.13%	11.45%	19.32	0.03%	0.00%	2.70%	2.39%	0.06%	1.28%	7.03%	17.32%	8.48%	6.87%	100%
40-60	5.04%	3.46%	19.93%	24.18%	19.07%	0.02%	0.00%	0.67%	3.48%	0.00%	1.29%	5.92%	3.43%	10.51%	3.00%	100%
60-80	4.64%	3.99%	29.74%	16.09%	14.89%	0.00%	0.00%	1.60%	0.17%	0.00%	3.48%	4.82%	5.37%	12.95%	2.26%	100%
80-100	14.79%	6.90%	31.28%	20.38%	8.40%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	6.38%	1.51%	8.74%	1.62%	100%
100-200	16.77%	8.02%	21.89%	19.65%	7.93%	0.00%	0.00%	0.00%	2.28%	0.00%	1.35%	3.07%	4.13%	14.26%	0.64%	100%
200-400	12.49%	21.45%	19.72%	8.98%	3.01%	0.00%	0.00%	0.00%	0.00%	0.00%	3.07%	0.98%	0.34%	28.87%	1.10%	100%
total	10.89%	6.94%	24.24%	17.91%	11.46%	0.00%	0.00%	0.68%	1.46%	0.01%	1.74%	4.46%	4.88%	13.34%	2.01%	100%

Table A.17: Plastic type distribution of plastics-3D in investigated gain size classes (GSC) in MMW.

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	1.75%	0.05%	3.54%	0.36%	0.00%	0.82%	4.11%	0.49%	0.17%	0.00%	0.00%	0.73%	3.29%	3.43%	0.15%	18.90%
40-60	1.72%	0.26%	4.36%	2.52%	0.00%	1.83%	2.06%	0.32%	0.07%	0.00%	0.01%	1.19%	0.61%	6.01%	0.08%	21.05%
60-80	0.91%	0.17%	7.54%	1.47%	0.00%	6.33%	0.38%	0.21%	0.00%	0.00%	0.00%	3.47%	0.44%	2.67%	0.06%	23.65%
80-100	0.17%	0.24%	4.64%	3.87%	0.00%	5.30%	0.35%	0.00%	0.00%	0.00%	0.00%	0.76%	0.00%	1.80%	0.04%	17.19%
100-200	0.00%	0.24%	9.78%	2.77%	0.00%	5.00%	0.27%	0.00%	0.00%	0.00%	0.00%	0.43%	0.07%	0.42%	0.05%	19.03%
200-400	0.00%	0.00%	0.10%	0.00%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.18%
total	4.55%	0.97%	29.96%	11.00%	0.00%	19.36%	7.16%	1.02%	0.24%	0.00%	0.01%	6.59%	4.41%	14.33%	0.40%	100%

Table A.18: Plastic type distribution of plastics-3D in investigated gain size classes (GSC) in MMW.

GSC	**LDPE**	**HDPE**	**PP**	**PVC**	**PUR**	**PET**	**PS**	**EPS**	**PC**	**PA**	**Oth_P**	**Comp**	**No_P**	**UnID**	**Res**	**total**
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	9.26%	0.28%	18.72%	1.93%	0.00%	4.35%	21.72%	2.61%	0.88%	0.00%	0.01%	3.85%	17.43%	18.14%	0.82%	100%
40-60	8.18%	1.25%	20.70%	11.99%	0.00%	8.69%	9.79%	1.54%	0.35%	0.00%	0.04%	5.64%	2.88%	28.55%	0.40%	100%
60-80	3.84%	0.71%	31.90%	6.20%	0.00%	26.78%	1.59%	0.87%	0.00%	0.00%	0.00%	14.69%	1.88%	11.31%	0.24%	100%
80-100	0.99%	1.41%	27.02%	22.54%	0.00%	30.86%	2.04%	0.00%	0.00%	0.00%	0.00%	4.44%	0.00%	10.45%	0.25%	100%
100-200	0.00%	1.26%	51.37%	14.55%	0.00%	26.30%	1.40%	0.00%	0.00%	0.00%	0.00%	2.28%	0.34%	2.22%	0.28%	100%
200-400	0.00%	0.00%	55.98%	2.70%	0.00%	36.68%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.63%	100%
total	4.55%	0.97%	29.96%	11.00%	0.00%	19.36%	7.16%	1.02%	0.24%	0.00%	0.01%	6.59%	4.41%	14.33%	0.40%	100%

Table A.19: Grain size distribution in investigated material types for plastics-2D of MCW.

