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Characterization, recyclability, and significance of plastic packaging in mixed municipal solid waste for achieving recycling targets in a Swedish city

John Laurence Esguerra *, Annica Carlsson, Joakim Johansson, Stefan Anderberg

Division of Environmental Technology and Management, Department of Management and Engineering, Linköping University, 581 83, Linköping, Sweden

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ABSTRACT

About 60% of plastic packaging in Sweden ends up in mixed municipal solid waste (MSW), which is incinerated with energy recovery. This status quo presents a missed opportunity to meet ambitious recycling targets. This study aims to provide a detailed characterization of plastic packaging in mixed MSW to assess its potential for recycling and its significance in improving the overall recycling rate. A case study involving a Swedish city was conducted wherein a sample of 5500 kg of mixed MSW from 920 households was characterized. From the 31% recycling rate, improvement of up to 59% can be achieved by diverting this misplaced plastic packaging into the existing recycling system. An additional 9% increase remains challenging to achieve due to the occurrence of non-recyclable attributes like black and multilayer packaging. The highlighted key enabler is the combination of correct household waste separation behavior and the establishment of mechanical sorting facilities to recover plastic waste from mixed MSW. These recycling potentials and associated challenges are discussed in the context of Sweden's ongoing efforts across the plastic packaging value chain. Furthermore, the importance of extended waste characterization is emphasized as a tool for identifying recycling potentials and monitoring the effectiveness of measures in enhancing circularity and resource-efficiency.

1. Introduction

The global production of plastics is continuously increasing owing to its versatility and numerous applications in industrial sectors (Geyer et al., 2017; Plastics Europe, 2023; Stegmann et al., 2022). However, plastic consumption comes with sustainability challenges related to its mainly fossil-based origin and inefficient and linear use (Jambeck et al., 2015; MacLeod et al., 2021). Such challenges have motivated recent policy initiatives and international negotiations aiming to achieve a new resource-efficient and circular plastic economy (EC, 2020; Nielsen et al., 2020; UNEP, 2022). Plastic packaging has received particular attention in this respect, being a major and often single-use application (Chen et al., 2021). To enhance the recycling of plastic packaging waste in Europe, EU Directive 2018/852 set recycling targets of 50% and 55% by 2025 and 2030, respectively (EC, 2018).

Developing circular plastic packaging flows is challenging as the current management involves different types of losses throughout the entire value chain (Eriksen et al., 2019; Picuno et al., 2021a). In 2021, 77% of the generated plastic packaging waste in the EU was recovered, and only 40% was subsequently recycled (Eurostat, 2023). A significant amount of residues occurs from mechanical and optical sorting in material recovery facilities (MRFs) and subsequent washing and granulation towards recycling (Antonopoulos et al., 2021; Eriksen and Astrup, 2019; Picuno et al., 2021b). These residues highlight the specific challenges brought by the material characteristics of plastic packaging. This includes black and multilayered packaging (Dahlbo et al., 2018; Hahladakis et al., 2018) as well as the thermo-mechanical degradation and immiscibility of polymer blends (Ragaert et al., 2017). To tackle this challenge, efforts are addressed both in terms of improvement in packaging characteristics following design for recycling and advancement of sorting and recycling technologies (Ding and Zhu, 2023).

Although the fulfillment of the new EU recycling targets for plastic packaging requires improvements in recycling processes and product design, a separate collection system (Knickmeyer, 2020; Roosen et al., 2022) is also essential. In Sweden, as in many other countries, a separate collection system plays a vital role in managing household waste (Rousta and Ekström, 2013; SEPA, 2022a). National producer responsibility for plastic packaging was introduced in the mid-1990s, and

* Corresponding author.
E-mail address: john.esguerra@liu.se (J.L. Esguerra).

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households are now expected to participate in a separate collection for material recycling (SME, 2020). There are collection bins situated nearby (<100m) single-family houses and apartment buildings and at farther central collection points specifically dedicated to bulky wastes (FTI, 2023; Hage et al., 2018). There is also a deposit-return system for polyethylene terephthalate (PET) beverage bottles, which works through consumer refunds (SME, 2005).

However, despite a separate collection system, about 60% of the plastic packaging still ends up in the mixed MSW that is bound for incineration plants (SEPA, 2022a). The significant material losses of plastic packaging to mixed MSW make it challenging to fulfill the EU recycling targets and to limit the fossil carbon emission of incineration plants. In Sweden, mixed MSW refers to heterogenous household waste that is separately collected like other fractions including organic waste and different packaging materials such as paper, glass, metal, and plastic.

In principle, the diversion of plastic packaging from the mixed MSW can be achieved through a separate collection system, mechanical and optical sorting, or a combination of the two approaches (Cimpan et al., 2015; Feil et al., 2017; Roosen et al., 2022). However, developing efficient sorting is always a multifaceted endeavor regardless of the selected approach. Here, knowledge of the material characteristics of plastic packaging waste can aid in pinpointing specific challenges and opportunities for accomplishing improved sorting and material recycling (Edjabou et al., 2015; Edjabou et al., 2021; Eriksen and Astrup, 2019; Faraca et al., 2019). To provide useful knowledge, plastics characterization needs to be detailed and include a range of features that can influence the recyclability of plastics. Such detailed knowledge about the material characteristics of plastic packaging in mixed MSW is lacking, both in Sweden and within the scientific literature.

