

Article

Technical Evaluation and Recycling Potential of Polyolefin and Paper Separation in Mixed Waste Material Recovery Facilities

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Abstract

Mixed municipal solid waste (MSW) of cities and tourist-heavy areas typically contains elevated amounts of recyclable materials. In Austria, numerous material recovery facilities exist for processing this waste; however, they primarily focus on separating metals, neglecting the recovery potential of other recyclables. To evaluate such potential for polyolefins and paper-based materials, two pilot-scale trials were conducted in a model region in Tyrol, Western Austria, accompanied by comprehensive sampling, waste characterisation, and material flow analysis. Pre-concentrates with up to 70% purity were obtained using two stages of near-infrared sorting, although challenges arose due to the presence of textiles and composite materials. This study found that separating polyolefins from mixed MSW could increase recycling rates in the region by up to 16% (absolute). Paper recovery also showed a modest increase. Polyolefin recovery slightly lowered, whereas paper recovery moderately raised the heating value. Recycling such materials is technically feasible, and forthcoming legislative changes are expected to create a market for these materials. Although fundamental questions remain regarding the optimal balance between recycling and refuse-derived fuel, as well as concerns about microbiological or chemical hazards, it can enhance resource efficiency, develop circularity, and aid comparison in regions with similar demographic and tourism characteristics.

Keywords: circular economy; municipal solid waste; plastic waste; recycling; material recovery facility; automated waste sorting



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1. Introduction

In industrial countries, the separate collection of municipal solid waste (MSW) was first introduced in the 1980s and underwent extensive expansion in the 1990s [1]. This marks an important milestone towards more sustainable waste management and effective utilisation of resources [2]. Nevertheless, despite decades of efforts and further expansion and improvements in household waste separation, a substantial amount of recyclable material is still erroneously disposed of in mixed MSW [3,4]. This is also the case in Austria, where mixed MSW contains approximately 10% plastics, 7% paper, 5% glass and 3% metals [5]. Current waste treatment practices regarding mixed MSW in industrial countries primarily focus on incineration, coupled with the recovery of metals prior to or post-incineration [6–8]. However, the remaining potential to recover additional recyclable materials continues to be largely untapped.

Within many industrialised countries, such as Germany or Austria, urban centres with high population densities present a high potential, especially [9]. City environments pose unique challenges for separate waste collection due to limited space availability on varying layers, ranging from individual flats to residential complexes and public spaces [10,11]. This scarcity is also intrinsically linked to conflicts of use: In addition to aspects such as odour concerns and varying socioeconomic factors, these space limitations lead to suboptimal capture rates, resulting in a higher proportion of valuable materials being disposed of in mixed MSW [9,12–14]. In Austria, approximately 54% of the population resides in urban areas [15]. Akin to other countries such as Switzerland, Slovenia, parts of Italy and France, Austria is represented by many rural but tourist regions, like the Alpine areas. These can also be affected by lower capture rates due to experiencing extensive tourism during both winter and summer seasons [16–18]. As Europe transitions towards a more circular economy, harnessing these neglected potentials within mixed MSW is imperative.

Hence, material recovery facilities (MRFs) play a crucial role in diverting recyclables contained in mixed MSW from waste incineration to recycling. Given the present network of mixed waste MRFs, Austria is well-positioned to implement further recovery from mixed MSW. Existing facilities usually aim to recover metals and produce refuse-derived fuel (RDF) or other waste fractions for incineration in an industrial combustion process. These facilities can be upgraded to expand the portfolio of recyclable materials to paper and plastics; however, comprehensive information on the quantities and qualities of the outputs is essential for making informed decisions about such undertakings. This is crucial for municipalities and plant operators as they plan future investments in infrastructure.

In this context, Blasenbauer et al. [19] assessed existing outputs of mixed waste MRFs and, based on literature information, stated that a 5 to 8% absolute increase in recycling rates for plastic packaging waste could be achieved in Austria with the recovery from mixed MSW. However, no other studies have hitherto analysed the sensor-based sorting efficiency of mixed waste MRFs in Austria, making it challenging to assess plant-specific yields and accurately investigate the true potential. Different authors have investigated mixed Waste MRFs and mechanical–biological plants in Cyprus, Germany, Greece, the Netherlands, Spain and the U.S. [9,20–23]. Thereby, plant efficiencies reported in those studies exhibit severe variability. For instance, Edo-Alcón et al. [21] describe that the recovery rates for metals, plastics, glass, and paper from mixed MSW typically remain below 30%. In contrast, (Thanos) Bourtsalas and Themelis [23] demonstrate that metal recovery rates in Greek MBT plants frequently exceed 80%, while certain plastics and paper achieve recovery rates of approximately 50% or higher. Such efficiency evaluations in the literature also extend to life cycle and economic assessments [22,24–27]. Furthermore, other researchers have investigated the composition and quality of RDF generated by such MRFs [23,28–31]. Nevertheless, assessments have predominantly focused on entire plants, and published studies remain scarce regarding specific sensor-based technologies and their sorting performance for mixed MSW. There remains a lack of data on smaller-scale investments and upgrades. Hence, limited information prevents meaningful comparisons of different options, *ceteris paribus*, and understanding their impacts on the MSW management system.

Moreover, literature from other countries is insufficient for a precise assessment, as Austria's waste composition differs due to inherent variations in collection systems. Additional factors, including regional waste management policies, tourism, and consumer disposal behaviours, further influence these differences, underscoring the need for a region-specific approach. This highlights a research lacuna in understanding local performance and recovery potentials, which are crucial for effectively modelling and enhancing waste management strategies. The workload associated with primary data acquisition is extensive, which typically results in it being infrequently conducted in conjunction with

modelling efforts. Thus, this paper addresses the existing knowledge gaps by answering the following research questions: What quantities and qualities of recyclable material—specifically polyolefins (PO) as well as paper, paperboard and cardboard (PPC)—can be recovered from mixed MSW by upgrading an existing MRF? How does the recovery of these materials impact the overall waste management system performance in terms of recycling and heating values regarding RDF and waste incineration?

This study focuses on PO and PPC, as glass already exhibits high recycling rates and is more effectively recovered post-incineration; similarly, polyethylene terephthalate (PET) is predominantly used in beverage packaging under a deposit return scheme [6]. In contrast, PPC shows declining recycling rates [32], a trend likely to continue in the future, and PO demonstrate both low recycling rates and high product versatility, warranting this targeted assessment. Hereby, the emphasis aligns with Austria's ongoing efforts to establish PO-specific post-sorting plants and chemical recycling technologies [33].

To answer these questions, two processing trials to update an existing MRF have been conducted, and six scenarios and their effects on the whole waste management system within the region were modelled. By employing a technical assessment of an MRF upgrade in combination with a material flow analysis (MFA), the research contributes to enhancing MSW management systems, supporting a transition towards a more circular and sustainable economy.

2. Materials and Methods

In order to determine process yields and purities of the recovery of PO and PPC from mixed MSW, this study is based on two processing trials using material sourced from a mixed waste MRF, which will be described in the first chapter of this section in greater detail. The input streams for both trials, equalling the MRF output streams, were systematically sampled and characterised. At the pilot scale, the material was processed using near-infrared (NIR) sorting technology, which is widely recognised as the state-of-the-art for the sensor-based classification and separation of non-metallic waste [34]. All resulting outputs following the trials were sampled and characterised through manual analysis, Fourier transform infrared spectroscopy (FTIR), and sink float separation to evaluate their composition. The results from these analyses enabled the calculation of key technical indicators, i.e., mass recovery rate, purity and yield, providing a quantitative evaluation of material properties and recovery efficiency. Furthermore, an overall assessment of the recovery potential of the investigated processing approaches is conducted via an MFA, as described in the second chapter. A detailed overview of the methodology is presented in Figure 1.

2.1. Investigated MRF for Mixed Waste

The investigated MRF is located in Tyrol in the western region of Austria, as displayed in Figure 2; its structure, outputs and process steps have already been described by Blasenbauer et al. [19], and the overall MRF is shown in Figure 3a. The parameters can be summarised as follows: the MRF serves a population of ~400,000 inhabitants (Districts of Innsbruck, Innsbruck-Land, Schwaz; 33% urban and 67% intermediate/rural) with an input of 80,000 t/yr of mixed MSW (65%), bulky and commercial waste (35%). The processes include shredding, sieving (>250 mm, <40 mm), metal separation (magnetic/non-magnetic) and ballistic separation resulting in the outputs of ferrous metals and non-ferrous metals; low calorific value fraction (LCVF, <40 mm) with a lower heating value (LHV) of $14.3 \text{ MJ}\cdot\text{kg}^{-1}$ based on dry matter, medium calorific value fraction (MCVF, 40–250 mm, 2D, $LHV_{dry} = 18.0 \text{ MJ}\cdot\text{kg}^{-1}$) and high calorific value fraction (HCVF, 40–250 mm, 3D, $LHV_{dry} = 21.0 \text{ MJ}\cdot\text{kg}^{-1}$).