GSC	**LDPE_n**	**LDPE_c**	**HDPE_n**	**HDPE_c**	**PP**	**PVC**	**PUR**	**PET**	**PS**	**EPS**	**Oth_P**	**Comp**	**No_P**	**UnID**	**Res**	**total**
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	1.92%	1.07%	0.27%	0.30%	1.97%	0.05%	0.01%	0.27%	0.23%	0.05%	0.21%	0.45%	1.00%	0.50%	0.23%	8.54%
40-60	3.01%	1.79%	0.52%	0.25%	1.50%	0.00%	0.00%	0.00%	0.19%	0.01%	0.09%	0.08%	1.31%	0.25%	0.08%	9.08%
60-80	5.25%	3.35%	1.02%	1.04%	1.48%	0.06%	0.01%	0.26%	0.25%	0.00%	0.10%	0.45%	0.83%	0.64%	0.20%	14.95%
80-100	4.41%	4.26%	0.48%	0.00%	1.17%	0.00%	0.00%	0.16%	0.00%	0.00%	0.00%	0.00%	0.10%	0.48%	0.20%	11.25%
100-200	13.50%	6.22%	5.39%	5.16%	1.91%	0.08%	0.00%	0.19%	0.11%	0.00%	1.20%	1.41%	0.80%	1.71%	0.31%	37.98%
200-400	11.13%	0.91%	3.16%	1.95%	0.28%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.30%	0.37%	0.11%	18.20%
total	39.22%	17.60%	10.83%	8.69%	8.31%	0.19%	0.03%	0.88%	0.78%	0.06%	1.60%	2.40%	4.34%	3.94%	1.13%	100%

Table A.20: Grain size distribution in investigated material types for plastics-2D of MCW normalised to 100%.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	22.48%	12.51%	3.22%	3.46%	23.13%	0.57%	0.16%	3.19%	2.65%	0.54%	2.49%	5.32%	11.75%	5.81%	2.73%	100%
40-60	33.10%	19.70%	5.70%	2.78%	16.47%	0.00%	0.00%	0.00%	2.10%	0.14%	1.03%	0.92%	14.41%	2.76%	0.88%	100%
60-80	35.14%	22.42%	6.80%	6.93%	9.92%	0.41%	0.09%	1.76%	1.67%	0.00%	0.65%	3.03%	5.57%	4.30%	1.32%	100%
80-100	39.19%	37.85%	4.25%	0.00%	10.41%	0.00%	0.00%	1.40%	0.00%	0.00%	0.00%	0.00%	0.92%	4.23%	1.75%	100%
100-200	35.55%	16.38%	14.18%	13.59%	5.03%	0.20%	0.00%	0.50%	0.30%	0.00%	3.15%	3.71%	2.10%	4.49%	0.83%	100%
200-400	61.15%	4.99%	17.34%	10.70%	1.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1.65%	2.04%	0.61%	100%
total	39.22%	17.60%	10.83%	8.69%	8.31%	0.19%	0.03%	0.88%	0.78%	0.06%	1.60%	2.40%	4.34%	3.94%	1.13%	100%

Table A.21: Grain size distribution in investigated material types for plastics-3D of MCW.