Characterization in terms of rigid or flexible plastic packaging was introduced (Sahimaa et al., 2015) and extended in terms of polymer types (Edjabou et al., 2015; Dahlbo et al., 2018). Subsequently, a more detailed characterization in terms of application, form, and color was further introduced to better assess the recyclability of plastic packaging (Eriksen and Astrup, 2019; Faraca et al., 2019). However, this detailed characterization is limited to plastic packaging waste that is either separately collected (Eriksen and Astrup, 2019; Faraca et al., 2019) or already sorted output from MRFs (Roosen et al., 2020). Accounting for the high heterogeneity of mixed MSW, detailed characterization of its plastic packaging component is lacking. Consequently, plastic packaging waste in mixed MSW tends to be excluded when assessing the potential for an improved recycling rate (Antonopoulos et al., 2021), hence leaving a knowledge gap in terms of its potential contribution to achieving ambitious recycling targets.

This study aims to provide a detailed characterization of plastic packaging in Swedish mixed MSW to assess its potential for material recycling and its significance in improving the overall recycling rate. The following questions have been in focus.

(i) What are the material characteristics of plastic packaging in mixed MSW?
(ii) What share of this plastic packaging is recyclable? This represents the portion that can potentially be sorted out and subsequently recycled.
(iii) How much can the overall recycling rate be improved if all the plastic packaging in mixed MSW is diverted to material recycling?

A case study is employed, focusing on one of Sweden's ten largest cities with about 160,000 inhabitants. This case study intends to exemplify the importance of detailed waste characterization and the type of information that it can provide towards achieving the recycling targets at the city level. The common case rationale is behind the selection of the single-case study design (Yin, 2017). Like the national situation, the case city has about 60% of plastic packaging ending up in mixed MSW bound for incineration (SEPA, 2022b). Similar to other Swedish cities, the annual characterization of mixed MSW is being performed and has been running since 2012 in the case city. In line with the aim of this study, an extended characterization of plastic packaging in the mixed MSW was conducted in 2022. The importance of diverting plastic packaging in mixed MSW from incineration to material recycling is investigated and subsequently discussed in relation to other suggested measures, such as improved packaging design, separate collection, sorting, and recycling processes. Emphasis is also laid upon the role of waste characterization as a means for facilitating the development and evaluation of such measures.

2. Material and methods

2.1. Sampling procedure

In the case city, plastic packaging waste is distributed within the waste management system in three main flows: separated in dedicated bins, handled within the deposit-return system (PET beverage bottles), and disposed of in mixed MSW bins. The first two flows are managed by the Swedish Packaging and Newspaper Collector, funded through the extended producer responsibility, while the last flow is managed separately by the local city government. The same sampling sites and procedures have been followed since 2012, according to the waste analysis protocol provided by the Swedish Waste Management Association (SWM, 2020). Within the last decade, the share of plastic packaging in mixed MSW has varied without a clear trend between 10% and 20%. This corresponds to around 50%–60% of plastic packaging ending up in mixed MSW despite a separate collection system.

According to the waste analysis protocol (SWM, 2020), mixed MSW from both single-family houses and apartment buildings should be sampled. This follows a stratified sampling procedure based on the type of housing (Dahlén and Lagerkvist, 2008; Edjabou et al., 2015) that should cover at least 100–200 households per stratum, but without a specified share of the total population (Nordtest, 1995). A total of 920 households were covered from both housing types. These numbers are based on the associated households that are supposed to be served by the selected sampling sites. The sampling procedure started with the collection of 5580 kg of mixed MSW as the main sample (Fig. 1). Samples were collected from mixed MSW bins near residential buildings (<100m) for two weeks in April 2022. The amount of collected samples from the covered number of households were considered representative of the waste generated in the case city. Specifically, the sampling sites represent residential area inhabited by typical middle-class family households located a few kilometers from the city center. The main sample was mixed using a wheel loader and divided into five flat and oblong columns. Equal subsamples were drawn from each column and then mixed to form a representative sample of 1090 kg or approximately 20% of the main sample (SWM, 2020). This representative sample was loaded into intermediate bulk containers, sealed, and transported to the contracted laboratory for waste characterization.

2.2. Waste characterization

A two-step procedure for waste characterization was performed (Fig. 2). In the first step, the representative sample of 1090 kg was manually sorted into 10 main waste categories (SWM, 2020), of which about 150 kg was *plastics* (I.A). This category was further sorted into plastic packaging in terms of *flexible plastics*, *styrofoam*, *rigid plastics,* and non-packaging applications labeled as *other plastics* (I.B). Given the focus on plastic packaging (EU Directive, 2018/852) in this study, the *other plastics* category was excluded. All packaging with any remaining content was emptied and dried together with the rest of the samples. Passive drying was performed by leaving the samples for two weeks in a storage room, which resulted in approximately 100 kg of dry plastic packaging. It should be noted however, that no washing of samples was performed

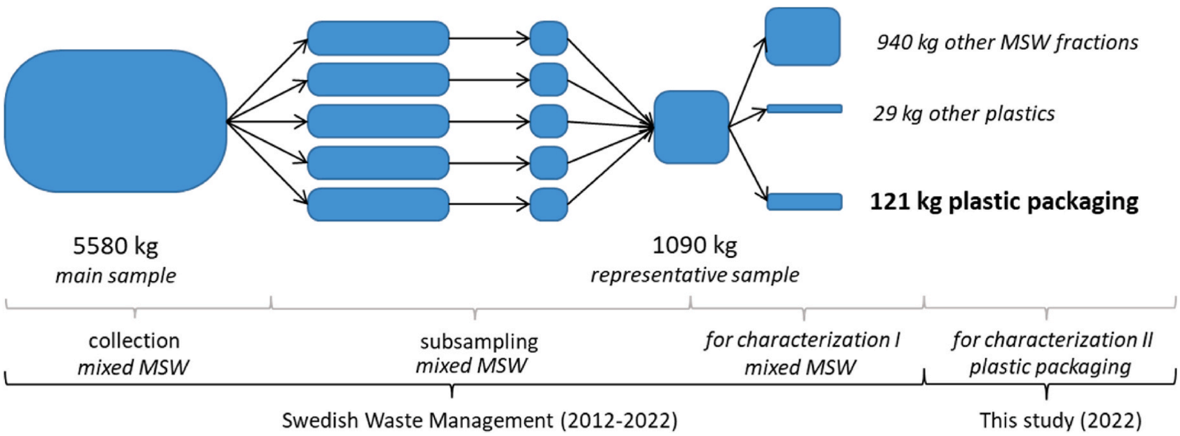

Fig. 1. Illustration of the subsampling procedure following the annual sampling program of mixed MSW in the case city (2012–2022). The component plastic packaging was sorted and subjected to an extended characterization for the purpose of this study (2022). Note: The values (in kg) are on a wet-weight basis.

