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Assessing the Sorting Efficiency of Plastic Packaging Waste in an Italian Material Recovery Facility: Current and Upgraded Configuration

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Abstract: The first step in reintroducing plastic waste into the recycling cycle is to use material recovery facilities (MRFs). However, while the composition and types of plastic waste are changing over time, the layout of MRFs does not always adapt to this change. In this paper, an existing MRF in Southern Italy was chosen as a reference to evaluate its current performance and to estimate possible improvements in sorting through a specific upgrade. First, an analysis of the amount, composition, and sources (in terms of type of waste and distance from the MRF) of the input waste was conducted. The composition of the input waste was then compared with the amount of selected output waste streams in order to calculate the current sorting efficiency of each stream and compare it with the values obtained from the upgrade. Lastly, the current performance of the plant was compared with a previous assessment of the same MRF in order to highlight possible variation. Results showed how the incoming waste was mainly composed of packaging plastic waste, and that some plastic waste not yet selected by the plant ended up in specific output streams. Therefore, the current performance of the MRF resulted high for PET and PE bottles (80.2% and 92.8%, respectively), in contrast to mixed or flexible packaging, where the efficiency achieved lower values (55–50%). These values were caused by a weakness in the 2D flow sorting line, which the upgrade mostly addressed. The upgraded configuration increased the production of recyclable waste from 34.32% to 50.39%, especially due to the recovery of small flexible packaging films in PE and biopolymers.

Keywords: PET bottles; bioplastics; sorting efficiency; material recovery facility; plastic waste

Citation: Gadaleta, G.; De Gisi, S.; Todaro, F.; D'Alessandro, G.; Binetti, S.; Notarnicola, M. Assessing the Sorting Efficiency of Plastic Packaging Waste in an Italian Material Recovery Facility: Current and Upgraded Configuration. *Recycling* **2023**, *8*, 25. https://doi.org/10.3390/recycling8010025

Academic Editor: Silvia Serranti

Received: 16 January 2023
Revised: 2 February 2023
Accepted: 10 February 2023
Published: 12 February 2023

1. Introduction

According to the European Union (EU) policies of a circular economy, one of the main challenges is to increase packaging recycling rates, especially for plastics, identified as highly responsible for environmental pollution [1]. Indeed, in 2020, the plastic packaging recycling rate in Europe was 34.6% [2], which is very far from the EU target of 50% by 2025 [3]. This means that the recycling of plastic packaging waste in EU has to increase by more than 15% in 5 years, which is an ambitious but necessary target since the amount of plastic waste globally produced is increasing over time [4].

Plastic recycling is, however, not an ordinary process since it is necessary to have homogeneous polymer streams in order to achieve high-quality products [5]. On the other hand, the most feasible and simple separate collection of plastic waste is a commingled collection of all the polymer types. Material recovery facilities (MRFs) are responsible for sorting of homogeneous polymer streams from the mixed plastic waste resulting from separate collection. MRFs can currently separate a wide variety of polymers and plastic waste through an automated and/or manual sorting process [6]. In Italy, the most common plastic packaging waste selected by these plants is PET and PE bottles, mixed PP packaging, PE packaging film, and bulky packaging, while non-recyclable plastics and/or nonpackaging items are collected in a specific stream (PLASMIX) and sent to an incineration plant for energy recovery [7]. Especially for PET bottles, which are the most valuable waste from an economic point of view [8], MRFs can achieve a stream purity of 95% and a recovery of 93% [9]. Generally, sorting efficiencies are higher for MRFs fed with commingled or lightweight packaging, as well as metals, PET, and HDPE [10].

On the other hand, some new packaging materials have emerged in the last few years, such as PET trays (mono- and multi-layer) or bioplastics. Regarding multi-layer PET trays, the various layers joined together cannot easily be separated from one another after use, and they are processed together as a mixture. This has a considerable effect on the mechanical recycling of PET trays, which results very challenging. Therefore, until now, much of this waste flow has not been recycled, instead being incinerated or ending up in landfills [11]. On the other hand, concerning bioplastics, there is a wide range of biopolymers on the market; despite it being known that a small presence of bioplastics can also affect the quality of conventional polymer recycling [12], the effect of such materials on an MRF is still not clear.

In order to reach the EU targets, MRFs have to be optimized and readapted to the spread of new waste types. In the literature, some examples of MRF upgrades have been reported. Four scenarios consisting of different plastic waste recovery routes (e.g., material recycling of clean, mixed plastics, and/or metals) were developed by Rigamonti et al. [13], but results confirmed the difficulty to clearly identify an optimal strategy for plastic waste management, since none of the examined scenarios emerged univocally as the best option for all impact categories. Furthermore, the upgrade of the sorting line of a Spanish MRF could achieve an unusable material content in the secondary source of recovered paper stream ranging from 11.9% to 8.2% [14]. Lastly, the most effective way to increase the recovery of aluminum packaging is the adoption of a specific sorting line in MRFs [15].