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	2.63%	0.00%	2.63%	0.83%	0.02%	0.44%	1.26%	0.91%	0.65%	0.12%	0.00%	0.25%	0.77%	3.69%	0.04%	14.24%
40-60	3.89%	0.03%	6.03%	1.59%	0.22%	3.46%	2.65%	2.40%	0.87%	0.23%	0.11%	0.97%	0.65%	6.09%	0.04%	29.23%
60-80	1.64%	0.53%	3.71%	0.23%	0.11%	5.43%	0.57%	1.26%	0.26%	0.10%	0.87%	0.96%	0.09%	4.20%	0.04%	20.02%
80-100	1.20%	0.00%	1.73%	0.65%	0.17%	4.96%	0.49%	0.53%	0.00%	0.40%	0.00%	1.24%	0.63%	2.37%	0.05%	14.43%
100-200	1.58%	0.01%	4.10%	3.57%	1.40%	3.24%	0.62%	0.16%	0.41%	0.39%	0.56%	0.00%	0.00%	3.08%	0.01%	19.12%
200-400	1.46%	0.00%	0.49%	0.00%	0.00%	0.37%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.65%	0.00%	2.97%
total	12.40%	0.57%	18.70%	6.87%	1.92%	17.89%	5.59%	5.26%	2.19%	1.24%	1.54%	3.42%	2.14%	20.08%	0.18%	100%

Table A.22: Grain size distribution in investigated material types for plastics-3D of MCW normalised to 100%.

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	18.49%	0.00%	18.49%	5.83%	0.17%	3.08%	8.89%	6.39%	4.54%	0.81%	0.00%	1.72%	5.40%	25.94%	0.25%	100%
40-60	13.30%	0.11%	20.62%	5.44%	0.74%	11.82%	9.05%	8.20%	2.98%	0.80%	0.39%	3.33%	2.23%	20.82%	0.15%	100%
60-80	8.20%	2.65%	18.54%	1.17%	0.57%	27.12%	2.86%	6.30%	1.32%	0.50%	4.37%	4.80%	0.43%	20.98%	0.19%	100%
80-100	8.33%	0.00%	12.02%	4.51%	1.18%	34.41%	3.43%	3.68%	0.00%	2.75%	0.00%	8.62%	4.35%	16.41%	0.32%	100%
100-200	8.25%	0.05%	21.44%	18.67%	7.32%	16.93%	3.22%	0.82%	2.14%	2.06%	2.91%	0.00%	0.00%	16.12%	0.06%	100%
200-400	49.09%	0.00%	16.63%	0.00%	0.00%	12.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	21.98%	0.00%	100%
total	12.40%	0.57%	18.70%	6.87%	1.92%	17.89%	5.59%	5.26%	2.19%	1.24%	1.54%	3.42%	2.14%	20.08%	0.18%	100%

Table A.23: Grain size distribution in investigated material types for plastics-2D of MMW.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	0.26%	0.20%	1.68%	1.06%	1.79%	0.00%	0.00%	0.25%	0.22%	0.01%	0.12%	0.65%	1.60%	0.78%	0.64%	9.25%
40-60	0.57%	0.39%	2.24%	2.72%	2.14%	0.00%	0.00%	0.08%	0.39%	0.00%	0.14%	0.66%	0.39%	1.18%	0.34%	11.23%
60-80	1.02%	0.87%	6.53%	3.53%	3.27%	0.00%	0.00%	0.35%	0.04%	0.00%	0.76%	1.06%	1.18%	2.84%	0.50%	21.94%
80-100	2.15%	1.00%	4.54%	2.96%	1.22%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.93%	0.22%	1.27%	0.24%	14.52%
100-200	5.94%	2.84%	7.75%	6.95%	2.81%	0.00%	0.00%	0.00%	0.81%	0.00%	0.48%	1.09%	1.46%	5.05%	0.23%	35.39%
200-400	0.96%	1.64%	1.51%	0.69%	0.23%	0.00%	0.00%	0.00%	0.00%	0.00%	0.24%	0.07%	0.03%	2.21%	0.08%	7.66%
total	10.89%	6.94%	24.24%	17.91%	11.46%	0.00%	0.00%	0.68%	1.46%	0.01%	1.74%	4.46%	4.88%	13.34%	2.01%	100.0%

Table A.24: Grain size distribution in investigated material types for plastics-2D of MMW normalised to 100%.