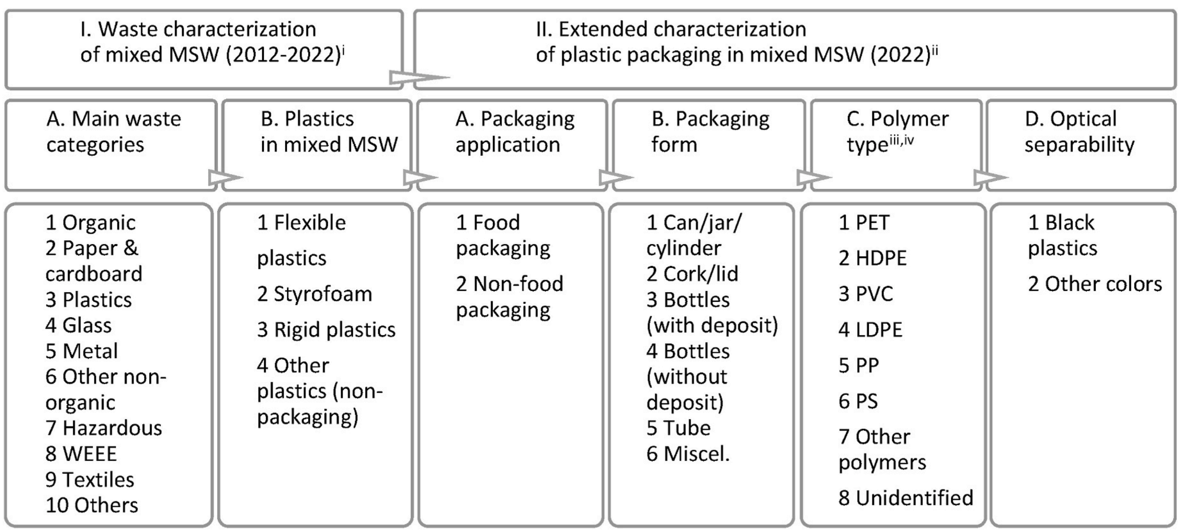

Fig. 2. Illustration of the two-step procedure for the characterization of (i) mixed MSW and extended characterization of (ii) plastic packaging.
Notes: [i] Sub-categories in accordance with the guidance manual for municipalities reporting of waste statistics to Swedish Waste Management (SWM, 2020)
[ii] This study. Adopted from Edjabou et al. (2015), Eriksen and Astrup (2019), Faraca et al. (2019); Fråne et al. (2015).
[iii] Following the standard numerical labeling for plastic packaging 1 PET-polyethylene terephthalate, 2 HDPE-high-density polyethylene, 3 PVC-polyvinyl chloride, 4 LDPE-low-density polyethylene, 5 PP-polypropylene, 6 PS-polystyrene, and 7 other polymers- (e.g., acrylic, polycarbonate, polylactic fibers, etc.)
[iv] Hereinafter, other polymers (II.C.7) and unidentified polymers (II.C.8) are grouped together as *others*.

leaving surface contaminants unaccounted for. The subsequent step was characterization that focused on determining the *packaging application*, *packaging form*, *polymer type,* and *optical separability* (II.A-D)*,* which are aspects recognized in previous studies as potential obstacles for efficient sorting and opportunities for recycling (Edjabou et al., 2015; Eriksen and Astrup, 2019; Faraca et al., 2019; Fråne et al., 2015). See Table A1 in the Appendix for comprehensive comparison of the characterization schemes among different studies and this study.

The second step of waste characterization was carried out by the contracted waste laboratory and the process was observed by the representatives of the research team. Here, each plastic packaging item was visually characterized. *Packaging application* (II.A) and *form* (II.B) were clearly discernible by appearance. *Polymer type* (II.C) was identified based on the printed standard numerical label for plastic packaging, from 1 to 7. For items without labels due to, for example, missing parts, the polymer type was estimated based on comparison to similar plastic packaging in the sample having the standard numerical label. Otherwise, they were categorized as *unidentified* (II.C.8). In the case of multilayer packaging, manually separable items like caps were also separated per polymer type, while the non-separable ones were accounted for as *unidentified*. Manual separation was primarily done to determine the material composition of the sample. However, it is acknowledged that these separable components will likely be sorted together with the main polymer type of the packaging in MRFs, similar to the non-separable ones. *Optical separability* was characterized based on black-colored plastics (II.D.1), which are difficult to sort by current near-infrared (NIR) technology in MRFs. The rest are categorized as other colors (II.D.2). The entire characterization was held indoors to reduce losses during sorting due to, for example, wind conditions. The same weighing scale with an accuracy of 0.001 kg was used for the whole sample and the weights per subcategory were documented on a dry basis in a predefined Excel-based protocol.