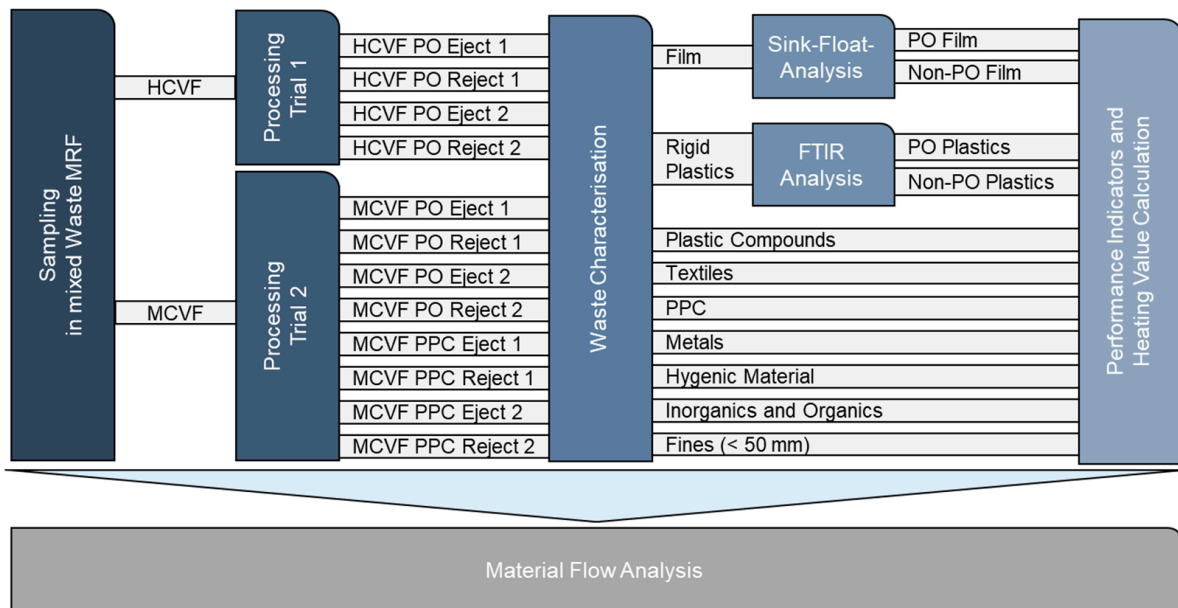


Figure 1. Methodological framework starting with sampling, followed by processing trials for polyolefin (PO) and paper, paperboard and cardboard (PPC) recovery, waste characterisation including sink float and Fourier transform infrared spectroscopy (FTIR), and the calculation of critical parameters of the high (HCVF) and medium calorific value fraction (MCVF) outputs of a mixed waste material recovery facility (MRF). Subsequently, all data are integrated to construct a material flow analysis.

Within the three districts, separate collection entails lightweight packaging waste, including plastic and metal packaging, PPC, and organic waste, with a door-to-door collection system, such as mixed MSW. Bulky waste must be taken to the collection point. Regarding climate aspects, the medium average temperatures in Innsbruck 2024 range around 12.5 °C, with the highest means in August (22.7 °C) and lowest in December (1.2 °C); Innsbruck has 166 h of yearly sun [35]. Yearly precipitation lies at 938 mm, with the driest month being November (10 mm) and June being the month with the most precipitation (168 mm) [35].

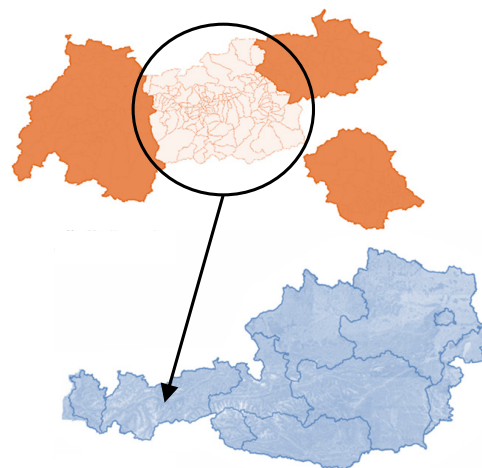


Figure 2. Map of the case study area: Districts of Innsbruck, Innsbruck-Land and Schwaz in Tyrol, Western Austria (adapted from [36,37]).

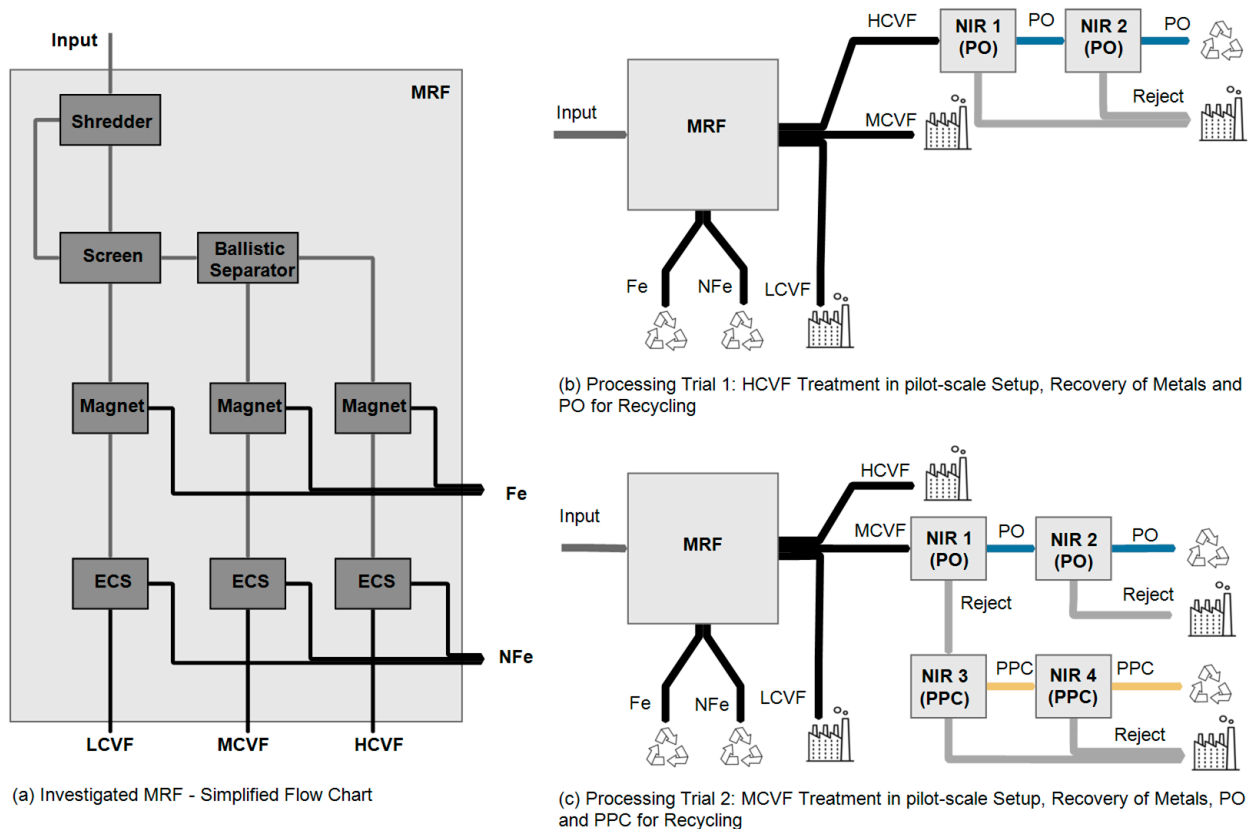


Figure 3. (a) Flow chart of the investigated material recovery facility (MRF), outputs include a high (HCVF), medium (MCVF) and low calorific value fraction (LCVF), as well as magnetic metals (Fe) and non-magnetic metals (NFe) recovered via an eddy current separator (ECS). (b,c) depict the investigated near-infrared (NIR) sorting processing trials for polyolefin (PO) and paper, paperboard and cardboard (PPC) recovery.

2.2. Pilot-Scale Processing Trials

2.2.1. Operational Parameters and General Design

The trials were performed at the so-called Digital Waste Research Lab; the setup is described in detail by Kandlbauer et al. [38]. It is designed to treat waste within a 30–300 mm particle size range. Input material was manually fed onto the inclined conveyor, which delivers the waste to a vibrating feeder for singulation, followed by a high-speed acceleration belt (working width: 1 m), operated at $3.5 \text{ m}\cdot\text{s}^{-1}$. On the acceleration belt, the NIR sensors performed material characterisation; sorting was carried out using a pneumatic nozzle comb consisting of 80 nozzles. The system's output belts were used to collect multiple samples of approximately 50 l at regular intervals throughout the trials. The method is further described in Section 2.2.2.

For the trials, a HELIOS G2-320 NIR camera (EVK DI Kerschhaggl GmbH, Graz, Austria) was employed, which records NIR spectra at a resolution of 9 nm and a rate of up to 446 Hz within a wavelength range of 900–1700 nm across 320 spatial pixels. An infrared halogen lamp served as the illumination source. The acquired spectral data have been processed, and a classification model was developed using the SQALAR software 3.4.2017.1 (EVK DI Kerschhaggl GmbH, Graz, Austria). A schematic of the facility is provided in the Supplementary Materials, Figure S1.

Trial 1: High Calorific Value Fraction

Two processing trials were performed on the MCVF and HCVF streams of the MRF to conduct a technical assessment for the recovery of recyclable materials. Both were carried out in early autumn/late summer (September). In the initial trial, see Figure 3b, ~1000 kg of unbaled HCVF were retrieved from the MRF and processed in a pilot-scale NIR setup. The HCVF stream underwent a two-stage sorting process with a rougher-cleaner configuration, focusing on the positive sorting of PO. The eject from the first NIR stage was reprocessed through the module to achieve the two-stage sorting. Thereby, the first stage is focused on maximum mass recovery of the target fraction (rougher) and the second stage on increasing purity (cleaner). The focus on PO is further justified by its prevalence as a major component of plastics within these waste streams [19]. Continuous sampling of the reject flow from the first NIR stage, as well as both the eject and reject flows from the second NIR stage, was conducted in the falling waste stream with a tub covering the whole belt width in order to avoid over- or underrepresentation of specific belt positions (see Figure S6 in the Supplementary Materials). Sampling took place every 10 s to ensure at least 30 increments per sample as defined by Gerlach and Nocerino [39].

Trial 2: Medium Calorific Value Fraction

For the second processing trial, as displayed in Figure 3c, ~520 kg of unbaled MCVF were extracted from the MRF and processed using the same pilot-scale NIR setup. The material input was subjected to a two-step rougher-cleaner configuration, initially focused on PO. The rejects from the first NIR stage were further sorted for PPC in an additional rougher-cleaner setup. Again, continuous sampling and manual sorting were conducted.