GSC	LDPE_n	LDPE_c	HDPE_n	HDPE_c	PP	PVC	PUR	PET	PS	EPS	Oth_P	Comp	No_P	UnID	Res	total
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	2.84%	2.11%	18.13%	11.45%	19.32%	0.03%	0.00%	2.70%	2.39%	0.06%	1.28%	7.03%	17.32%	8.48%	6.87%	100.0%
40-60	5.04%	3.46%	19.93%	24.18%	19.07%	0.02%	0.00%	0.67%	3.48%	0.00%	1.29%	5.92%	3.43%	10.51%	3.00%	100.0%
60-80	4.64%	3.99%	29.74%	16.09%	14.89%	0.00%	0.00%	1.60%	0.17%	0.00%	3.48%	4.82%	5.37%	12.95%	2.26%	100.0%
80-100	14.79%	6.90%	31.28%	20.38%	8.40%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	6.38%	1.51%	8.74%	1.62%	100.0%
100-200	16.77%	8.02%	21.89%	19.65%	7.93%	0.00%	0.00%	0.00%	2.28%	0.00%	1.35%	3.07%	4.13%	14.26%	0.64%	100.0%
200-400	12.49%	21.45%	19.72%	8.98%	3.01%	0.00%	0.00%	0.00%	0.00%	0.00%	3.07%	0.98%	0.34%	28.87%	1.10%	100.0%
total	10.89%	6.94%	24.24%	17.91%	11.46%	0.00%	0.00%	0.68%	1.46%	0.01%	1.74%	4.46%	4.88%	13.34%	2.01%	100.0%

Table A.25: Grain size distribution in investigated material types for plastics-3D of MMW.

GSC	LDPE	HDPE	PP	PVC	PUR	PET	PS	EPS	PC	PA	Oth_P	Comp	No_P	UnID	Res	total
0-20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
20-40	1.75%	0.05%	3.54%	0.36%	0.00%	0.82%	4.11%	0.49%	0.17%	0.00%	0.00%	0.73%	3.29%	3.43%	0.15%	18.90%
40-60	1.72%	0.26%	4.36%	2.52%	0.00%	1.83%	2.06%	0.32%	0.07%	0.00%	0.01%	1.19%	0.61%	6.01%	0.08%	21.05%
60-80	0.91%	0.17%	7.54%	1.47%	0.00%	6.33%	0.38%	0.21%	0.00%	0.00%	0.00%	3.47%	0.44%	2.67%	0.06%	23.65%
80-100	0.17%	0.24%	4.64%	3.87%	0.00%	5.30%	0.35%	0.00%	0.00%	0.00%	0.00%	0.76%	0.00%	1.80%	0.04%	17.19%
100-200	0.00%	0.24%	9.78%	2.77%	0.00%	5.00%	0.27%	0.00%	0.00%	0.00%	0.00%	0.43%	0.07%	0.42%	0.05%	19.03%
200-400	0.00%	0.00%	0.10%	0.00%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.18%
total	4.55%	0.97%	29.96%	11.00%	0.00%	19.36%	7.16%	1.02%	0.24%	0.00%	0.01%	6.59%	4.41%	14.33%	0.40%	100.0%

Table A.26: Grain size distribution in investigated material types for plastics-3D of MMW normalised to 100%.