However, an investigation based on the Italian context is still missing, as is a specific assessment on new plastic packaging types such as PET trays and bioplastics, as already discussed above. In Italy, the collection and recycling of PET trays have already been studied for specific events (related to running and sports) or only as a management model [16,17]. On the contrary, only a few references analyzed the performance of an Italian MRF [7,9] without focusing on possible upgrades and/or the selection of specific packaging waste not yet selected by the plant.

Thus, the aim of this study was to investigate the MRF sorting efficiency according to a plant layout currently adopted by most MRFs in Italy. Accordingly, a case study of the Azienda Servizi Municipalizzati (ASM) facility in Molfetta (Southern Italy) was considered. For an entire month, the input and output waste streams were monitored in order to estimate their detailed composition. From these results, the sorting efficiency of each selected waste stream in the current MRF configuration was calculated according to a formula recently adopted by COREPLA (the Italian consortium for plastic packaging waste) to evaluate the MRF performance. Then, an upgraded layout of the ASM MRF for the sorting of other plastic waste (rarely selected by most Italian MRFs) was assumed, as planned by ASM to increase the number and the amount of selectable waste. The same sorting efficiency was calculated and compared to the current one, in order to highlight the improvement of this future configuration and to provide a scientific decision-making indicator.

2. Results

2.1. Input Waste Stream

During the month of the assessment, the ASM MRF processed 870 tons of plastic waste, divided into 799 (92%) and 71 (8%) tons of multi- and mono-material, respectively. It is clear that the plant mainly processed waste streams directly from separate collection (multi-material) than pre-sorted collection (mono-material).

The number of multi-material streams, divided across the 16 municipalities that sent their waste to the ASM MRF, is visible in Figure 1.

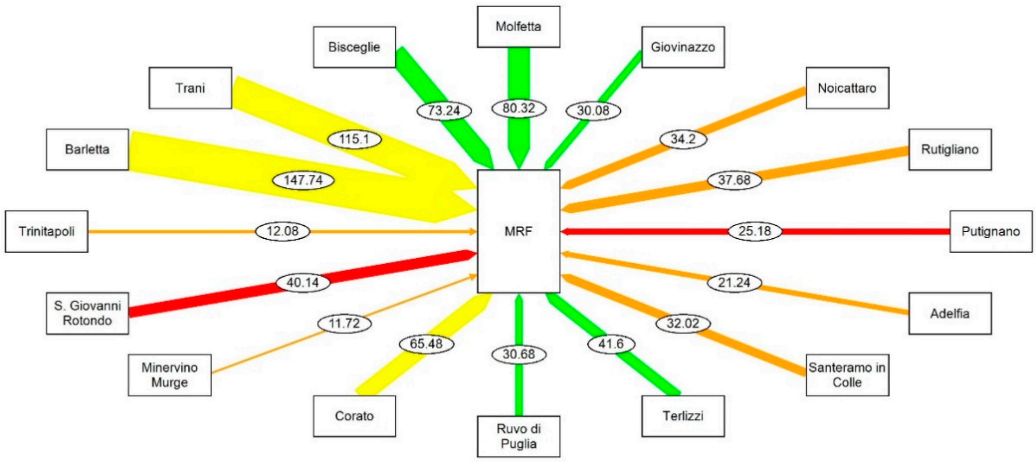


Figure 1. Multi-material waste streams coming from 16 municipalities to the ASM MRF (green, yellow, orange, and red flows indicate municipality–MRF distances of <15 km, 15–30 km, 30–60 km and >60 km, respectively).

From Figure 1, it is possible to note that the waste streams mainly came from municipalities at a low (32.1%) and medium–low (41.1%) distance; instead, municipalities at a medium–high and high distance accounted for 17.1% and 9.7% of the input waste, respectively. Streams that exceeded 100 tons came from the most populated cities (Barletta and Trani with 148 and 115 tons of waste, respectively), followed by Molfetta, Bisceglie, and Corato with 80, 73, and 66 tons of waste, respectively. The remaining municipalities ranged between 40 and 25 tons of waste; two municipalities (Trinitapoli and Minervino Murge) sent nearly 10 tons of waste.

In terms of composition, the main waste categories of the input waste are shown in Figure 2.

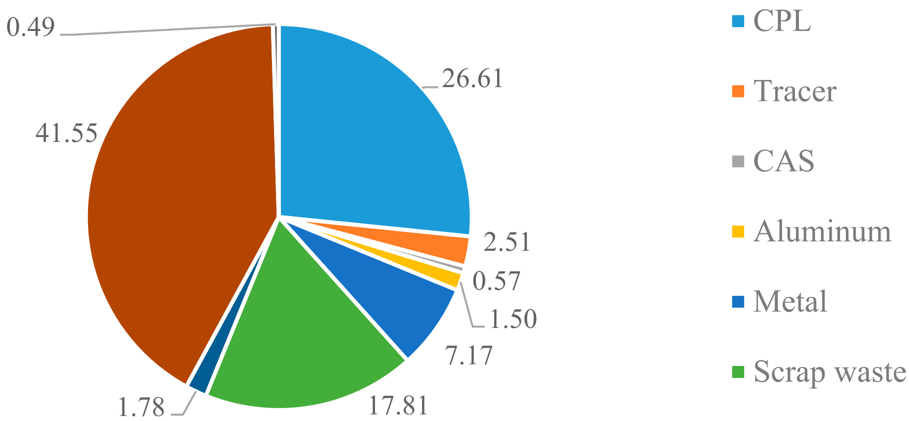


Figure 2. Multi-material waste composition (%) in terms of main categories as bottles for liquid (CPL), tracer, plastic crates (CAS), aluminum and metal packaging, scrap waste, rigid polyolefin packaging (MPR), other plastic packaging, and fine fraction.