2.2.2. Waste Stream Characterisation: Sampling and Sorting

The minimum sample mass for each output was calculated according to the method of Skutan and Brunner [40], which is based on Gy's theory of sampling for heterogeneous materials [41]. By this means, the sample mass M in kg is determined via Equation (1), whereby the estimated concentration of the targeted fraction in the stream to be sampled c [kg kg^{-1}], the desired standard deviation of the sample $\sigma_{desired}$ [kg kg^{-1}], the maximum particle mass of the targeted fraction m_{max} [kg] as well as the 10th percentile of the particle mass distribution $m_{10\%}$ [kg] were determined in advance by empirical values. The concentration of the target fraction within a particle is referred to as $c_{expected}$ [kg kg^{-1}]. In this case, $c_{expected}$ is set to 1 kg kg^{-1} because the investigation was carried out at object level (particles) and not at molecular level. By calculating the sampling masses a priori, the sampling error can be kept below a certain limit [42].

$$M = \frac{c_{expected}^2}{c \cdot \sigma_{desired}^2} \cdot \frac{m_{max}}{1 + 3 \cdot \lg\left(\frac{\sqrt[3]{m_{max}}}{\sqrt[3]{m_{10\%}}}\right)} \quad (1)$$

All sampled outputs from the trials were sorted according to the material characterisation framework outlined by Blasenbauer et al. [19]; a step-by-step sorting matrix is displayed in Figure S2 in the Supplementary Materials. During manual characterisation, the wet sample was spread on a 50 mm screen and in the first step, the sample was divided into main categories by product type and material: *films*, *rigid plastics*, *plastic composites*, *paper and paper-based cardboard (PPC)*, *textiles*, *metals*, *hygiene products*, *inorganics and organics*, and *finer (<50 mm)*.

A second step further characterised film and rigid plastics, as well as PPC (processing trial 2 only). Film and rigid plastics were sorted into *packaging (food/non-food)* and *non-packaging* film. Using visual recycling codes and FTIR spectroscopy, rigid plastics

were divided into *PET*, *high-density polyethylene (HDPE)*, *polyvinylchloride (PVC)*, *low-density polyethylene (LDPE)*, *polypropylene (PP)*, *polystyrene (PS)*, *other*, and *multilayer*. Again, rigid plastics were split into *packaging (food/non-food)* and *non-packaging* fractions. FTIR analysis was attempted for black products, though some were ultimately assigned to “unknown” if no clear spectrum was obtained. The PPC fractions were sorted into *paper*, *white paper board packaging*, *corrugated cardboard packaging*, *corrugated cardboard non-packaging*, *beverage cartons*, *composite packaging*, *thermal and other paper*, and *impurities*.

In the third step, the PO content in the overall film fractions from step one was determined via sink-float analysis. Therefore, samples were first shredded to 15 mm particle size (7M Precyzja RF137 two-shaft shredder) and divided into ~100 g subsamples; sample mass reduction was conducted with a riffle splitter. The float-sink test was conducted over a 48 h period in 18 l of water at 25 °C, with a drop of dish soap added to reduce the surface tension. Stirring was performed six times equally over the 48 h. The resulting floating and sinking fractions were dried at 60 °C until mass-stable and weighed [43].

2.2.3. Performance Indicators

Indicators have been determined to compare and assess the processing trials. For each of the processing trials, as displayed in Figure 3b,c, the generated streams and their compositions were evaluated in terms of mass recovery, purity and yield [44]. Thereby, the indicator of mass recovery (R) expresses the proportion of an output (i) in relation to the total input mass:

$$R_i = \frac{m_{i,out}}{m_{in}} \quad (2)$$

Since a sorted waste stream consists of different target fractions (j) together with extraneous material and contaminants, its purity (P) can be calculated via their ratio to each other. At the same time, P corresponds to the concentration ($c_{i,j}$) within the analysed stream:

$$P_{i,j} = \frac{m_{i,j}}{m_i} = c_{i,j} \quad (3)$$

In analogy to the total mass recovery, the yield (Y) for a specific material (j) can further be calculated using the input and output masses, as well as the concentration of the material:

$$Y_{i,j} = \frac{m_{i,out} \cdot c_{i,j,out}}{m_{in} \cdot c_{j,in}} \quad (4)$$

A distinction can be made between total system and process parameters for both the mass recovery and yield. Regarding a system, the denominator is represented by the total input; for processes, it is the respective process input.

The standard deviation of the concentration (purity) $\sigma_{P_{i,j}}$ is calculated via the relative standard deviation (*RSD*), which results from ensuring that the sampling error, as seen in Equation (1), is kept below a specific limit [42]. The standard deviations of all R_i and $Y_{i,j}$ were calculated using Gaussian error propagation. Thereby compensations of errors amongst each other are accounted for. Here, Equations (5)–(7) display the calculation of the standard deviation for each indicator.

$$\sigma_{P_{i,j}} = RSD \cdot c_{i,j} \quad (5)$$

$$\sigma_{R_{i,j}} = \sqrt{\left(\frac{\partial R_i}{\partial m_{i,out}}\right)^2 \cdot \sigma_{m_{i,out}}^2 + \left(\frac{\partial R_i}{\partial m_{in}}\right)^2 \cdot \sigma_{m_{in}}^2} \quad (6)$$

$$\sigma_{Y_{i,j}} = \sqrt{\left(\frac{\partial Y_{i,j}}{\partial m_{i,out}}\right)^2 \cdot \sigma_{m_{i,out}}^2 + \left(\frac{\partial Y_{i,j}}{\partial c_{i,out}}\right)^2 \cdot \sigma_{c_{i,out}}^2 + \left(\frac{\partial Y_{i,j}}{\partial m_{in}}\right)^2 \cdot \sigma_{m_{in}}^2 + \left(\frac{\partial Y_{i,j}}{\partial c_{j,in}}\right)^2 \cdot \sigma_{c_{j,in}}^2} \quad (7)$$

2.3. Technical Potential Assessment for Recovery of PO and PPC

To evaluate the implications of upgrading the MRF on the broader waste management system within the region, an MFA was conducted for both processing trials and the entire service area for the base year 2021. The method was chosen due to its effectiveness in mapping material flows, making it a valuable tool for informed decision-making [45] and enabling the calculation of performance indicators, as detailed in the previous chapter. Thereby, the approach of MFAs is based on the law of mass conservation and is employed at the level of goods (waste flows, e.g., mixed MSW and separately collected packaging waste) and subgoods (e.g., film and rigid plastic packaging). In this study, the software STAN (subSTance flow ANalysis) 2.6.801 was utilised to model and calculate material flows and processes [46]. The regularisation approach of the employed IAL-IMPL2013 algorithm allowed for error propagation and data reconciliation [47,48]. The underlying model is depicted in Figure 4; sub-processes are coloured grey and detailed in Figures S3–S5 in the Supplementary Materials. It includes mixed MSW, bulky waste, commercial waste, lightweight packaging waste, and PPC waste; MRFs for mixed and lightweight packaging waste; and a simulated recycling process for plastics, paper, and metals. Input data were received from the plant operators of the MRF or collected from a status report on plastic waste by the Austrian Federal Environment Agency [49] or from the municipalities and waste collectors of the regions. For detailed information on input data, see Supplementary Materials Tables S1 and S2.

Table 1. Scenario description for material flow analysis. Scenarios entail both polyolefin (PO) and paper, paperboard and cardboard (PPC) recovery by means of near-infrared (NIR) sorting from the high (HCVF) and medium calorific value fraction (MCVF) of a material recovery facility (MRF).

No.	Name	Description	HCVF Upgrade	MCVF Upgrade	No. of NIR Sorters
Status quo	Baseline	No Upgrades, only metal separation	-	-	-
Scenario I	PO Recovery I	Parameters determined by processing trial 1, see Figure 3b	PO	-	2
Scenario II	PO Recovery II	Parameters determined by processing trial 2, see Figure 3c	-	PO	2
Scenario III	PO + PPC Recovery	Parameters determined by processing trial 2, see Figure 3c	-	PO + PPC	4
Scenario IV	Enhanced PO Recovery	Parameters determined by processing trials 1 and 2, see Figure 3b,c	PO	PO	4
Scenario V	Intensive Sorting for Maximum Recovery	Parameters determined by processing trials 1 and 2, see Figure 3b,c	PO	PO + PPC	6

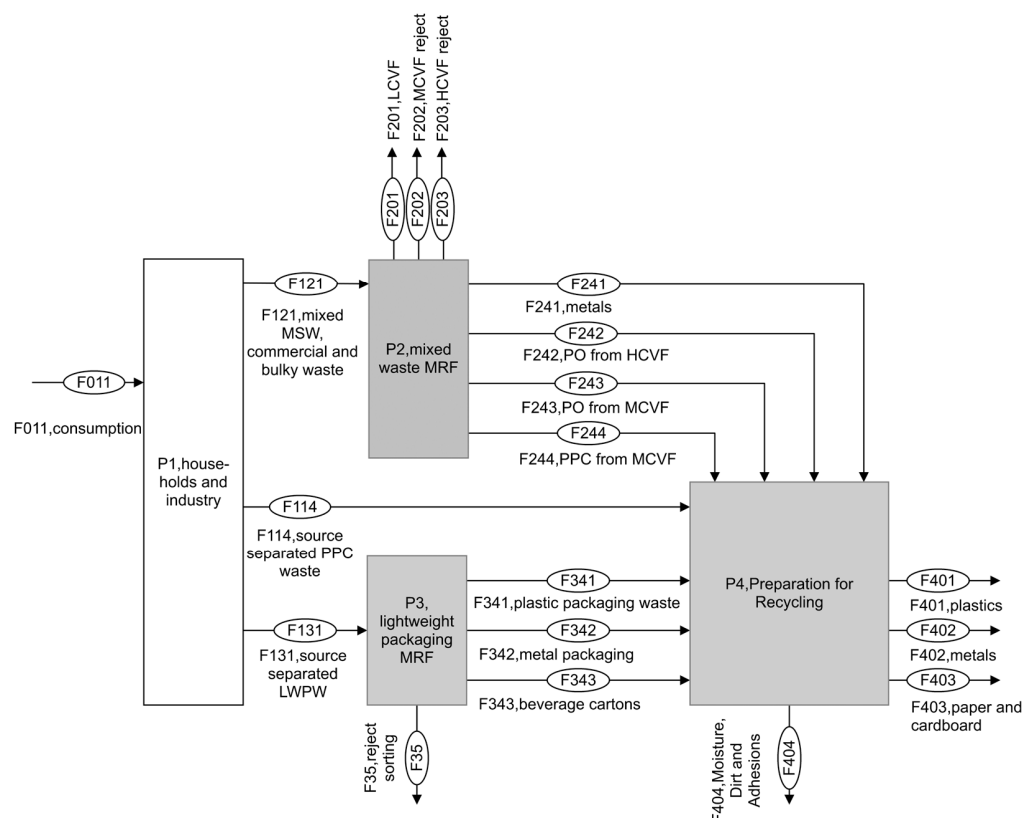


Figure 4. Model for material flow analysis, including waste collection, sorting in material recovery facilities (MRFs) and preparation for recycling in accordance with the EU calculation rules. Shaded processes entail sub-processes displayed in the Supplementary Materials Figures S3–S5, including the scenarios described in Table 1 regarding polyolefin (PO) and paper, paperboard and cardboard (PPC) recovery from the high (HCVF) and medium calorific value fraction (MCVF) from the mixed waste MRF.