GSC	**LDPE**	**HDPE**	**PP**	**PVC**	**PUR**	**PET**	**PS**	**EPS**	**PC**	**PA**	**Oth_P**	**Comp**	**No_P**	**UnID**	**Res**	**total**
0-20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20-40	9.26%	0.28%	18.72%	1.93%	0.00%	4.35%	21.72%	2.61%	0.88%	0.00%	0.01%	3.85%	17.43%	18.14%	0.82%	100%
40-60	8.18%	1.25%	20.70%	11.99%	0.00%	8.69%	9.79%	1.54%	0.35%	0.00%	0.04%	5.64%	2.88%	28.55%	0.40%	100%
60-80	3.84%	0.71%	31.90%	6.20%	0.00%	26.78%	1.59%	0.87%	0.00%	0.00%	0.00%	14.69%	1.88%	11.31%	0.24%	100%
80-100	0.99%	1.41%	27.02%	22.54%	0.00%	30.86%	2.04%	0.00%	0.00%	0.00%	0.00%	4.44%	0.00%	10.45%	0.25%	100%
100-200	0.00%	1.26%	51.37%	14.55%	0.00%	26.30%	1.40%	0.00%	0.00%	0.00%	0.00%	2.28%	0.34%	2.22%	0.28%	100%
200-400	0.00%	0.00%	55.98%	2.70%	0.00%	36.68%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	4.63%	100%
total	4.55%	0.97%	29.96%	11.00%	0.00%	19.36%	7.16%	1.02%	0.24%	0.00%	0.01%	6.59%	4.41%	14.33%	0.40%	100%

APPENDIX B – PUBLICATION 2

Table B.1: Cumulative particle size distribution of the screen overflow over investigated mesh sizes for all generated fine fractions for both investigated setups and test runs for MCW.

Mesh size	B_MCW_T1_FFB	B_MCW_T2_FFB	S+B_MCW_T1_FFS	S+B_MCW_T1_FFB	S+B_MCW_T2_FFS	S+B_MCW_T2_FFB
0	100%	100%	100%	100%	100%	100%
10	36%	38%	48%	55%	36%	48%
20	26%	28%	38%	48%	30%	43%
40	14%	15%	26%	34%	20%	32%
60	5%	4%	13%	17%	10%	16%
80	0%	0%	0%	0%	0%	0%

Table B.2: Cumulative particle size distribution of the screen overflow over investigated mesh sizes for all generated fine fractions for both investigated setups and test runs for MMW.

Mesh size	B_MMW_T1_FFB	B_MMW_T2_FFB	S+B_MMW_T1_FFS	S+B_MMW_T1_FFB	S+B_MMW_T2_FFS	S+B_MMW_T2_FFB
0	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
10	30.29%	31.58%	38.35%	48.46%	38.51%	44.57%
20	20.86%	22.10%	30.10%	39.03%	30.52%	35.97%
40	9.76%	9.65%	19.62%	24.44%	20.80%	23.04%
60	2.54%	2.36%	11.10%	10.72%	11.47%	11.71%
80	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table B.3: Total composition of the 2D-fractions from the ballistic separator for B_MCW_V1.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	12.52	17.33	17.89	7.65	10.39	14.19	13.33	3.63
3D-plastics	42.45	40.13	13.98	34.41	19.39	14.98	27.56	11.80
Fines	13.57	2.74	5.62	7.87	9.81	4.06	7.28	3.65
Inert	1.03	0.60	0.63	0.10	0.59	0.05	0.50	0.33
Comp	3.17	2.33	3.12	6.61	4.52	3.63	3.90	1.38
P&C	1.85	3.48	6.18	4.46	5.57	5.83	4.56	1.52
Metals	6.36	3.67	4.45	4.84	4.60	9.05	5.50	1.78
Textile	6.98	15.06	30.04	16.77	20.93	21.05	18.47	6.99
Wood	12.08	14.65	18.09	17.29	24.20	27.16	18.91	5.23