It is interesting to note that almost 70% (68.17%) of the input waste was composed of plastic packaging: 26.61% bottles for liquid (CPL) and 41.55% other types of packaging. The remaining main fraction was scrap waste (17.81%), indicating a significant presence of non-packaging items, which should not be collected within the plastic packaging waste stream; thus, this is an indicator of contamination. Regarding aluminum and metal packaging, it is possible to see that metal packaging was almost five times as common as aluminum packaging. Lastly, fractions such as tracers, rigid polyolefin packaging (MPR), plastic crates (CAS), and fine fractions accounted for less than 3%.

In line with Figure 1, a detailed composition of each category is shown in Table 1.

Table 1. Detailed composition of multi-material plastic waste streams, divided into different subcategories.

Waste Fraction	Average (%)	St. Dev.
Bottles for liquid (CPL)	**26.61**	**±3.52**
Selectable PET bottles	17.91	±2.52
Selectable PE bottles	4.92	±0.94
Non-selectable PET bottles	2.78	±1.24
Non-selectable PE bottles	1.00	±0.63
Tracers	**2.51**	**±1.57**
Plastic crates (CAS)	**0.57**	**±0.39**
Aluminum packaging	**1.50**	**±0.58**
Metal packaging	**7.17**	**±2.18**
Scrap waste	**17.81**	**±3.56**
Paper	1.15	±0.71
Glass	0.67	±0.06
Bioplastics	1.22	±0.26
Other	14.77	±4.77
Rigid packaging in polyolefin (MPR)	**1.78**	**±0.26**
Other packaging	**41.55**	**±6.23**
PE film < A3 (FIL/S)	13.67	±3.69
PE film > A3 (FIL/S)	7.22	±2.43
Rigid PS	2.58	±0.93
Expanded PS	1.47	±0.57
Mixed PP packaging (IPP)	8.86	±1.27
PET trays	2.34	±0.58
Others	5.41	±1.95
Fine fraction	**0.49**	**±0.19**

Concerning bottles for liquid (CPL), the main polymer of the selectable bottles was PET (17.91%), while PE represented 4.92%. In terms of proportion, the non-selectable bottles were made manly of PE. It is important to note that not completely empty bottles were identified as non-selectable CPL. This could overestimate the presence of such items, since their presence was calculated according to their weight; indeed, a nonempty bottle weighs more than an empty one. Regarding the other plastic packaging, flexible packaging was the majority (20.89%), typically smaller than an A3 sheet (FIL/S). A significant amount of mixed PP packaging (IPP) was also detected (8.86%). The composition of scrap waste showed how contamination from other materials only represented 3.04%, while the remaining proportion (14.77%) was composed by non-recyclable plastic items. This indicated a proper performance of plastic separate collection by the users, which were undoubtedly familiar with the process. It is important to note that bioplastics accounted for 1.22% of the incoming plastic waste, despite their intended collection in Italy with the organic fraction of municipal solid waste if they meet the compostable criteria [18]. Lastly, since the sources of plastic waste can be domestic or non-domestic, this may have affected the variability of some fractions, such as tracers, which showed the highest standard deviation compared to the average value.

2.2. Output Waste Streams

Over 1 month, the ASM MRF selected 13 homogeneous waste streams, whose amounts are shown in Table 2.

Table 2. Amount of the selected waste streams in terms of output from the ASM MRF: light (CTL), bluish (CTA), and colored (CTC) PET bottles, PE bottles (CTE), PE film > A3 sheet (FIL/M), rigid polyolefin packaging (MPR), plastic crates (CAS), mixed PP packaging (IPP), aluminum and metal packaging, and PLASMIX end line (EL), additional (Add.), and fine.

Selected Waste Stream	Amount (tons)	Amount (%)
CTL	47.65	5.5
CTA	43.44	5.0
CTC	33.95	3.9
CTE	99.75	4.6
FIL/M	30.61	3.5
MPR	2.94	0.3
CAS	3.93	0.5
IPP	43.65	5.0
Aluminum	3.23	0.4
Metal	49.46	5.7
PLASMIX E.L.	215.53	24.8
PLASMIX Add.	337.44	38.8
PLASMIX fine	18.55	2.1
Total	870.12	100.0

The ASM MRF produced 34.3% of recyclable materials and 65.7% of non-recyclable waste for energy recovery in 1 month. Concerning recyclable material, bottles (CTL, CTA, CTC, and CTE) were the main streams (18.9%), along with mixed PP packaging (IPP) and large packaging films (FIL/M), which accounted for 5.0% and 3.5% of the total output, respectively. Outside of plastic packaging, metal packaging achieved the highest amount. On the other hand, concerning non-recyclable materials, PLASMIX additional was the highest (38.8%), composed of flexible items. PLASMIX end line also had significant importance (24.8%), revealing how flexible and tridimensional non-recyclable streams were comparable.