2.3.1. Upgrade Scenarios

By exploring different scenarios, the MFA assessed how much additional recyclable material can be recovered from mixed waste streams, thereby contributing to circular economy goals and determining the implications for incineration. Table 1 outlines the specific parameters for the respective scenarios, detailing the level and type of sorting applied to the mixed waste. Each scenario incorporates baseline metal separation and recycling; recovery is analysed based on the additional mass of recyclable materials diverted from incineration. The status quo (Baseline) serves as a reference point.

2.3.2. Lower Heating Values

As the streams typically fed to an incinerator are depleted of high-calorific parts by the further recovery of PO and PPC, the resulting changes in heating values warrant detailed examination. This is particularly relevant for all reject streams, as they continue to be utilised for incineration. In this study, a calculation approach based on the elemental composition of these streams was employed to assess the changes systematically. The method is based on *Dulong's formula*, which established that the sum of the mass fractions of carbon, hydrogen, oxygen, sulphur, nitrogen, water, and ash in a fuel equals unity. Dulong originally derived an equation for estimating the *LHV*, which has since undergone continuous refinement. For this analysis, the formulation by Kost [50] was utilised, as it is specifically tailored towards waste and RDFs:

$$LHV = 33.146C - 10.384O + 103.469H - 2.441W \quad (8)$$

Equation (8) calculates the LHV in $MJ \cdot kg^{-1}$; C, O, H and W represent the proportion of carbon, oxygen, hydrogen, and water in $kg \cdot kg^{-1}$, respectively. Uncertainties were calculated using Gaussian error propagation.

The samples' elemental compositions were determined based on the previously conducted waste characterisation and combined with Kost's [50] analyses. Kost investigated the elemental composition of different waste sub-fractions, such as rigid plastic packaging or hygiene products. While the direct calorimetric determination of the LHV would have provided valuable empirical data, it was not performed due to the extensive sample pre-processing and preparation required, which falls beyond the scope of the study. Additionally, prior research has demonstrated a strong linear correlation between the experimentally measured and the calculated LHV [50–52], supporting the validity of the applied calculation approach.

3. Results and Discussion

3.1. Pilot-Scale Processing Trials

For both processing trials, the mass flows and their compositions were determined. The following two chapters will outline and discuss the results regarding PO and PPC recovery. Table 2 shows every streams' respective system mass recovery rates in both trials and the purities and system yields. The connected standard deviations originating from sampling and weighing errors were evaluated with Equations (5)–(7). Moreover, in Figure 5, the mass flows of the product streams are depicted, and in Figure 6, the compositions of those streams are shown. The processing trial outputs and photos of the product streams are displayed in the Supplementary Materials Figures S6 and S7, as well as finer resolution data in Tables S4 and S5.

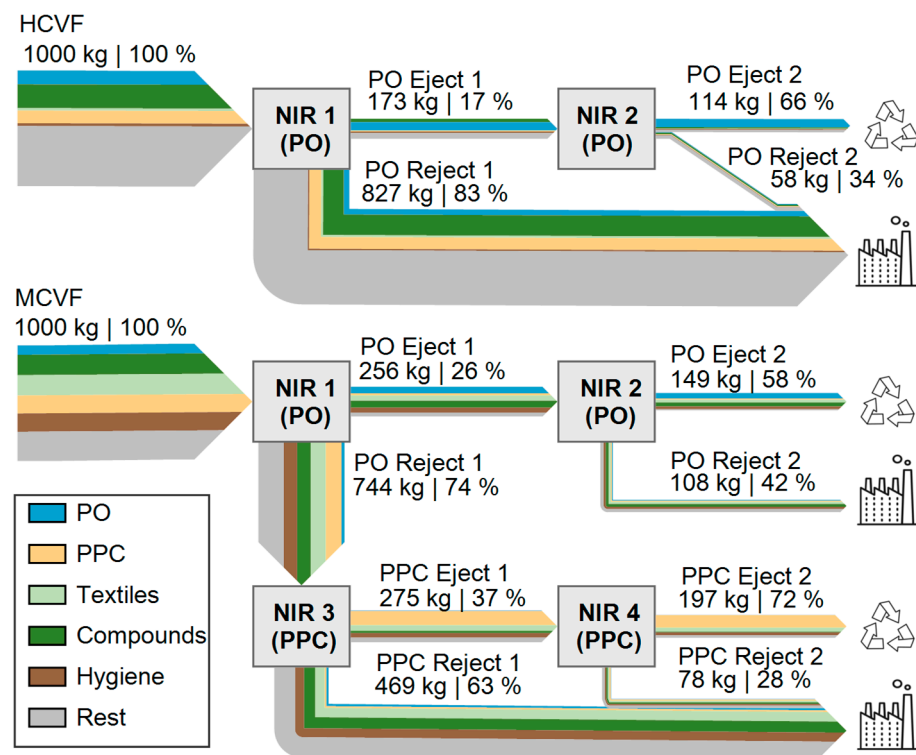


Figure 5. Mass flows of the processing trials nominated to 1 t input material (HCVF or MCVF) for PO, PPC, textiles, plastic compounds and hygiene products and process mass recovery rates for each process. Inorganic material, bio waste, other plastics (non-PO), glass, metal and fines are aggregated within the rest fraction.

Table 2. Total system mass recovery (R_i), purity/concentration ($P_{i,j}$) of mono-polyolefins (PO), PO including compounds and textiles (PO + comp + tex) as well as paper, paperboard and cardboard (PPC) and their respective system yield ($Y_{i,j}$) regarding each flow i of the processing trials 1 and 2 of the high (HCVF) and medium calorific value fraction (MCVF). Values are shown as mean values \pm standard deviation based on wet matter and rounded to two significant digits.

Trial	Material	Flow i	System Mass Recovery in wt. %		Purity in wt. %			System Yield in wt. %		
			R_i	$P_{i,PO}$	$P_{i,PO+comp+tex}$	$P_{i,PPC}$	$Y_{i,PO}$	$Y_{i,PO+comp+tex}$	$Y_{i,PPC}$	
1	HCVF	Input	100 \pm 1.1	12 \pm 1.2	15 \pm 1.5	12 \pm 1.2	100 \pm 14	100 \pm 14	100 \pm 14	
1	HCVF	PO Reject 1	83 \pm 1.3	5.8 \pm 0.58	5.8 \pm 0.58	14 \pm 1.4	41 \pm 5.9	33 \pm 4.8	94 \pm 13	
1	HCVF	PO Eject 2	17 \pm 1.1	41 \pm 4.1	57 \pm 5.7	4.8 \pm 0.48	59 \pm 8.6	67 \pm 9.7	6.9 \pm 1.5	
1	HCVF	PO Reject 1	5.8 \pm 1.1	11 \pm 1.1	26 \pm 2.6	10 \pm 1.0	5.3 \pm 1.3	10 \pm 1.8	5.0 \pm 1.0	
1	HCVF	PO Eject 2	11 \pm 1.1	63 \pm 6.3	73 \pm 7.3	1.0 \pm 0.10	54 \pm 1.3	57 \pm 8.2	2.0 \pm 0.41	
2	MCVF	Input	100 \pm 1.2	7.8 \pm 0.78	16 \pm 1.6	16 \pm 1.6	100 \pm 14	100 \pm 14	100 \pm 14	
2	MCVF	PO Reject 1	74 \pm 1.4	3.5 \pm 0.35	3.5 \pm 0.35	18 \pm 1.8	33 \pm 4.9	16 \pm 2.5	88 \pm 13	
2	MCVF	PO Eject 1	26 \pm 1.2	20 \pm 2.0	54 \pm 5.4	7.4 \pm 0.74	67 \pm 9.7	84 \pm 12	12 \pm 2.2	
2	MCVF	PO Reject 2	11 \pm 1.2	7.3 \pm 1.5	7.3 \pm 1.5	21 \pm 4.2	10 \pm 2.6	4.8 \pm 0.69	6.3 \pm 1.1	
2	MCVF	PO Eject 2	15 \pm 1.2	31 \pm 3.1	53 \pm 5.3	6.3 \pm 0.63	57 \pm 2.6	80 \pm 11.6	6.0 \pm 1.1	
2	MCVF	PPC Reject 1	46 \pm 1.2	5.5 \pm 1.1	5.5 \pm 1.1	11 \pm 2.2	33 \pm 7.4	15 \pm 2.5	32 \pm 4.6	
2	MCVF	PPC Eject 1	28 \pm 1.3	2.1 \pm 0.42	2.1 \pm 0.42	44 \pm 8.9	0.51 \pm 7.4	0.24 \pm <0.10	55 \pm 7.9	
2	MCVF	PPC Reject 2	9.1 \pm 1.3	4.1 \pm 0.83	4.1 \pm 0.83	16 \pm 3.1	0.32 \pm 4.7	0.15 \pm <0.10	6.3 \pm 0.40	
2	MCVF	PPC Eject 2	19 \pm 1.2	0.81 \pm 0.16	0.81 \pm 0.16	55 \pm 11	0.19 \pm 2.7	<0.10 \pm <0.10	49 \pm 7.0	