Table B.4: Total composition of the 2D-fractions from the ballistic separator for B_MCW_V2.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	11.66	14.82	8.59	20.93	8.33	9.00	12.22	4.50
3D-plastics	16.36	15.43	17.47	22.22	13.37	10.42	15.88	3.64
Fines	7.24	7.56	21.37	11.41	10.12	8.96	11.11	4.81
Inert	1.26	1.06	0.84	0.78	1.72	3.18	1.47	0.82
Comp	10.64	7.31	4.86	5.61	5.46	5.65	6.59	1.96
P&C	9.90	18.44	23.55	23.11	12.29	13.97	16.88	5.23
Metals	6.65	3.08	3.06	2.78	1.47	1.21	3.04	1.78
Textile	22.09	17.96	16.73	9.08	44.64	44.84	25.89	13.87
Wood	14.20	14.33	3.53	4.08	2.60	2.78	6.92	5.22

Table B.5: Total composition of the 2D-fractions from the ballistic separator for S+B_MCW_V1.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	20.83	14.02	20.57	18.10	12.03	11.10	16.11	3.92
3D-plastics	20.45	26.78	28.02	21.47	12.51	13.78	20.50	5.86
Fines	0.51	1.22	2.89	5.03	1.74	1.68	2.18	1.46
Inert	0.00	0.51	0.00	0.35	0.10	0.44	0.23	0.21
Comp	11.39	21.32	8.02	9.73	13.59	19.85	13.99	4.98
P&C	9.64	9.24	10.22	14.73	17.49	20.22	13.59	4.21
Metals	14.38	7.05	4.67	5.89	14.46	9.99	9.41	3.89
Textile	20.08	17.20	20.52	19.86	19.88	17.76	19.22	1.26
Wood	2.71	2.64	5.09	4.85	8.19	5.17	4.78	1.86

Table B.6: Total composition of the 2D-fractions from the ballistic separator for S+B_MCW_V2.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	23.77	17.68	20.69	22.69	14.33	12.42	18.60	4.19
3D-plastics	21.56	19.06	10.84	11.84	14.54	17.98	15.97	3.88
Fines	2.03	3.56	4.04	2.10	0.92	0.75	2.23	1.23
Inert	0.36	0.00	0.00	0.17	0.00	1.63	0.36	0.58
Comp	7.40	17.74	10.14	8.15	10.21	13.51	11.19	3.51
P&C	12.92	10.65	13.42	12.20	19.20	18.77	14.53	3.27
Metals	2.58	6.22	14.93	9.11	6.57	3.27	7.11	4.11
Textile	17.29	16.29	19.25	29.72	26.47	24.32	22.22	4.95
Wood	12.10	8.80	6.69	4.02	7.76	7.35	7.79	2.42

Table B.7: Total composition of the 2D-fractions from the ballistic separator for B_MMW_V1.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	13.18	14.08	12.23	11.45	17.09	17.72	14.29	2.35
3D-plastics	11.85	13.25	10.70	10.15	8.76	14.74	11.57	1.98
Fines	11.06	12.88	11.11	14.44	11.53	9.34	11.73	1.59
Inert	0.65	0.57	0.58	1.13	0.86	2.28	1.01	0.60
Comp	17.52	20.63	19.63	20.53	19.96	20.29	19.76	1.06
P&C	6.42	11.64	8.59	9.00	8.33	11.87	9.31	1.91
Metals	8.71	6.37	6.04	6.68	5.45	6.92	6.69	1.02
Textile	25.41	15.29	25.31	21.69	23.52	13.37	20.77	4.75
Wood	5.19	5.30	5.81	4.93	4.49	3.47	4.87	0.74

Table B.8: Total composition of the 2D-fractions from the ballistic separator for B_MMW_V2.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	15.83	18.58	16.73	2.74	13.72	15.02	15.97	1.64
3D-plastics	11.38	11.09	12.81	2.77	9.94	11.35	11.32	0.91
Fines	13.47	8.71	16.33	87.09	28.90	6.09	14.70	7.95
Inert	1.43	0.95	0.79	0.11	0.40	1.57	1.03	0.43
Comp	18.15	12.08	15.14	1.16	16.47	12.63	14.89	2.29
P&C	9.72	12.74	11.46	1.01	8.39	20.75	12.61	4.33
Metals	7.01	7.41	5.91	0.51	6.76	7.09	6.84	0.51
Textile	19.56	21.82	18.31	4.50	12.18	18.65	18.10	3.20
Wood	3.45	6.62	2.52	0.10	3.24	6.86	4.54	1.83