For some of these selected streams, a further analysis on their composition was carried out, as summarized in Table 3.

Table 3. Composition of selected waste streams in terms of non-selectable PET bottles, PE films < A3 (FIL/S), PET trays, rigid PS, and bioplastics.

Output Streams	Non-Selectable PET (%)	FIL/S (%)	PET Trays (%)	Rigid PS (%)	Bioplastics (%)
CTA	0.28 ± 0.12		1.66 ± 0.77		
CTC	1.22 ± 0.28		0.86 ± 0.20		
CTL	1.39 ± 0.17		3.68 ± 1.20		
IPP	1.08 ± 0.28	2.74 ± 0.69			0.40 ± 0.03
FIL/M		2.45 ± 0.71			0.38 ± 0.03
PLASMIX E.L.		10.10 ± 2.10	3.09 ± 0.44	3.42 ± 0.48	
PLASMIX Add.		27.36 ± 5.70	2.10 ± 0.67	2.32 ± 0.74	3.30 ± 0.55
PLASMIX fine			3.13 ± 0.62	3.46 ± 0.69	

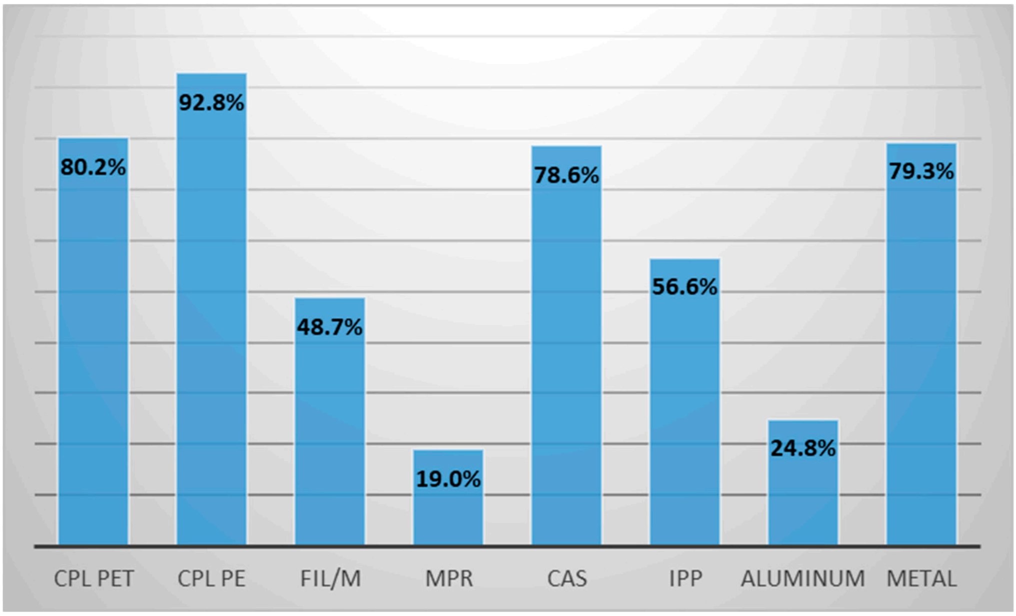
Non-selectable PET bottles could mainly be found in the colored and light PET bottles streams or in the mixed PP packaging stream (IPP). The bluish PET bottle stream was not affected significantly by the presence of non-selectable PET bottles.

The PE packaging film < A3 (FIL/S) was investigated in the streams where the presence of flexible items could be possible. The results showed how the main presence of FIL/S was in the PLASMIX streams, mainly in the additional one (which is characterized by the presence of two-dimensional items). For the same reason, bioplastics (mostly shoppers or carrier bags) were meanly detected in the same stream (3.30% of PLASMIX Add. stream).