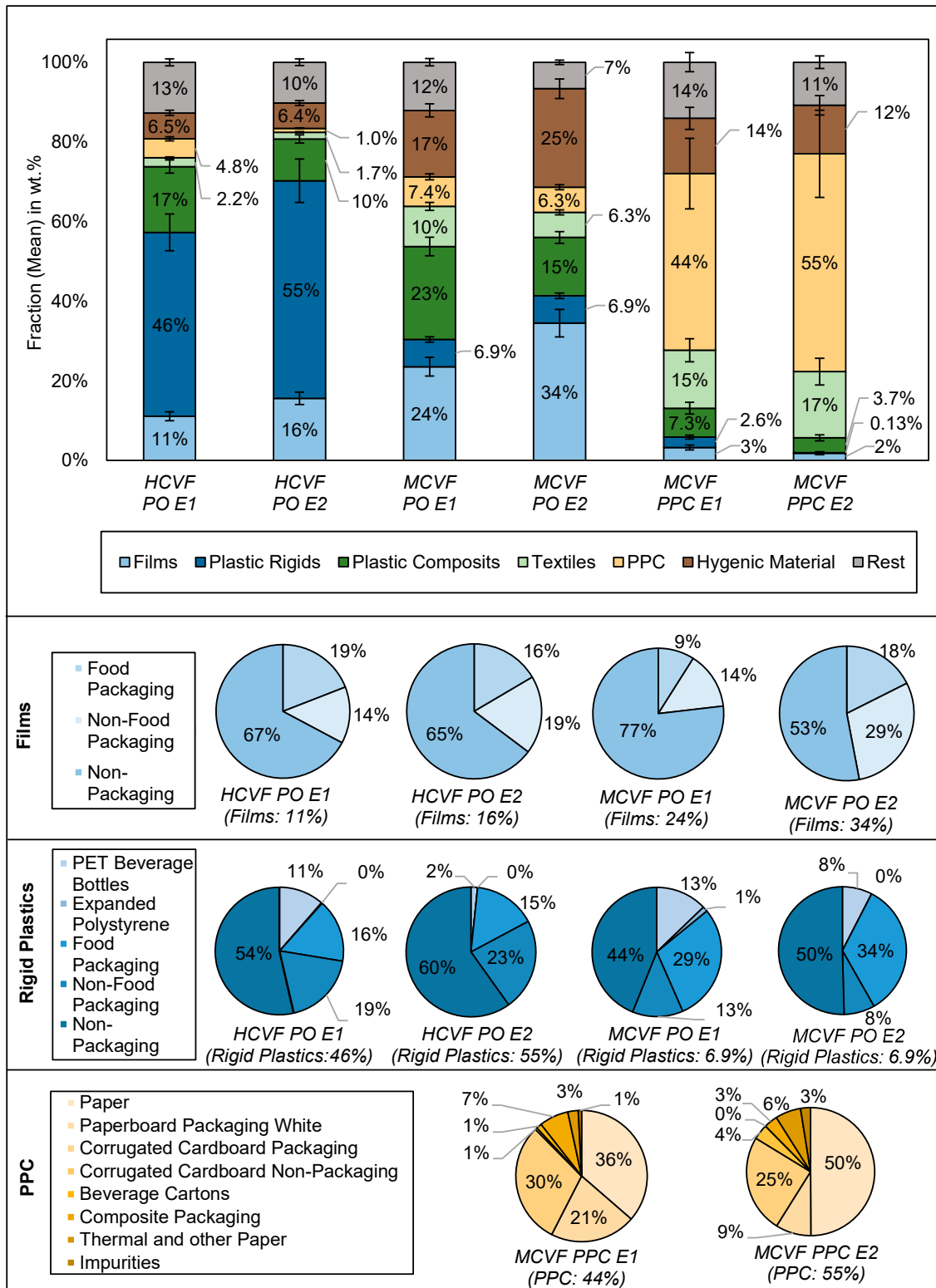


Figure 6. Compositions of the product flows (ejects—E) from the processing trials of the high (HC VF) and medium calorific value fraction (MC VF) recovering polyolefins (PO), as well as paper, paperboard and cardboard (PPC) based on manual sorting combined with density separation and Fourier transform infrared (FTIR) spectroscopy. Total composition is shown in the bar chart above, and details of films, rigid plastics and PPC are in the pie charts below. Values are shown as mean values \pm standard deviation based on wet matter and rounded to two significant digits. The relative standard deviation is $<10\%$, except for MC VF PPC E1 and E2 ($<20\%$). All data can be found in the Supplementary Materials Table S4 (HC VF) and Table S5 (MC VF), as well as a more detailed depiction in Figure S8.

3.1.1. Trial 1 and 2: PO Recovery

In both processing trials, the input compositions of the HCVF and the MCVF were comparable to data reported by Blasenbauer et al. [19], who sampled and analysed both the HCVF and the MCVF. For trial 1, approximately 17% of the total input was recovered as PO concentrate in the first NIR sorting step, with a purity of ~40% on the mono-plastics level ($P_{i,PO}$) and ~60% technical purity ($P_{i,PO+comp+tex}$) as seen from the NIR sorter's perspective, including compounds and textiles. As intended, considerable proportions of mono plastics—objects constituted of only one resin type, e.g., PP—are present in the eject streams. The respective spectral data are displayed in Figure 7.

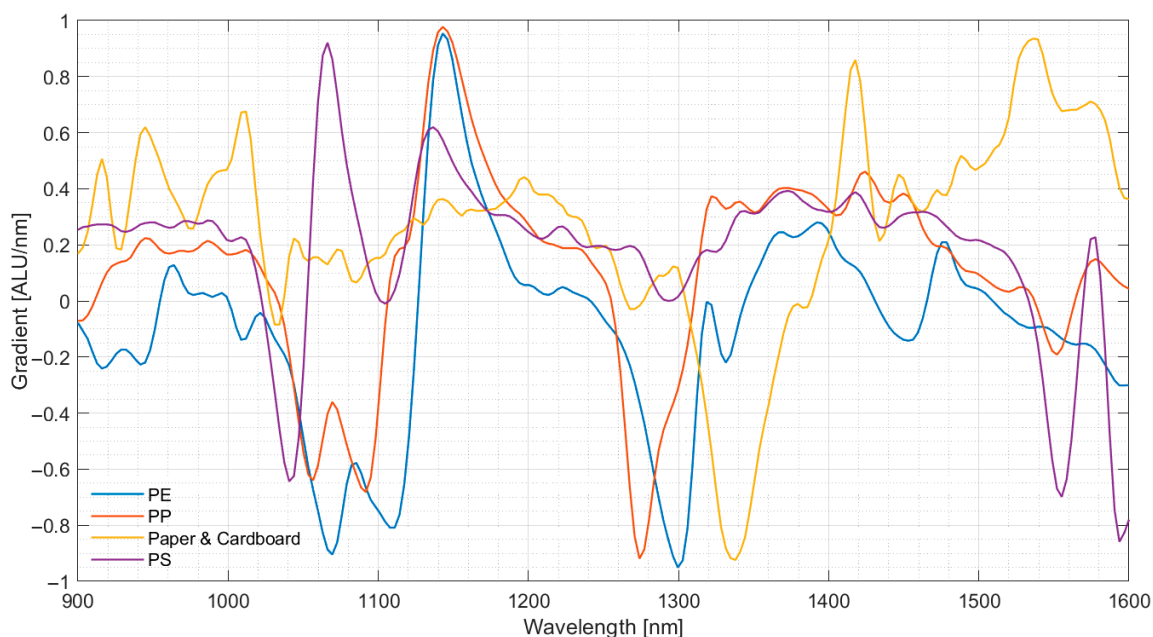


Figure 7. Near-infrared spectra of polyethylene (PE), polypropylene (PP) and polystyrene (PS)—resins considered PO—as well as paper and cardboard.

After the second sorting step for the HCVF, the PO concentrate amounted to around 11% of the total input mass, achieving a purity of ~60% on the mono-plastics level and ~70% technical purity. The resulting yields (Y) range between 50% and 70%. Compounds, as they are particularly present in this input material, pose special challenges. The treatment of mixed MSW and bulky waste results, for example, in the entry of urethane foams coated with other textiles or various plastics with metal screw connections. Generally, lower yields can be attributed to the presence of compounds and composite plastics that create a trade-off between purity and overall yield. In addition, fines are considered extraneous material, but it must be acknowledged that they are partially composed of PO particles. Consequently, the purity on an object basis may be higher than reported values. Regarding the composition of the product streams, all PO streams exhibit a high proportion of non-packaging for both film and rigid plastics, as seen in Figure 6.

Regarding the MCVF in processing trial 2, approximately 26% of the total mass was recovered as PO concentrate in the first step, and 15% by the second NIR sorter. By employing a rougher-cleaner setup, the purity of the mono-plastic level was improved from ~20% to above 30%. In terms of technical purity, both values remained approximately at 55%; no further purity increase could be observed. Total system yields are equal to around 60% and 50%. The MCVF input material exhibits a higher film concentration, which is concentrated in eject 1. In the second sorting step, the higher film content leads to overlapping particles and different trajectories; other factors, such as multilayer materials,

large surface area, as well as low thickness and weight, characterise films' inherent difficulty in the NIR sorting process [34]. Comparably, typical rigid PO yields range around 14% to 73%, and PO fractions with high film contents range between 20% and 60% [20].