2.3. *Analysis of recyclability*

Here, *recyclability* is defined as the potential to be sorted out and subsequently recycled in the corresponding industrial facilities for sorting and recycling. Similar to Eriksen and Astrup (2019) and Faraca et al. (2019), the assessment of recyclability of plastic waste was linked with characterization step in which *black plastics* and *others* were considered not well-recyclable due to the aforementioned technical limitations in current sorting and recycling processes. These fractions can become impurities, lowering the quality of the monopolymer targets. On the other hand, the characterized monopolymer fractions were considered well-recyclable. The recyclable share of each polymer fraction was quantified based on the sorting and recycling efficiencies, which differ for flexible and rigid plastics (Table 1). Primary data was collected from Svensk Plaståtervinning (SPÅ), which handles more than 90% of plastic packaging waste in Sweden. In November 2023, the expanded Site Zero facility of SPÅ was inaugurated as the world's largest and most advanced facility for plastic recycling. It has an annual capacity of 200,000 tons and the technological setup includes: shredder (2), bag opener (4), magnet (5), trommel (4), disc screen <50 mm (2), vibrating screen <15 mm (2), vacuum (8), ballistic separator (6), NIR (60), laser(3), metal detector (2), camera with AI (3), and baler (4). The collected sorting efficiencies refer directly to the performance of the SPÅ facility, while recycling efficiencies refer to the average performance of identified relevant industrial facilities as surveyed by SPÅ. For comparison, secondary data were also collected from Antonopoulos et al. (2021), summarizing the efficiencies of several industrial facilities in the EU. Notably, the sorting and recycling efficiencies collected from SPÅ are close to the future targets based on the 75% percentile of the dataset (n) to represent the best available technologies for each target polymer. In addition, the average and maximum sorting efficiencies from SPÅ are the same for all polymers except for PS. The maximum sorting efficiencies from SPÅ and the average recycling efficiencies from relevant industries were used in the material flow analysis in this study (Section 2.4).

In principle, the recyclability depends on the combination of different characteristics of the packaging in question such as *polymer types, packaging form,* and whether they are *flexible or rigid plastics*. These characteristics have been shown to influence sorting and recycling efficiencies (Eriksen and Astrup, 2019; Faraca et al., 2019). For instance, MRFs have larger difficulties in handling flexible plastics than rigid plastics, and in terms of packaging form, sorting efficiencies for bottles are generally higher than in other forms (Eriksen and Astrup, 2019; Faraca et al., 2019). Furthermore, the *packaging application* is also relevant because when different applications of packaging are mixed, the material quality of the output from the recycling process is influenced (EC, 2022). To facilitate high-quality material recycling, applications such as food-grade and non-food-grade packaging can thus be separated prior to the MRFs (Eriksen et al., 2019; Schmidt and Laner, 2021). Another important characteristic is the particle size distribution that influences sorting efficiency (Feil and Pretz, 2020; Möllnitz et al., 2020). Depending on the specific technical setup, small items can be sieved out while large items can lead to false detection. However, particle size distribution was not determined in this study. Since no industrial characterization was performed, the actual influence of particle size distribution, unwashed samples, and visually characterized monopolymer fractions on recycling estimates remains as the limitation of the study.

2.4. Material flow analysis and the potential improvement of the overall recycling rate

The subsequent analysis focuses on how the complete diversion of plastic packaging from mixed MSW to material recycling would influence the overall recycling rate in the case city (Fig. 3). This means that the assessed occurrence and recyclability of plastic packaging in the mixed MSW (Section 2.3) was taken into account together with that from separate collection and deposit-return systems to calculate the potential improvement of the recycling rate from 31% in 2022 (Statistics Sweden, 2022). The recycling rate (EC, 2019a) was calculated considering (i) the amount of potential output materials from the sorting process as the calculation point, divided by (ii) the amount of plastic packaging put on the market (Fig. 3). While the EU scope definition was the focus of this study, calculation point after the recycling process was also considered to supplement the extended discussion on potential downstream material losses (Arduin et al., 2019).

Material flow analysis (MFA) was performed to quantify the annual amount of plastic packaging flows (ton/year) in the case city in 2022 following the mass-balance principle (Brunner and Rechberger, 2016). The total amount of plastic packaging put on the market was estimated given the Swedish annual data per capita and the case city's population (Statistics Sweden, 2022). The share in the deposit-return system was estimated given the annual PET put on the market which is separately reported (Statistics Sweden, 2022). The remaining share that is either separately collected or loss to mixed MSW was calculated given that 37% goes to the former and the rest to the latter as reported in the case city (FTI, 2022). The potential diversion of plastic packaging from mixed MSW to material recycling was explored, and the quantity of recyclable fractions was calculated based on the maximum sorting and recycling efficiencies collected from the SPÅ Site Zero facility (Table 1). An MFA diagram showing the potential recycling of plastic packaging from MSW was established, specifying both rigid and flexible plastics, constituent polymer types, and consequent amounts after sorting and recycling processes. For the comprehensive list of data, see Tables B1, D1, and E1 in Appendix. The illustration was aided by an open-access MFA software called STAN (Cencic and Rechberger, 2008).

The subsequent discussion followed the types of plastic packaging with the highest to the lowest potential contribution in improving the overall recycling rate. Furthermore, the corresponding strategies to accomplish the improvements in recycling rate were discussed in terms

Table 1
Efficiencies of sorting and recycling in Sweden (SPÅ Site Zero facility) and the EU (Antonopoulos et al., 2021).

	sorting efficiency							recycling efficiency			
	EU industries			SPÅ				EU industries			Relevant industries
	current	future	n	Average		Maximum		current	future	n	average
				mono	PO mix	mono	PO mix				
Rigid plastics rowhead											
PET	0.85	0.91	10	0.80	0.02	0.80	0.02	0.81	0.91	8	0.70
HDPE	0.85	0.91	11	0.85	0.09	0.85	0.09	0.88	0.93	6	0.92
PVC	0.73	0.73	1	0.75	0.00	0.75	0.00	0.80	0.80	1	UD
PP	0.64	0.79	8	0.85	0.09	0.85	0.09	0.66	0.85	7	0.90
PS	0.37	0.65	5	0.50	0.00	0.94	0.01	0.66	0.71	2	UD
Flexible plastics rowhead											
LDPE	0.59	0.73	10	0.60	0.30	0.90	0.10	0.71	0.86	5	0.95
PP	–	–	–	0.60	0.30	0.90	0.10	–	–	–	0.90

Note: n = no. of industries, current = average of n, future = 75% percentile of n, mono = monopolymer, PO mix = polyolefin mix, UD = under development (including the recycling of rigid and flexible PO mix).