Table B.9: Total composition of the 2D-fractions from the ballistic separator for S+B_MMW_V1.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	20.86	19.35	19.61	18.44	14.84	18.27	18.56	1.87
3D-plastics	8.39	7.02	7.75	6.52	21.05	6.11	9.47	5.23
Fines	7.85	4.80	4.57	6.08	7.07	10.90	6.88	2.14
Inert	0.09	0.33	0.25	0.21	0.72	0.42	0.34	0.20
Comp	22.70	33.92	26.82	35.70	21.12	30.98	28.54	5.45
P&C	14.34	10.29	20.12	17.87	11.99	9.63	14.04	3.86
Metals	6.02	4.44	5.06	3.23	4.48	3.85	4.51	0.88
Textile	18.55	19.42	14.77	11.11	17.44	18.64	16.66	2.89
Wood	1.21	0.43	1.05	0.83	1.30	1.18	1.00	0.30

Table B.10: Total composition of the 2D-fractions from the ballistic separator for S+B_MMW_V2.

Fraction name	P1	P2	P3	P4	P5	P6	MW	STAB
2D-plastics	1.23	20.38	22.66	21.26	20.35	10.66	21.16	0.94
3D-plastics	0.94	10.23	11.31	17.07	10.36	10.33	12.24	2.82
Fines	87.93	8.98	4.00	1.79	8.97	44.22	5.93	3.14
Inert	0.00	1.42	0.00	0.24	1.41	0.01	0.77	0.65
Comp	2.28	19.03	19.57	15.50	19.00	6.88	18.28	1.62
P&C	0.15	17.56	19.71	16.45	17.54	6.43	17.81	1.18
Metals	1.12	4.28	4.87	7.94	4.28	3.25	5.34	1.52
Textile	6.27	16.52	16.20	19.15	16.50	17.57	17.09	1.19
Wood	0.09	1.60	1.68	0.60	1.60	0.65	1.37	0.44

Table B.11: Effects of pre-screening on purity and yield of the 3D-plastics out of the 3D-fraction from the ballistic separator of the investigated wastes for MCW

	Purity B_MCW_V1	**Yield B_MCW_V1**	**Purity B_MCW_V2**	**Yield B_MCW_V2**	**Purity S+B_MCW_V1**	**Yield S+B_MCW_V1**	**Purity S+B_MCW_V2**	**Yield S+B_MCW_V2**
Min	7.67	7.36	1.95	1.31	0.85	1.56	9.31	2.02
Q25	87.55	86.30	90.37	87.64	92.16	93.00	85.59	89.80
Median	3.96	2.46	3.48	1.13	0.89	1.51	5.87	3.07
Q75	1.81	2.29	2.84	0.95	1.37	1.50	2.81	3.02
Max	1.22	6.85	0.03	0.79	2.29	1.53	0.13	1.85

Table B.12: Effects of pre-screening on purity and yield of the 3D-plastics out of the 3D-fraction from the ballistic separator of the investigated wastes for MMW

	Purity B_MMW_V1	**Yield B_MMW_V1**	**Purity B_MMW_V2**	**Yield B_MMW_V2**	**Purity S+B_MMW_V1**	**Yield S+B_MMW_V1**	**Purity S+B_MMW_V2**	**Yield S+B_MMW_V2**
Min	1.64	0.76	0.04	2.19	2.69	2.50	0.02	0.11
Q25	88.39	91.75	92.63	92.29	91.10	93.00	93.49	95.78
Median	3.29	0.38	0.76	1.10	1.38	2.50	0.93	0.24
Q75	2.83	0.50	0.99	0.76	0.65	2.18	1.15	0.64
Max	0.27	1.10	0.75	1.19	0.51	1.54	0.69	1.30