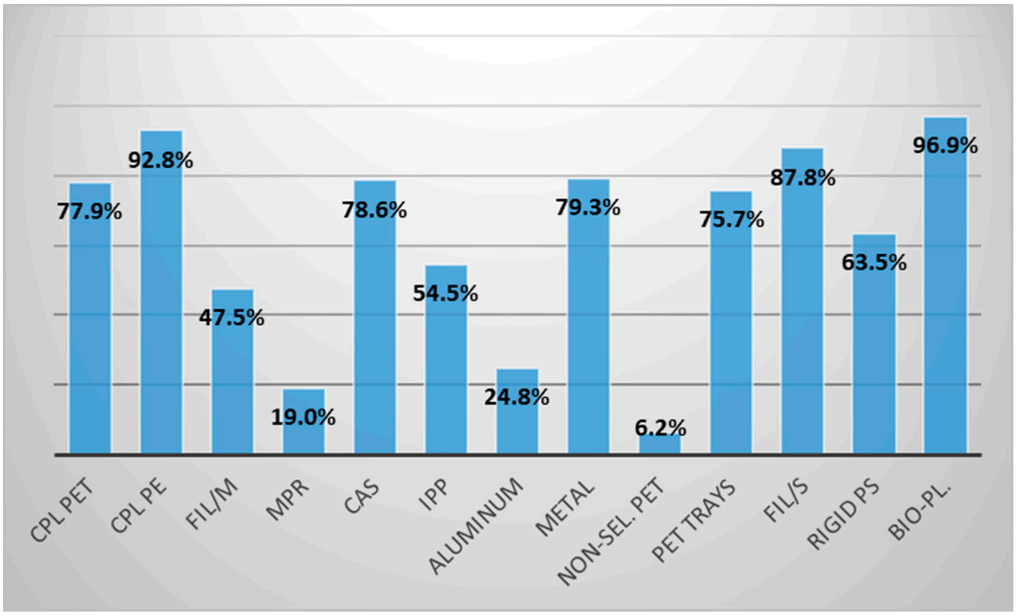
Lastly, rigid PS packaging and PET trays were equally distributed in the PLASMIX streams. In particular, PET trays could be obviously found in the PET bottle streams, mainly bluish (CTA; 1.66%) and light (CTL; 3.68%) ones. The reason could be attributed to the transparency of PET trays, which allowed them to be mixed with light PET bottles.

2.3. Current and Upgraded MRF Sorting Efficiencies

The current performance of the ASM MRF, described by the sorting efficiency (E_s) index for each selected waste stream, is shown in Figure 3a.



(**a**)



(**b**)

Figure 3. Sorting efficiency (E_s) of each selected waste stream performed by the ASM MRF plant in the current (**a**) and upgraded (**b**) configuration.

The ASM MRF plant achieved a high efficiency for the sorting of bottles for liquids in PET and PE (80.2% and 92.8%, respectively). This result showed a good performance for the sorting of the most valuable packaging waste for recycling [19]. High performance was also achieved for plastic crates (CAS) and metal packaging, reaching a sorting efficiency of about 80% for both. Indeed, the former is easily collected through a manual selection at the beginning of the sorting line due to its large dimension. On the other hand, during collection, trucks usually press the collected waste to reduce their volume, which breaks the plastic crates. Those pieces then ended in the PLASMIX streams, limiting the CAS sorting efficiency. Despite aluminum and metal packaging seeming similar, their sorting efficiency presented a significant difference, whereby the ECS system (used for aluminum sorting) had a lower performance than the magnet one. Concerning FIL/M (PE packaging films with a dimension > A3 sheet), the sorting efficiency did not exceed 50%. The cause of this result could be the lack of an appropriate selection line for flexible packaging, which has been limited to FIL/M only since 2018 [9]. Indeed, the smaller flexible items were not recovered, and they ended mainly in PLASMIX additional stream, as confirmed by Table 3. For the same reason, mixed PP packaging achieved a sorting efficiency of 56.6%, since PP packaging could have a 3D or 2D shape [20]. Lastly, the lowest efficiency was registered for the rigid packaging in polyolefin (MPR), highlighting an urgent improvement for this stream.

The current performance of the ASM MRF could be enhanced, hypothesizing a possible upgrade of the current selection line. Indeed, if specific sorting units could be placed along the current sorting line along with waste not yet selected by the plant, the amount of recovered material for recycling would increase. With this purpose in mind, the selection five 5 new packaging waste materials was assumed to be performed by the ASM MRF, namely, non-selectable PET bottles, PET trays, PE film with a dimension < A3 sheet (FIL/S), rigid PS packaging, and bioplastics. Then, the sorting efficiency of each selected waste stream was calculated, as shown in Figure 3b.

At first glance, the sorting efficiency of the waste streams already selected by the ASM MRF in the current configuration remained unchanged (CPL PE, MPR, CAS, and aluminum and metal packaging) or slightly decreased (CPL PET, FIL/M, and IPP). On the other hand, high sorting efficiency could be obtained by the new waste streams selected from the upgrade. Starting with the PET trays, the results showed that, by just placing a separation unit in the PET sorting line (as introduced by the value in Table 3), a sorting efficiency of 75.7% could be obtained. In addition, by strengthening the 2D sorting line with a specific sorting unit of FIL/S and bioplastics, sorting efficiencies of 87.8% and 96.9% were achieved for the former and the latter, respectively. Since rigid PS packaging was mainly present in the PLASMIX streams, high performance was obtained by this material (63.5% of E_s). Lastly, a sorting efficiency of non-selectable PET bottles of 6.2% was achieved. This result could be explained by two main reasons. First, only PET streams were investigated in this work, excluding the PLASMIX ones (which could have contained a significant amount of these items). Second, the amount of non-selectable PET bottles could have been overestimated since they may not have been completely empty and, hence, may have weighed more. Along the sorting line, bottles could have lost their content, thus reducing their weight and resulting lighter. It is important to highlight that this methodology did not allow estimating the possible sorting efficiency improvement due to the reduction in the input stream to a sorting unit. Thus, with the reduction in the amount of waste in the FIL/M sorting line, its sorting efficiency could further increase.