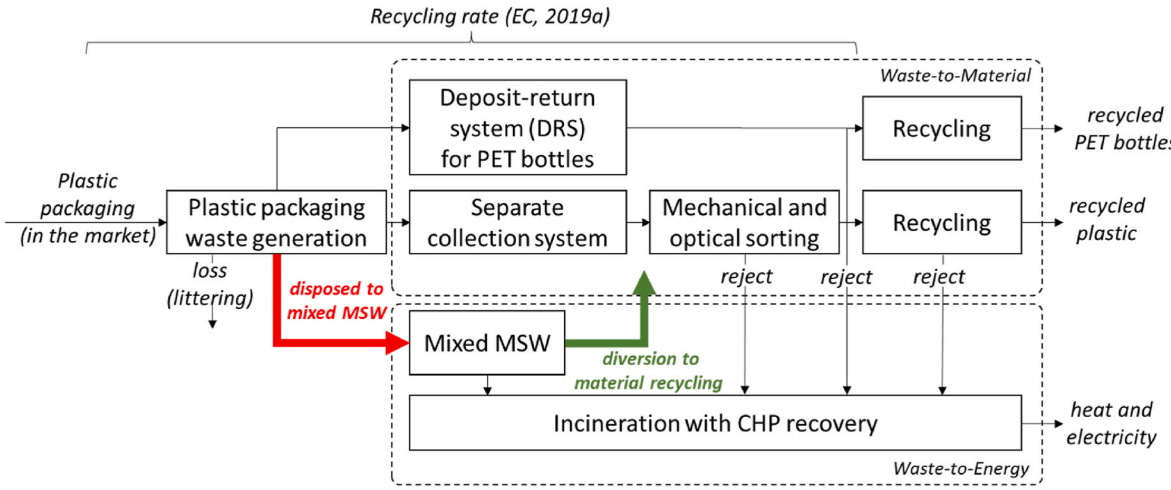

Fig. 3. Waste management system for plastic packaging in the Swedish case city. Potential increase in the overall recycling rate is shown by diverting the plastic packaging loss in mixed MSW from waste-to-energy to waste-to-material recycling.

of the need for a well-functioning separate collection (i.e., what if the households perform correct separate collection?) and better design policy (i.e., what if *others* and *black plastics* packaging are phased out?). Related challenges for the realization of these strategies in general and the latest developments in Sweden were also discussed.

3. Results

3.1. Characteristics of plastic packaging in mixed MSW

Following the annual characterization of mixed MSW in the case city, the amount of flexible and rigid plastics was identified (Fig. 4). Based on approximately 100 kg sample (dry weight) of plastic packaging in mixed MSW, the share of flexible plastics (55%) was higher than that of rigid plastics (45%). The dominance of flexible plastics has been observed since 2012, when the characterization campaign in the case city started. In terms of packaging form, flexible plastics are mainly bags (85%), while rigid plastics are mainly jars (55%) and bottles (20%) with a lid and cap, respectively. In terms of polymer types, LDPE and PP were dominant, followed by PET and HDPE, which altogether made up about 75%. LDPE was the most dominant polymer type of flexible plastics, while it was PP and PET for rigid plastics. In terms of application, food packaging was the most common, with a share of 61%, and the rest were non-food packaging. PP was the most dominant polymer type of food packaging, followed by LDPE and PET, while LDPE was the most dominant for non-food packaging, followed by PP, HDPE, and PET.

Apart from the identified major polymer types, a significant share of 23% was categorized as *others,* of which 15% was flexible plastics used as food packaging. The images of each category from the picking analysis are shown in Figures C1-C3 in the Appendix. In terms of color, *black plastics* accounted for 8% of the total plastic packaging in mixed MSW. There was a lower share of *black plastics* in flexible (2%) than in rigid (6%) plastic packaging. In terms of product application, almost equal shares of *black plastics* are used in food and non-food packaging, while in terms of polymer type, 39% of *black plastics* were made of PP, followed by the *others* at 31%. The share of *black plastics* per polymer type and the comprehensive characterization results are shown in Table D1 in the Appendix.

The presented characteristics of plastic packaging in mixed MSW showed some similarities and differences in comparison with the more studied plastic packaging from separate collection. The main difference is that the latter has a lower share of flexible plastics, from 10% to 40% (Eriksen and Astrup, 2019; Schmidt and Laner, 2021; Antonopoulos et al., 2021). However, similar findings were reported regarding the dominant polymer types such as PP, PE, and PET, as they are the main commodity polymers (Kawecki et al., 2018), which also correspond to the respective applications in food and non-food packaging (Eriksen and Astrup, 2019; Erselius, 2021; Schmidt and Laner, 2021). The same