Generally, considerable differences between mono-plastic and technical purity are due to the high proportion of compounds and textiles, as seen in Figures 5 and 6, as well as Figure S7a–e in the Supplementary Materials. Within MRFs for lightweight packaging waste, it was observed that polyester textiles can be detected and sorted into PET streams by NIR systems, thereby contributing to contamination in the outputs, with their level's acceptability depending on downstream processors' requirements for the final application [53]. Regarding the processing trials conducted in this study, these phenomena are also evident for PO-based textiles, as indicated by the elevated textile content. Such textiles are commonly utilised in functional apparel, footwear, furniture, upholstery, and carpeting [54,55]—items typically discarded via mixed MSW or bulky waste. Moreover, these textiles also act as contaminants in mechanical PO recycling processes and may not be desired in the product. As a result of the amendment to the EU waste framework directive, the separate collection of used textiles became mandatory in 2025 [56], probably reducing the textile content within the investigated waste stream. However, the EU does not specify the condition or coverage of the textiles to be separately collected. In Austria, the collection is conducted primarily through reusable clothing channels, while damaged textiles continue to be disposed of as residual waste [57]. Additionally, the separate collection does not extend to other fibre applications beyond apparel.

Contamination issues regarding mechanical recycling could be solved by a complementary application of thermochemical recycling, as it exhibits more tolerance towards mixed plastics [58]. In Austria, an evident focus on pyrolysis is prevalent: The OMV ReOil[®] plant has been operational since 2024 with an input capacity of 16,000 t·yr⁻¹ [19,59]. Thereby, a mixture of plastic melt and a high-boiling refinery by-product, acting as a solvent, is heated below 500 °C in a tubular reactor, where the plastic is broken down into short-chain hydrocarbons that are separated via distillation, while the heavier solvent and unconverted polymers are recirculated, producing liquid hydrocarbons for refinery processing alongside small amounts of gas and coke [33,60].

Pyrolysis processes impose stringent requirements on feedstock purity and face particular challenges with PVC contamination [61]. PVC in pyrolysis produces highly corrosive hydrogen chloride gas, which compels strict requirements on equipment materials; furthermore, hydrogen chloride needs to be removed from the final refinery product [61]. Halogens severely limit the ability of wastes to be used as petrochemical feedstock, with typical standards limiting chlorine content to below 10 ppm [61,62]. In this study, the PVC content, which was determined by FTIR analysis, is more critical for streams with a high proportion of rigid materials (specifically HCVF), as the PVC amount in the product stream (HCVF PO Eject 2) equals approximately 1.2%, whereas it remains below 0.01% for the MCVF PO Eject 2, indicating a need for further processing to be suitable for chemical recycling.

While chemical recycling consistently outperforms incineration and RDF usage with respect to life cycle impacts concerning climate change mitigation, resource conservation, and energy efficiency [63,64], it exhibits substantially higher burdens in other impact categories, notably human toxicity and marine eutrophication [64]. Furthermore, the life cycle impacts associated with the mechanical recycling of plastics are generally lower overall [63]. Moreover, chemically recycled plastics cannot yet be added to the EU recycling rate; currently, a first framework for PET bottles is being discussed by the European Commission [65].

3.1.2. Trial 2: PPC Recovery

For the recovery of PPC from the MCVF in the first step, a purity of ~44% was achieved, which was increased to ~55% in the second step. The main impurities are textiles and hygienic material, although a vast majority of the fraction is considered PPC, as sanitary paper, in purely material terms. Both PPC fractions exhibited a mean water content of 20%. While PPC from mixed MSW after collection was reported to have a comparably lower water content of around 17% [32], the processing of PPC tends to increase water contents due to the exposure to waste fluids during treatment [66].

The system yield for PPC after two processing steps ranges around 50%, which aligns with the lower yields in MRFs described in other studies. For instance, (Thanos) Bourtsalas and Themelis [23] documented system yields from multiple European mechanical-biological treatment (MBT) plants with an average of 63% for PPC, a minimum of 58% and a maximum of 70%. Other plants' yields for PPC include 13% at Ecoparc 4 (Spain), although with 98% purity, 45% at Larnaca (Cyprus), and a maximum of 39% for all plants in Castilla y León (Spain), where the average yield across eight facilities was 12% [20,26]. Here, variations in yields may also be attributed to differences in water content. Moreover, compared to other publications, hygienic paper was not considered a target fraction of PPC in this study, consequently leading to a substantial reduction in overall PPC yield.

Contrasting the results of the MCVF sorting to PPC recovery from lightweight packaging shows that the processing trial achieved considerably higher mass recovery rates: around 28% recovery of the PPC fraction in the first sorting step and 19% in the second step, compared to 4.8% to 5.7% as reported by Spies et al. [67]. However, the impurity level in this study was also higher, at a total of 32%, with textiles comprising 18% (see Figure 6). Similarly to the PO recovery streams, the high prevalence of textiles in mixed MSW, which are subsequently concentrated into the two-dimensional MCVF of the investigated MRF, leads to this increased level. Moreover, cotton, viscose, and PPC all share a cellulose-based composition, complicating sorting due to their overlapping spectral characteristics. Cotton is primarily composed of cellulose type 1, whereas viscose and PPC are made from cellulose type 2, and all three materials exhibit similarities in NIR spectra, as can be seen in the Supplementary Materials Figure S9. In some cases, subtle differences can be observed between the spectra of cardboard and cotton, but the distinction between viscose and cardboard is even less apparent. This effect has also been observed in other studies [68].

On a different note, a substantial share of high-quality fibre (e.g., graphic paper) could be observed within the PPC fraction, as seen in Figure S7g–l in the Supplementary Materials. After each sorting step, over 50% of the PPC fraction comprised paper and white paperboard. Nevertheless, lower-quality fractions, such as sanitary paper, are still prevalent to a certain extent. The characterisation analysis showed a similar sanitary paper content to other studies, with 12% to 14% compared to 15% and 19% in Spies et al. [67]. Similarly, the fine content was analogous despite the waste originating from mixed MSW. Generally, it has to be acknowledged that, in this case, the received PPC exhibits worse quality than that of separate collections, which is typical for commingled collected paper fractions [69]. True material quality can only be accurately assessed during recycling: An increase in pulper rejects is inevitable as the recovered fractions exhibit greater contents in plastics and other impurities [67,69,70]. This issue will probably intensify with the growing use of paper composites [71].

Additionally, a strong correlation has been observed between material quality and storage duration, whereby prolonged storage leads to fibre disintegration due to the high moisture content in recovered PPC. This emphasises the necessity for rapidly processing PPC materials from mixed waste origins. Moisture content was considered by promptly processing the materials to minimise evaporation and ensure consistent conditions to limit

moisture-related interference in the NIR spectra and improve the reliability of sorting performance. The HCVF exhibited a moisture content of 5.4%, while the MCVF showed 14.7%. These values fall on the lower end of the typical range reported by Blasenbauer et al. [19], which is expected given the level of material manipulation. Water contents of each fraction can be found in the Supplementary Materials Table S3.

3.2. Technical Potential Assessment for Recovery of PO and PPC

3.2.1. Implications for PO and PPC Recycling

This study demonstrates the potential for material recovery from mixed MSW beyond theoretical assumptions by the integration of empirical process data derived from experimental trials. Connected effects towards material recycling are explicated within the present subsection, with results concerning waste incineration and RDF in the following subchapter. The MFA findings show that upgrading the HCVF with two NIR sorters can increase, in absolute terms, the recycling of PO in the region by 5.7% (scenario I), while upgrading the MCVF result in a 10% increase (scenarios II and III). Implementing NIR sorting in both outputs leads to a 16% rise (scenario IV and V), corresponding to 530 t·yr⁻¹, 960 t·yr⁻¹ and 1500 t·yr⁻¹ of PO fed into recycling, respectively. The recycled mass flows of all scenarios are displayed in Figure 8, and detailed results can be found in the Supplementary Materials Figures S10–S45. Whilst the potential, processability and feasibility of plastics recycling from mixed wastes have been demonstrated repeatedly [72–75], reluctance towards investments prevails.

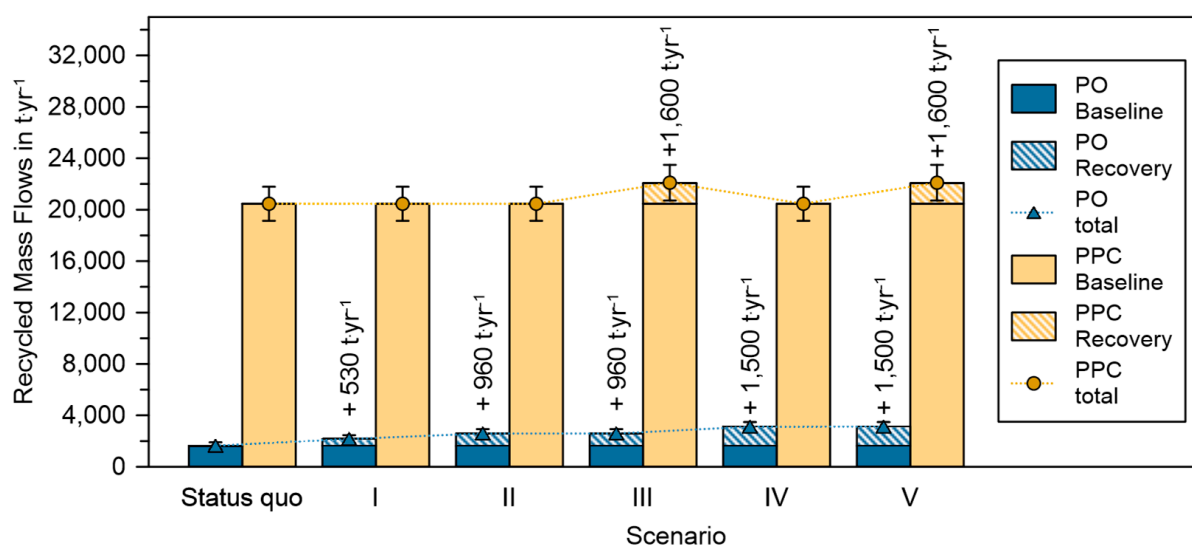


Figure 8. Recycled mass (mean \pm standard deviation, two significant digits) of polyolefins (PO, triangles) and paper, paperboard and cardboard (PPC, circles) in the modelled area, baseline and scenarios including recovery from the high (HCVF) and medium calorific value fraction (MCVF). Contributions to the recycling rate from separate collection are displayed as coloured bars; dashed bars on top show the contribution from mixed waste. Separate collection does not include quantities of commercial origin.