Table 4 summarizes the sorting efficiency in the current and upgraded configurations, pointing out how, with the upgrade, the production of recyclable waste streams could increase from 34.32% to 50.39%. In particular, a great contribution was achieved in the recovery of FIL/S, reaching 12% with the upgraded output. Overall, it can be noted that the upgraded configuration resulted in a significant improvement for the ASM MRF, which would allow actually pursuing the feasibility of this new scheme by the plant.

Table 4. Sorting efficiency (E_s) for each selected waste stream from the ASM MRF in the current and upgraded configuration.

Selected Stream	Input (%)	Output (Current) (%)	E_s (%)	Output (Upgraded) (%)	E_s (%)
CPL PET	17.91	14.37	80.2	13.96	77.9
CPL PE	4.92	4.57	92.8	4.57	92.8
FIL/M	7.22	3.52	48.7	3.43	47.5
MPR	1.78	0.34	19.0	0.34	19.0
CAS	0.57	0.45	78.6	0.45	78.6
IPP	8.86	5.02	56.6	4.83	54.5
Aluminum	1.50	0.37	24.8	0.37	24.8
Metal	7.17	5.68	79.3	5.68	79.3
Non-sel. PET	2.78			0.17	6.2
PET trays	2.34			1.77	75.7
FIL/S	13.67			12.00	87.8
Rigid PS	2.58			1.64	63.5
Bioplastics	1.22			1.18	96.9
Tot.		34.32		50.39	

3. Discussion

The assessment of the ASM MRF performance was compared with that carried out from 2016 to 2018, as explained in Gadaleta et al. [9], and then with other similar experiences in Europe.

The first finding can be highlighted regarding the comparison of the input to the MRF. In the previous assessment, the multi-material stream accounted for 22%, whereas, in this study, it accounted for 92%. This change resulted in an environmental benefit since more material could come from the neighboring municipalities, which were mainly within a radius of 30 km, thereby reducing the impact related to waste transportation [21,22]. Furthermore, the analysis of the multi-material waste composition showed a reduction in scrap waste, which decreased from 26.9% to 17.8%. This reflected a general improvement of users in the domestic separate collection of waste, especially in the southern regions of Italy [23]. On the other hand, the overall amount of packaging was still predominant in the incoming waste, and the ratio between bottles for liquid (CPL) and other packaging types resulted unchanged. It is important to note how the presence of incoming PET packaging waste found in 2022 in the ASM MRF (Italy) was significantly higher than that registered in Europe or Finland. On the other hand, proportions of packaging made from PS and HDPE were almost comparable, while PP and LDPE packaging resulted in a significantly lower amount than registered in the European context [24]. Focusing on PET trays, the amount of this packaging in Italy was much lower than that in North Europe, such as the Netherlands (7%) [25], indicating how the incoming waste strongly depends on the habits of the waste collection users.

Concerning the performance of the ASM MRF, two different methodologies were applied in the present work and in Gadaleta et al. [9]. The former analyzed the sorting efficiency of each selected waste in terms of output by comparing the amount of incoming waste with the produced one; the latter evaluated the purity and the recovery of each stream through a detailed composition investigation of each stream. However, despite the two methodologies adopted, the results confirmed similarities, especially in the recovery of liquid bottles made from PET and PE, where an efficiency of >80% could be found in both assessments. Other European MRFs could achieve the same sorting efficiency for PET (81%), but the sorting of PE bottles performed better in the ASM MRF than in Europe, where the average was 76%. A similar efficiency between ASM and European MRFs could be achieved for PP (on the average 57% in Europe) [26]. As already introduced before, FIL/S (PE film < A3 sheet) sorting being halted in 2018 had a negative effect on the recovery of flexible packaging, especially as IPP (mixed PP packaging) and FIL/M (PE film > A3 sheet). Indeed, in 2018, the efficiency of IPP and FIL/M was 97.41% and 85.18%, respectively, reducing to 56.6% and 48.7%, respectively, in the recent assessment. A low sorting efficiency could also be found in the Netherlands, where the proportion of correctly sorted PE packaging film < A4 was 24% [25]. It is not possible to compare the performance of aluminum and metal packaging recovery since, in the previous study, it was not possible to estimate their recovery. Thus, the results proposed in this work are the first data available for these two fractions. Lastly, despite the sorting efficiency of plastic crates (CAS) remaining high, that for rigid packaging in polyolefin (MPR) decreased drastically, probably due to the significant change in the input.