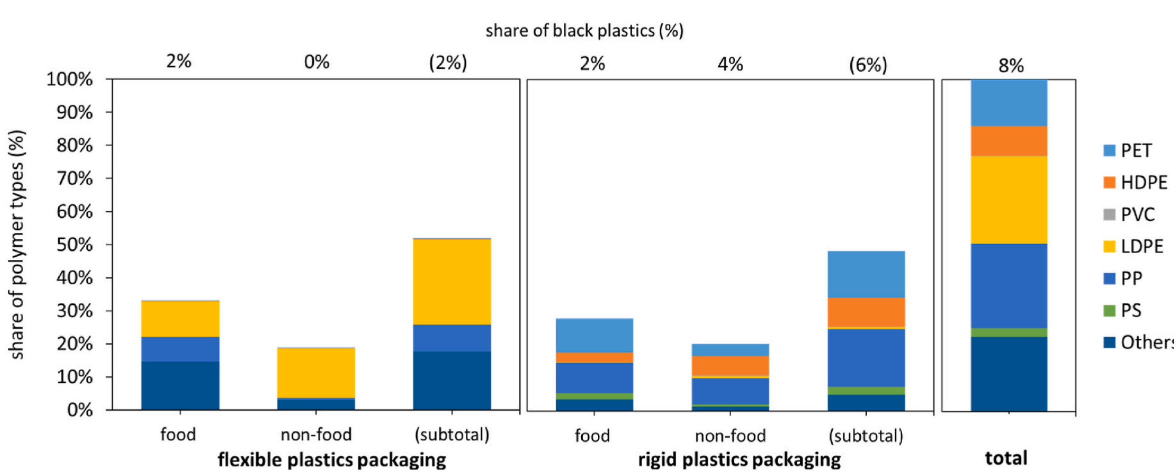

Fig. 4. Extended characterization (in %w/w of the sample, on a dry basis) of plastic packaging in mixed MSW from the Swedish case city. From the share of rigid and flexible plastics (2012–2022), characterization was extended in this study (2022) in terms of product application, polymer type, and share of black plastics.

dominant polymer types were reported in a related Swedish case limited to only rigid plastics in mixed MSW (SWM, 2019). Moreover, the share of *black plastics* in this study is within the reported range in different studies, from 5% to 15% (Brouwer et al., 2018; Eriksen and Astrup, 2019; Turner, 2018).

3.2. Potential recyclability based on the current waste management system

The extended characterization identified the potential for recycling plastic packaging in mixed MSW. About 30% of the sample, consisting of *black plastics* and *others*, are not well-recyclable. The 8% made up of *black plastics* remain rejected due to a low reflectance of light in NIR, making it undetectable in current optical sorting (Becker et al., 2017; Rozenstein et al., 2017; Turner, 2018). Recent advancements suggest the use of mid-wave infrared radiation (MIR) instead of NIR (Brunner et al., 2015; Turner, 2018). However, MIR technology has yet to be scaled up following the research on improving optical resolution and measurement speed while lowering hardware costs (Becker et al., 2017; Rozenstein et al., 2017). Ending up as a reject is also 23% of those categorized as *others*. The multilayer characteristic presents a known challenge for recycling (Dahlbo et al., 2018; Hahladakis et al., 2018). Whether or not this fraction is incinerated or further recycled into mixed plastics depends on different national recycling schemes (Picuno et al., 2021b), but the majority often ends up being incinerated (Ragaert et al., 2017). Furthermore, *others* were mainly composed of flexible plastics, and there are limited efficiencies reported for sorting multilayer films from household waste (Eriksen and Astrup, 2019). Brouwer et al. (2019) reported that 8% of laminated flexibles was faultily sorted into other sorted products such as flexibles (DKR 310), of which 72% was incinerated.

The remaining 70% are well-recyclable and based on the sorting and recycling efficiencies collected from the SPÅ Site Zero facility, 53% of which can be recycled. The well-recyclable fraction is composed of the dominant polymer types such as PP, PE, and PET, which current sorting and recycling facilities can process (Eriksen and Astrup, 2019; Kawecki et al., 2018; Schmidt and Laner, 2021; Antonopoulos et al., 2021). The recyclability of these polymer types varies depending on whether they are flexible or rigid plastics. For rigid plastics, sorting and recycling efficiencies are generally higher than those for flexible plastics, and they are more differentiated per polymer type. About 31% of the rigid plastics can be sorted (80%–85% sorting efficiency), and a subsequent 25% can be recycled (70%–90% recycling efficiency) as monopolymer recyclates (Rigamonti et al., 2014; Brouwer et al., 2018), while about 30% that are flexible plastics can be sorted (90% sorting efficiency) and a subsequent 28% can be recycled (90%–95% recycling efficiency) as monopolymer recyclates as well. In summary, up to 62% of the plastic packaging in mixed MSW can be sorted out, and subsequently, 53% can be recycled as monopolymer recyclates in the case city.

It should be noted that the remaining polymer types, such as PVC and PS, are excluded as the recycling of these polymers remains under development according to SPÅ. However, these are minor fractions that account for about 1% of additional recyclates, considering the sorting efficiencies of SPÅ for PVC and PS (75% and 94%) and the corresponding recycling efficiencies (Antonopoulos et al., 2021) from other EU industries (80% and 71%). Using similar assumptions, a more significant recyclate at 3% is a PO mix that is composed of different polymer types. The PO mix is the remainder after sorting monopolymer targets, which can be used to manufacture products that tolerate a high share of impurities, such as outdoor furniture and fences (Briassoulis et al., 2013; Rigamonti et al., 2014; Brouwer et al., 2018). However, according to SPÅ, the PO mix is also under development, like PVC and PS.

3.3. On achieving the recycling target

In 2022, the Swedish recycling rate for plastic packaging is 31%, which only accounted for plastic packaging in a separate collection system and PET bottles in deposit-return system (Statistics Sweden, 2022) (Fig. 5). This is far behind the EU recycling targets of 50% and 55% by 2025 and 2030, respectively (EC, 2018). However, there is a potential for improvement considering the recyclability of plastic packaging in mixed MSW (Section 3.2). Assuming a similar recycling rate of 31% in the case city, the following analysis quantifies the potential contribution of diverting plastic packaging from mixed MSW to achieving the EU recycling target, adopted in the city level. The EU scope definition of the recycling rate was used, where the calculation point refers to the amount of output materials from the sorting process that enter the subsequent recycling process.