In the Netherlands, MRFs have established the ability to recover recyclable plastics of comparable quality, leading to legislative acceptance of MSW-recovered plastics in national recycling targets; a similar approach could be crucial for Austria to meet its recycling objectives [19,76]. Generally, mechanically recycled PO from mixed MSW origin shows no fundamental differences in mechanical properties [77], with only minor variations in purity and odour to recycled plastics derived from separately collected waste [78]. However, recycled plastic quality remains application-dependent [79], and plastics from

mixed MSW tend to perform worse than those from separate collections in terms of odour and contamination [72,80].

The processing trials have confirmed that plastic recovery is technically achievable through relatively minor system upgrades. However, the implementation of such recovery processes is often impeded by the lack of a viable market for the resulting secondary material streams [53] as they have an economic disadvantage to (imported) virgin plastics [81,82]. Nonetheless, the new EU packaging and packaging waste regulation [83], which introduced mandatory minimum recycled content by 2030, is anticipated to stimulate demand for lower-grade recycled plastics, as high-quality secondary material will be prioritised for use in the packaging industry. Legacy additives present a critical aspect in recycled plastics, and the EU established equal thresholds for virgin and recycled plastics; only specific low-risk use cases might deviate [77,84,85]. In this context, standardised hierarchical classification approaches for recycled plastics have been discussed to boost market acceptance and demand as well as safe application [77]. Nevertheless, research regarding the introduction and fate of legacy additives or substances of concern through mixed waste origin is lacking; further investigations should focus on such contaminants with concerns to consumer health and safety.

In order for recycled plastics from mixed waste streams to be effectively utilised, additional incentives for the use of recycled plastics must be established. Such incentives could, for example, take the form of economic benefits, whereby the incorporation of recycled material could result in reduced licensing fees for packaging under extended producer responsibility (EPR) schemes [86]. Furthermore, taxing packaging plastics without recycled content within the EPR might be another policy option [86]. However, the prerequisite for producing high-quality recycled plastics for usage in, e.g., plastic packaging remains the implementation of design-for-recycling principles, which ensure that materials can be effectively recovered and reprocessed [61].

The recovery of PPC from mixed waste streams cannot contribute to a substantial absolute rise in recycling within the region due to prevalent uncertainties (see Figure 8). PPC recovery yields vary widely in the literature [23,25,26,67], partly due to inconsistencies in the definitions for target materials, such as the inclusion of sanitary paper and conflicting reference values for dry and wet matter. This issue is further complicated by differing stakeholder interests: while dry mass measurements allow for better comparability, facility operators prioritise wet mass balances because they align with their day-to-day business and commercial interests. Typically, output streams are sold in quantities of wet matter within a framework of quality parameters. Additionally, in the model region, paper and cardboard are already well-separated, and the potential for additional PPC recovery is relatively low, though this may differ in areas with less efficient infrastructure for separate collection.

Microbial contamination remains another critical obstacle in PPC recycling, particularly for paper sourced from mixed waste streams. Research on microbial activity in paper made from, e.g., mixed MSW is still ongoing, and naturally, high microbial loads in PPC waste can restrict its usability; however, existing hygienisation technologies, such as hot dispersion under high pressures, could help mitigate this issue [87].

Moreover, higher recycling rates contribute to the degradation of paper quality and lead to the accumulation of contaminants in PPC. When recycling rates exceed 50%, concerns are raised about pollutant retention and accumulation in recycled materials [88,89]. PPC from mixed MSW may lead to the inadvertent input of contaminants, e.g., mineral oil, which tends to occur at higher levels in PPC obtained from such waste streams [90,91]. Sustainable waste paper management relies on maintaining clean material cycles and the disposal of contaminants; this means that pollutants must be disposed of and directed into

designated sinks to prevent their accumulation in recycled materials [92], which could compromise both product quality and health safety. Generally, the mixed MSW collection system is designed to facilitate the disposal of materials that cannot or should not be recycled due to contamination, material degradation, or other limiting factors. Extracting PPC from mixed MSW for recycling exhibits risks regarding the introduction of unsuitable or contaminated fractions into the recycling stream. Their type, quantity and whereabouts, as well as related concerns regarding consumer protection, should be the subject of further analysis and investigation.

In this regard, for both PPC and PO recovery, emerging sorting technologies show considerable promise in enhancing product purity by enabling the prior detection and removal of contaminants. Recent advances include artificial intelligence-assisted object detection combined with NIR sorting [93], as well as deep learning and neural networks, which can improve safety and broaden the range of applications for sorted materials [94]. Future developments should particularly address the removal of contaminated plastics, such as waste electrical and electronic equipment containing brominated flame retardants [77]. For PPC, effective detection and elimination of sanitary paper is crucial, as it can introduce pathogens into recycling processes.

Textiles, being one of the most observed contaminants in the study, may be more effectively removed in the investigated MRF by replacing the ballistic separator with a wind sifter, which could generate a PO and PPC-rich light fraction with reduced textile content, as textiles typically accumulate in the heavy fraction [19]. Moreover, for PO, wet mechanical processing combined with density separation has been shown to further increase purity [95].

To increase the mass recovery rate, so-called recovery NIRs can be implemented: Such sorters further process the rejects, sort out the target fractions, and then return them to the input. These have also been tested: For PO from the HCVF, a total of 4.1% can be added to the mass recovery rate, 2.7% of which is achieved by a recovery sorter at reject 1 and the rest from reject 2. For the MCVF, a recovery NIR sorter for PO and PPC was tested on the PO reject 2 and the two PPC rejects, resulting in an increase of 16%.

3.2.2. Implications for Incineration and Refuse-Derived Fuels

Utilising MFA, the annual variations in mass and heating values of flows determined for incineration were calculated. The separation of PO from mixed MSW in the region resulted in a ~10% mass reduction in the HCVF and a ~15% decrease in MCVF, while the recovery of PPC led to a reduction of over 30%. The corresponding annual quantities and associated *LHV* are presented in Table 3. The calculated lower heating values exhibit a fluctuation of around $\pm 10\%$, indicating that no substantial change in the raw *LHV* was evident over the scenarios. In contrast to slight *LHV* decreases through sorting out PO, the removal of the relatively high-moisture PPC fraction appears to contribute to an increase in the raw *LHV*. The considerable heterogeneity reflected in the waste composition and water content uncertainties, as well as unavoidable sampling errors, lead to substantial variability in elemental composition, mainly causing uncertainties in the results. For underlying data on water content and elemental waste composition, see Supplementary Materials Tables S3 and S6.

Table 3. Raw lower heating values (*LHV*) of raw flows destined for incineration and respective annual mass flows (*m*) of the high (HCVF) and medium calorific value fraction (MCVF).

	HCVF		MCVF	
	<i>LHV</i> in MJ·kg ⁻¹	<i>m</i> in kt·yr ⁻¹	<i>LHV</i> in MJ·kg ⁻¹	<i>m</i> in kt·yr ⁻¹
Status Quo	17.9 ± 1.70	10.5	13.4 ± 2.11	27.3
Scenario I	17.1 ± 1.67	9.4 ± 0.1	13.4 ± 2.11	27.3
Scenario II	17.9 ± 1.70	10.5	12.7 ± 2.00	23.2 ± 0.2
Scenario III	17.9 ± 1.70	10.5	13.1 ± 2.55	18.0 ± 0.2
Scenario IV	17.1 ± 1.67	9.4 ± 0.1	12.7 ± 2.00	23.2 ± 0.2
Scenario V	17.1 ± 1.67	9.4 ± 0.1	13.1 ± 2.55	18.0 ± 0.2

Previous studies have demonstrated that improved separate collection reduces the proportion of plastics and textiles in RDF [96]. This trend of reducing textiles and plastics in RDF will likely be further reinforced if PO is increasingly removed from mixed MSW on a large scale. The precise impact on heating values remains uncertain, though a reduction is anticipated. From a quantitative perspective, Austria remains a net exporter of RDF [97], suggesting that the recovery of PO could occur without causing a domestic shortfall. However, the broader transnational implications must also be considered, as a reduction in RDF may lead to increased reliance on fossil fuels beyond Austria. A detailed energy balance is beyond the scope of this study, but current evidence indicates that at least Austria's RDF demand can be met even with PO recovery from mixed MSW. Nevertheless, the potential implications of large-scale PO recovery for domestic energy markets and fossil fuel reliance merit further investigation, as well as the optimal balance between RDF production and recycling. Regionally defined case studies, such as the present study, can support research on the interactions between recycling and RDF by providing primary data on recovery efficiencies and purities from mixed MSW.

3.2.3. Further Economic and Environmental Implications

Regarding the economic implications of mixed MSW sorting, Feil et al. [9] studied upgrading an MRF to recover plastics by integrating an additional air separator and two NIR sorters. In 2016, total investment costs for two NIR sorters equalled roughly 1 Mio. €; yearly total capital expenditures and operational costs were estimated at 270,000 €·yr⁻¹ with linear amortisation over 8 years [9]. Their results show that while the investment can substantially reduce landfill and disposal expenses, the overall savings do not fully offset the additional costs, making the upgrade economically unviable under typical conditions. To address this, financial mechanisms were set in place in the Netherlands, offering 817 €·t⁻¹ of sorted plastics in recovery fees and enhancing the economic viability for MRF operators [9]. For the case of the investigated MRF, at least six NIR sorters would be needed; in light of the low revenues that can be achieved with PPC [23] and given that its recovery from mixed MSW is not absolutely necessary to achieve the EU recycling rates, PPC recovery cannot be seen as economically viable.