The upgraded facility targeted improvements in the 2D stream sorting line. Indeed, restoring of the FIL/S selection could resurrect the same issues for which it was blocked in 2018. It is widely known that flexible films are among the most challenging waste types mainly due to a lack of efficient sorting technologies, leading to an open-loop mechanical recycling process in most cases [27]. Indeed, in addition to the difficulties related to its sorting and the poor purity of its stream, China's announcement that it would no longer accept international plastic waste for recycling from the beginning of 2018 has exacerbated the problem of flexible packaging mechanical recycling [28]. On the other hand, several technologies for efficient FIL/S sorting exist [29], which could be implemented in an MRF [6], albeit with some economic and technical efforts, resulting in a significant improvement of the MRF performance compared to other European MRFs [26]. Another benefit from the possible ASM MRF upgrade would be the selection of PET trays and non-selectable CPL bottles, which are not commonly selected by the majority of Italian MRFs. In particular, in order to reduce the issues related to bottles not being fully empty (leading to their non-selection), a specific bottle-drilling machine could be implemented in the plant.

Lastly, this work considered bioplastics in the plastic waste stream, which is, to our best knowledge, the first case in the Italian context. Indeed, this study estimated the amount of bioplastics in the Italian plastic waste stream, showing how their amount is still limited but non-negligible, especially in the context national policies highlighting these materials as the best substitutes for packaging made from conventional fossil polymers [30], which will drastically increase their presence in all MSW streams [31]. Although bioplastics should be managed within the organic fraction of municipal solid waste (if they meet the criterion of compostability), this results in several issues, since the time required for a full biodegradation is significantly different between bioplastics and food waste [32]. On the other hand, treatment with conventional biological treatments (especially anaerobic digestion) is optimal for these materials [33]. As already pointed out by De Gisi et al. [34], the management of bioplastics in plastic waste streams could be a viable option; bioplastics could be selected on the sorting line and managed by their own consortia (Biorepack, Milano, Italy) through anaerobic digestion. Indeed, this option is already being pursued for other non-plastic waste, such as aluminum and metal packaging.

4. Materials and Methods

4.1. ASM Material Recovery Facility

The ASM MRF under investigation is located in Molfetta (Italy, province of Bari); it receives plastic waste from neighboring cities in the Apulia Region of Italy, as described in Figure 4. The ASM MRF processes waste with the following European Waste Codes (EWCs): plastic packaging (150102); mixed packaging (150106); plastic and rubber (191204); other waste (including mixed materials) from mechanical waste treatment (191212); rigid plastic waste from (separate) collection (200139).

Figure 4. Municipalities that send their plastic waste to the ASM MRF in Molfetta.

The input waste processed by ASM SSC consisted of the following:

- Multi-material packaging stream (composed of plastic, aluminum, and metal packaging waste) from municipal separate collection;
- Mono-material packaging stream (composed of only plastic waste, without aluminum and metal waste) from pre-selection plants, where the separate collected plastic waste was preliminarily selected and cleaned in order to increase the stream quality.

The input waste is sorted, producing different homogeneous waste streams through a combination of automated techniques and manual operations; the valuable streams are recycled into secondary raw materials, whereas non-recyclable streams (called PLASMIX) are sent to incineration plants for energy recovery. The MRF sorting line is composed of bag opener units, followed by two-dimensional ballistic separators for the separation of 3D, 2D, and fine (waste with an approximate size <40 mm) waste flows. Then, an automated sorting chain composed of magnetic, optic, and eddy current separators allows sorting different plastic packaging streams, as well as aluminum and metal ones. Lastly, a further manual sorting removes any waste incorrectly selected by previously sorted waste streams, leaving the non-recyclable PLASMIX flow at the end of the sorting line.

The main recyclable waste streams are the following:

- Light (CTL), bluish (CTA), and colored (CTC) PET bottles;
- PE liquid containers (CTE);
- PE packaging film larger than an A3 sheet (FIL/M);
- Mixed PP packaging (IPP);
- Plastic crates (CAS);
- Rigid polyolefin packaging (MPR);
- Aluminum and metal packaging.

In addition to these valuable plastic waste streams, PLASMIX is sorted by the plant into three different streams: fine (composed of non-recyclable plastic waste with a dimension

<40 mm), additional (mainly composed of films and flexible items), and end line (composed of any remaining material at the end of the sorting line, mainly scrap waste).

A more detailed description of the ASM MRF sorting line and the waste streams was presented in Gadaleta et al. [9].

4.2. Input and Output Waste Analysis

For the whole month of June 2022, a survey on the input waste composition was carried out at the ASM MRF. The assessment involved only the multi-material waste streams from the 16 municipalities that use the ASM MRF. The amount of incoming waste was collected by the ASM database, which registers the daily input of waste from each municipality at the MRF entry scale. The following categories (extended to different subcategories) were investigated in the input waste streams:

- Bottles for liquid (CPL): PET and PE bottles and vials with a capacity between 0.33 and 5 L. This fraction could be further divided into the following subcategories:
    - PET bottles, selectable and non-selectable (e.g., capacity <0.33 L, bottles still filled with liquid to more than 5% of their capacity, bottles covered by a label, etc.);
    - PE bottles, selectable and non-selectable (e.g., capacity <0.33 L, bottles still filled with liquid to more than 5% of their capacity, bottles fully covered by a label, etc.);
- Tracers: flexible packaging films with a dimension > A2 sheet (42×59.4 cm); strapping; bin bags;
- Plastic crates (CAS);
- Aluminum and metal packaging;
- Rigid polyolefin packaging (MPR);
- Other plastic packaging: all plastic packaging not included in liquid bottles, such as the following:
    - PE packaging film larger (FIL/M) or smaller (FIL/S) than an A3 sheet;
    - Rigid and expanded PS food packaging;
    - Mixed PP packaging (IPP);
    - PET trays;
    - Other packaging type;
- Fine fraction (fine materials such as powdered plastics <40 mm);
- Scrap waste, including no plastic packaging or other materials such as paper, glass, or bioplastic (these materials should not be collected within the plastic packaging waste stream from separate collection; they are an indicator of contamination).