The dominant polymer types such as PP, PE, and PET have the largest potential contribution to increasing recycling rate, which altogether amounts to 1350 tons of sortable plastics from mixed MSW. Considering the entire plastic packaging waste management system, this means an addition of 28% to the recycling rate in 2022, leading to an increase from 31% to 59% (Fig. 5), thereby fulfilling the 55% recycling target for 2030. The fulfillment of the recycling target still holds when the output from the subsequent recycling process is considered with 4% material loss. Such a significant increase in recycling rate is achievable when plastic packaging in mixed MSW is correctly separated at the source. In essence, there is a need for a well-functioning separate collection system, which refers to an ideal separation solely dependent on the waste separation behavior of the households.

Together with a well-functioning separate collection system, further improvement is needed to go beyond the ambitious recycling target. From the waste characterization in this study, packaging design, such as complex polymers in *others* and *black plastics,* leads to the difficulty in recycling a significant share of plastic packaging. Hence, design policy interventions, primarily on restriction of polymers and phasing out of black plastic, can lead to an improved separability in connection with separate collection, sorting, and recycling (Brouwer et al., 2020; EASAC, 2020). Considering the entire plastic packaging waste management, phasing out *black plastics* means an additional 81 tons of recyclable plastics. This accounts for only the *black plastics* made of PP, PE, and PET, which can otherwise be sorted out in the current system if not for their color. Similarly, if the *others* that are applied in food packaging are restricted to single polymers such as PET and PP (Eriksen and Astrup, 2019; Erselius, 2021; Schmidt and Laner, 2021), this means an additional 449 tons of recyclable plastics. Phasing out *others* and *black plastics* can lead to about 9% improvement in the recycling rate. Together with the well-functioning separate collection system, this design policy can aid in going beyond the recycling target of 55% by 2030. It is acknowledged, however, that monopolymer design also face challenges, especially for flexible food packaging, such as shortening food shelf lives, and the continued incorporation of additives that lower the quality of recycled products (Bauer et al., 2021; Lange, 2021).

4. Discussion

4.1. Relevance and challenges of addressing plastic packaging in mixed MSW

So far, several studies have focused on plastic packaging in a separate collection system, and on how its sorting and recycling can be further improved through more efficient processes, market interventions, and product design (Eriksen and Astrup, 2019; IVA, 2020; Schmidt and Laner, 2021). Although such measures on separately collected packaging are important, they are also insufficient as most of the generated plastic packaging waste still ends up in mixed MSW, in Sweden (SEPA, 2022a) and elsewhere (Eurostat, 2023). As demonstrated by this study, measures to re-direct such plastic packaging from mixed MSW to