From both environmental and economic perspectives, reducing the fossil carbon content and calorific value of waste sent to incineration is a more beneficial aspect. On the one hand, this creates additional capacity in incineration facilities; on the other, it contributes to lowering greenhouse gas emissions [98]. The EU Emissions Trading System (ETS) was recently revised and expanded to align with the *European Climate Law* 2030 target to cut net greenhouse gas emissions by 55% compared to 1990 levels [99,100]. Since 2024, municipal waste incineration plants have been required to report emissions under the EU-ETS1, but without participating in allowance surrender [101]. The European Commission

is mandated to assess the inclusion of these facilities in the EU-ETS2 by 2026, with possible implementation by 2028 [102]. Several initiatives are advocating for this policy shift and the active inclusion of allowance surrender for municipal solid waste incineration within the EU-ETS2 [103,104].

Within this context, Schmidt and Laner [105] demonstrated that sorting reduces the fossil carbon content of mixed MSW for incineration by 27%, resulting in a 17% decrease in direct scope 1 emissions, primarily due to the removal of plastics. If waste incineration is brought under the ETS, this reduction would not only lower climate impacts but also translate into substantial cost savings in the form of avoided emission allowance purchases, with expected EU-ETS2 prices between 71 and 261 €·t⁻¹ CO₂ in 2030 [106]. Another economic advantage of mixed MSW sorting is the potential release of incineration capacities: because Austrian waste incineration plants are constrained by the relatively high heating value of the input, the separation of high-calorific material could allow additional throughputs, albeit this cannot be quantified within the applied system boundaries.

Considering both economic and environmental dimensions, the recovery of plastics from mixed MSW, in addition to separate collection, represents an increasingly relevant strategy, as it contributes to reducing fossil-derived CO₂ in incineration inputs and supports compliance with EU recycling targets. It is further underlined by the stagnating performance of separate collection systems and the complex, slow-to-change influence of human behaviour for enhanced source-segregation [12].

4. Conclusions

Despite a well-established waste collection infrastructure, the capture rates of plastics and PPC in Austrian separate collection systems have stagnated, leaving considerable amounts of valuable materials within mixed MSW. While MRFs for this waste stream exist, they primarily focus on metal separation, and plant operators remain hesitant to upgrade their material recovery portfolio due to a lack of data on quantity and quality. This study specifically demonstrated the yields, purities and recovery potentials of PO and PPC from mixed MSW in a case study region in Tyrol, Austria. A direct generalisation of the results cannot be made; however, it may be suggested that comparable outcomes could be achieved in regions exhibiting similar combinations of urban–rural population structures, tourism intensity, and collection system design.

The results indicate that a two-step near-infrared sorting system can produce a PO concentrate with 50–70% purity, leading to a 6–16% increase in the region's recycling. PPC recovery, however, does not contribute as much to recycling quantities as separate collection systems for paper in the region already function effectively, though this outcome may vary in other areas. Importantly, the raw heating values of the residual waste streams decreased with PO recovery due to the removal of high-calorific fractions; PPC recovery increased the heating values because of its high moisture content. Naturally, amounts decreased. Due to the reduction in available RDF, the question of whether increased material recovery leads to greater reliance on fossil fuels, connected to a potential greenhouse gas emission shift, necessitates further investigation.

The recovery from mixed MSW has the potential to contribute to circular material flows and resource efficiency; however, regulatory intervention is required if the low cost of virgin materials continues to hinder the economic viability of recycling. While small-scale upgrades in MRFs can achieve satisfactory purities, challenges persist in optimising the trade-off between recovery rates and impurity levels. Moreover, fundamental questions arise concerning the perception of mixed MSW: the advertisement and classification as non-recoverable, raising critical questions regarding the justification for extracting valuable fractions and marketing products. Additionally, the presence of substances of concern

and microbial contamination demands further research to ensure the long-term safety of recycled material from mixed waste origins.

While the recovery of recyclables from mixed MSW offers opportunities towards closing material loops, separate collection must remain the priority to prevent a shift towards a techno-deterministic approach that undermines established collection systems. Further research is needed to assess the impacts of large-scale recovery from mixed MSW on household separation behaviour. While reliance on back-end sorting is sometimes hypothesised, it has not been empirically demonstrated, and it is unclear whether most residents possess sufficient knowledge of waste management infrastructure to (negatively) adjust sorting practices. Investigating these potential behavioural responses is essential for designing effective, integrated waste management systems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/recycling10050176/s1>. Figure S1: Schematic depiction of the Digital Waste Research Lab of the Chair of Waste Processing Technology and Waste Management (Lehrstuhl für Abfallverwertungstechnik und Abfallwirtschaft–AVAW), Montanuniversität Leoben (© AVAW); Figure S2: Sorting Matrix; Figure S3: Sub-process P2: MRF for mixed waste. The NIR sorters 1 and 2 are integrated in scenario I, IV and V; NIR sorters 3 and 4 in scenario II–IV; and the NIR sorters 5 and 6 in scenario II and IV; Figure S4: Sub-process P3: MRF for lightweight packaging waste (LWPW); Figure S5: Sub-process P4: Simulated recycling of plastics, paper and metal; Figure S6 continued: Selected photos from the processing trials; Figure S7: Selected photos from the processing outputs; Figure S8: Details compositions of the product flows (ejects—E) from the processing trials of the high (HCVF) and medium calorific value fraction (MCVF) recovering polyolefins (PO), as well as paper, paperboard and cardboard (PPC) based on manual sorting combined with density separation and Fourier transform infrared (FTIR) spectroscopy. Values are shown as mean values \pm standard deviation based on wet matter and rounded to two significant digits (data in Tables S4 and S5). The relative standard deviation is $<10\%$, except for MCVF PPC E1 and E2 ($<20\%$); Figure S9: NIR Spectra of cotton, cardboard, paper and viscose; Figure S10: Material flow of goods status quo for subprocess in t/yr; Figure S11: Material flow of goods status quo for subprocess P2, mixed waste MRF, in t/yr; Figure S12: Material flow of PO status quo in t/yr; Figure S13: Material flow of PO status quo for subprocess P2, mixed waste MRF, in t/yr. ; Figure S14: Material flow of PPC status quo in t/yr; Figure S15: Material flow of PPC status quo for subprocess P2, mixed waste MRF, in t/yr. ; Figure S16: Material flow of goods in scenario I in t/yr; Figure S17: Material flow of goods in scenario I for subprocess P2, mixed waste MRF, in t/yr.; Figure S18: Material flow of PO in scenario I in t/yr; Figure S19: Material flow of PO in scenario I for subprocess P2, mixed waste MRF, in t/yr; Figure S20: Material flow of PPC in scenario I in t/yr; Figure S21: Material flow of PPC in scenario I for subprocess P2, mixed waste MRF, in t/yr; Figure S22: Material flow of goods in scenario II in t/yr; Figure S23: Material flow of goods in scenario II for subprocess P2, mixed waste MRF, in t/yr. ; Figure S24: Material flow of PO in scenario II in t/yr; Figure S25: Material flow of PO in scenario II for subprocess P2, mixed waste MRF, in t/yr. ; Figure S26: Material flow of PPC in scenario II in t/yr; Figure S27: Material flow of PPC in scenario II for subprocess P2, mixed waste MRF, in t/yr. ; Figure S28: Material flow of goods in scenario III in t/yr; Figure S29: Material flow of goods in scenario III for subprocess P2, mixed waste MRF, in t/yr; Figure S30: Material flow of PO in scenario III in t/yr; Figure S31: Material flow of PO in scenario III for subprocess P2, mixed waste MRF, in t/yr; Figure S32: Material flow of PPC in scenario III in t/yr; Figure S33: Material flow of PPC in scenario III for subprocess P2, mixed waste MRF, in t/yr; Figure S34: Material flow of goods in scenario IV in t/yr; Figure S35: Material flow of goods in scenario IV for subprocess P2, mixed waste MRF, in t/yr; Figure S36: Material flow of PO in scenario IV in t/yr; Figure S37: Material flow of PO in scenario IV for subprocess P2, mixed waste MRF, in t/yr; Figure S38: Material flow of PPC in scenario IV in t/yr; Figure S39: Material flow of PPC in scenario IV for subprocess P2, mixed waste MRF, in t/yr; Figure S40: Material flow of goods in scenario V in t/yr; Figure S41: Material flow of goods in scenario V for subprocess P2, mixed waste MRF, in t/yr; Figure S42: Material flow of

PO in scenario V in t/yr; Figure S43: Material flow of PO in scenario V for subprocess P2, mixed waste MRF, in t/yr; Figure S44: Material flow of PPC in scenario V in t/yr; Figure S45: Material flow of PPC in scenario V for subprocess P2, mixed waste MRF, in t/yr; Table S1: Input data for flows; Table S2: Input data for transfer coefficients (TC); Table S3: Water contents of all streams of processing trials 1 and 2; Table S4: All waste characterisation data for processing trial 1—high calorific value fraction (HCVF). Data are rounded to two significant digits \pm standard deviation; Table S5: All waste characterisation data for processing trial 2—medium calorific value fraction (MCVF). Data are rounded to two significant digits \pm standard deviation; Table S6: Background data for heating values (mean \pm standard deviation) [107–113].

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Abbreviations

The following abbreviations are used in this manuscript:

EPR	Extended Producer Responsibility
ETS	Emissions Trading System
HDPE	High-Density Polyethylene
HCVF	High Calorific Value Fraction
LCVF	Low Calorific Value Fraction
LDPE	Low-Density Polyethylene
LHV	Lower Heating Value
MCVF	Medium Calorific Value Fraction
MFA	Material Flow Analysis
MRF	Material Recovery Facility
MSW	Municipal Solid Waste

NIR	Near-Infrared
PE	Polyethene
PET	Polyethene Terephthalate
PO	Polyolefins
PP	Polypropylene
PPC	Paper, Paperboard and Cardboard
PS	Polystyrene
PVC	Polyvinylchloride

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