Each sample was characterized according to the ADEME procedure, dividing the sample into four parts, choosing one and weighting the waste of each category [35].

The amounts of selected waste streams produced in the same period were recorded by weighting each bale of produced waste, as reported daily by ASM (information available from the ASM database). Some bales were further investigated (using the same methodology as for the input waste) in order to estimate the presence of some waste types not yet selected from the plant, as summarized in Table 5.

Table 5. Sub-fractions investigated for the selected waste streams in output from the ASM MRF.

Output Streams	Non-Selectable PET	FIL/S	PET Trays	PS Rigid	Bioplastics
CTA	✔		✔		
CTC	✔		✔		
CTL	✔		✔		
IPP	✔	✔			✔
FIL/M		✔			✔
PLASMIX E.L.		✔	✔	✔	
PLASMIX Add.		✔	✔	✔	✔
PLASMIX Fine			✔	✔	

4.3. Sorting Efficiency

The performance of ASM MRF was evaluated through the sorting efficiency (E_s) of each selected waste stream, according to the following equation:

$$E_s\ x = \frac{produced\ x}{x\ in\ input} \times 100, \tag{1}$$

where "$E_s\ x$" is the sorting efficiency of the x stream in output, "*produced x*" is the percentage of the stream x from the whole amount of selected streams in output, and "*x in input*" is the percentage of the waste x of the whole amount of the input waste. The use of this equation was recently adopted by the Italian consortium of plastic packaging waste (COREPLA) as an index for the MRF efficiency, according to which COREPLA allows each MRF to continue its sorting activity [36].

The sorting efficiency was calculated for each selected waste stream, aggregating the CTA, CTL, and CTC streams into a single stream of selectable PET bottles.

As described in the aim of the work, a possible future upgrade of the ASM MRF was assumed in this work. The upgrade is consistent with the aim of the company to increase the amount of recovered material, and it is planned for implementation if the results give positive feedback. It consists of a specific sorting unit along the sorting line for non-selectable PET bottles, FIL/S, PET trays, rigid PS packaging, and bioplastics, which are not currently selected by the plant. The recovery rate of each product was assumed equal to 90%, according to Kleinhans et al. [37]. Then, the sorting efficiency was extended to these streams, and the overall amount of recovered material was compared with the current state.

5. Conclusions

This work dealt with the topic of plastic waste sorting in Italian MRF. The case of ASM MRF in Molfetta was chosen as a reference to estimate the current sorting performance and evaluate future improvements for a possible upgrade. The results showed that contamination of the input waste, mainly composed of plastic packaging, has been reduced over time. However, several plastic waste components not yet selected by the plant were detected in specific outgoing waste streams, suggesting the possibility of implementing a specific sorting unit in these streams. The results revealed how the upgraded sorting line assumed in this study (and actually intended by the ASM company) achieved great improvements in terms of the amount of plastic waste recovered. With this option, the current sorting efficiency, which was particularly high for PET and PE bottles, resulted in a further improvement, leading to an increase in selected material for recycling from 34.32% to 50.39% of the output stream. This would allow the ASM company to pursue the implementation of such a scheme; in this case, further analysis would be necessary to assess the actual efficiency of the adopted sorting line.

This work also highlighted the importance of differentiating the analysis of waste streams from domestic and nondomestic users, since they resulted in different compositions. In addition, since flexible plastics are becoming more frequent in several packaging applications; hence, an improvement of the 2D sorting line should be pursued by MRFs. However, in order to better estimate the amount of non-selectable PET bottles and, thus, their sorting efficiency, a detailed investigation into the composition of PLASMIX streams is required. Lastly, the applicability of bioplastic sorting in MRFs needs to be further investigated to provide possible future options for handling these materials.

Author Contributions: Conceptualization, G.G. and G.D.; methodology, G.G., S.D.G., F.T. and G.D.; validation, G.D., S.B. and M.N.; formal analysis, G.G.; investigation, G.G.; resources, S.B.; data curation, G.G., S.D.G. and G.D.; writing—original draft preparation, G.G., S.D.G. and F.T.; writing—review and editing, G.D., S.B. and M.N.; supervision, G.D. and M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors express their gratitude to all the staff of the ASM MRF in Molfetta (Southern Italy) for sharing their time and know-how with members of the research group.

Conflicts of Interest: The authors declare no conflict of interest.

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