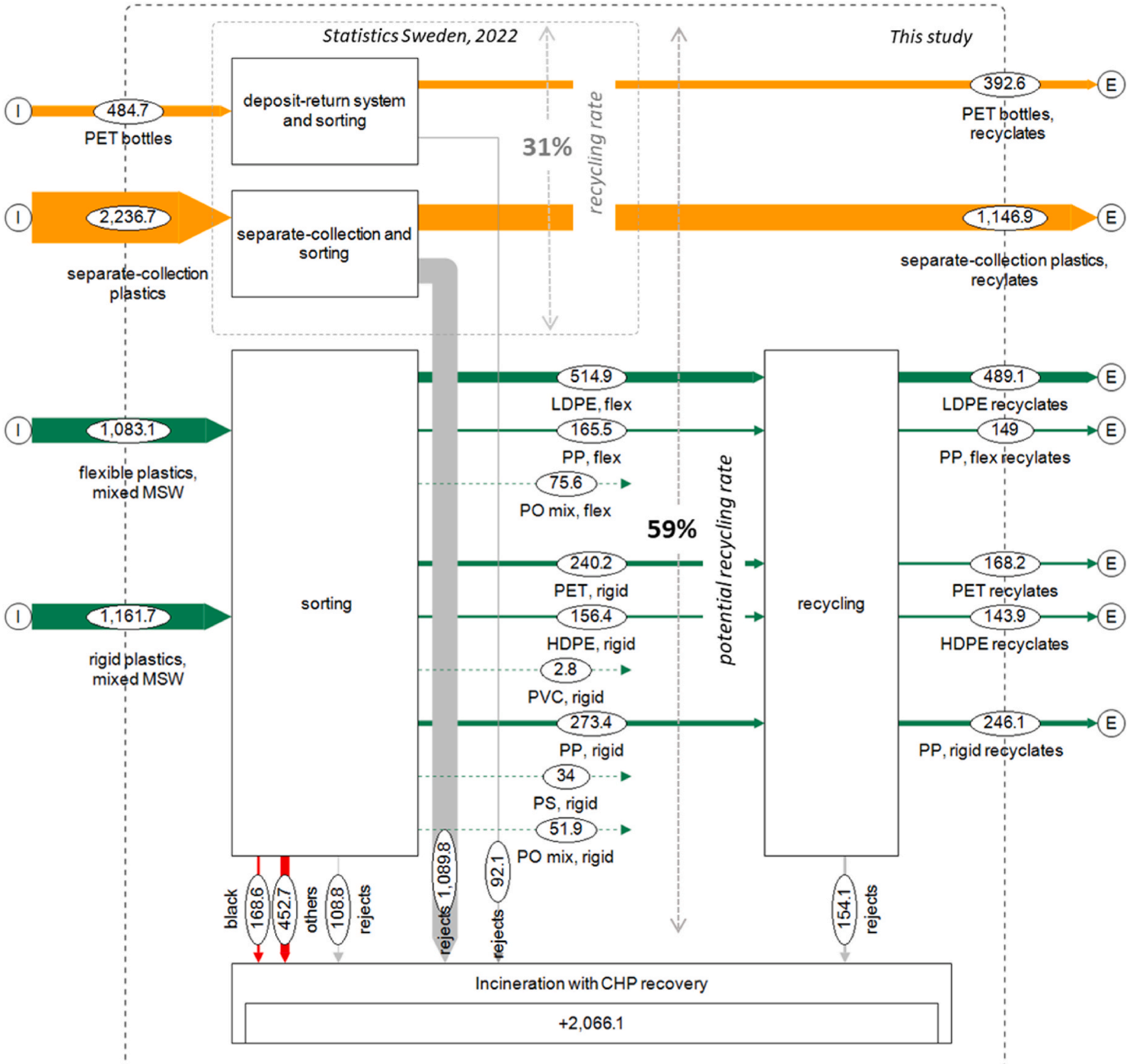

Fig. 5. Material flow diagram (in tons, on a dry basis) of the potential recycling of plastic packaging in mixed MSW, shown in relation to the overall plastic packaging waste management system including separate-collection and deposit-return system in the Swedish case city in 2022. Note: orange = calculated from secondary data, green = calculated using primary data, gray = calculated using mass-balance, red = assumed not well-recyclable. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

material recycling are therefore fundamental for fulfilling the EU recycling targets and boosting the effects of other ongoing improvements. It should be noted, however, that these targets are to be achieved at the national level. By taking the common case rationale (Yin, 2017) in selecting the studied city, similar improvement measures apply to other Swedish cities to contribute towards achieving the EU recycling targets.

A separate collection system is advocated in Europe (EC, 2018) to facilitate materials recycling. However, establishing a well-functioning separate collection system is a great challenge in providing people the convenience, knowledge, and motivation to participate (Goh et al., 2022; Knickmeyer, 2020). In Sweden, an ongoing initiative to ensure household participation in improved collection is through an additional separate collection system based on housing types, such as bins near single-family houses and collection rooms within apartment buildings (Berglund et al., 2022; FTI, 2023; Rousta and Ekström, 2013). However, it is unlikely that this initiative alone will be sufficient to address the massive loss of plastic packaging to mixed MSW. In fact, a large share of households already has the access to nearby separate collection system. In municipalities where such systems have been implemented, only moderate improvement in the collection rate of up to 26% was observed (Hage et al., 2018). Moreover, correct household waste separation behavior is another aspect to consider, in which public dissemination of information alone is shown to be insufficient and on-site supervision is even suggested (Li et al., 2022).

The challenges of educating and motivating households to correctly participate in a separate collection system have resulted in increased interest in investing in the advanced mechanical and optical sorting of mixed MSW. This additional intermediate process primarily diverts the plastic packaging from mixed MSW to material recycling instead of direct incineration (SWM, 2019). Internationally, such ambitious approaches to sorting plastics from mixed MSW are rare (Cimpan et al., 2015), with a few operating MRFs in Norway and The Netherlands. In Austria, MRFs for mixed MSW were also established however, they must be designed to recover plastics to realize their potential contribution to an estimated 10% improvement in the recycling rate (Blasenbauer et al., 2024). In Sweden, there is only one operating plant located in Stockholm with a reported 11,000 tons of recovered plastics, or a 37% increase in collection rate (Stockholm Exergi, 2022). With such improvement, additional MRFs are being constructed (SWM, 2019). Although financially challenging to implement, this combination of nearby separate collection system and advanced mechanical sorting of the mixed MSW displays a potential for substantially increasing the current collection rates of plastic packaging (Stockholm Exergi, 2022; SWM, 2019). However, reaching a situation where virtually all plastic packaging waste is distributed to material recycling is a challenging endeavor to both improve the conditions and practices of separate collection systems and the efficiency of subsequent sorting and recycling processes.

This study also shows that about 30% of plastic packaging in mixed MSW is not well-recyclable in existing material recycling processes. This pertains to plastic packaging design, such as black plastics and multi-layer characteristics. Hence, redirecting such not-well-recyclable plastic to material recycling would not make sense at present as it would nevertheless end up as a residual flow bound for incineration or as impurities in monopolymer targets. Similar to the separate collection of plastic packaging, design policies to phase out black plastics and stimulate the use of monopolymers are needed to increase the recyclability of plastic packaging in mixed MSW. In Sweden, the development of such design policies is included in the extended producer responsibility that recently introduced eco-modulation of fees for plastic packaging placed in the market (SEPA, 2022a). The objective of differentiated fees is to account for the actual recycling costs thereby encouraging producers to opt for packaging designs and polymers that are easily recyclable by current technologies. Certain attributes have been identified as factors motivating higher fees. These include black plastic, which poses challenges for optical sorting. Additionally, packaging with multi-layers of different polymers or composite materials also incurs higher costs. Although these measures incentivize both producers and consumers to choose packaging designs that facilitate efficient recycling, their overall effect on the plastic packaging waste flow is yet to be evaluated.

Two important aspects of recycling that are not dealt with in this study are the market demand and quality of recycled plastics (Eriksen et al., 2019; Schmidt and Laner, 2021). Market demand plays an important role in ensuring that recycled plastics are transformed into new, valuable products. On the one hand, the absence of market demand essentially leads to another residue generation as there is no outlet for recycled plastics. On the other hand, excess production of recycled plastics beyond the market demand leads to similar results. The latter is observed for recycled PET following the EU Directive 2019/904 on single-use plastics, targeting the incorporation of recycled plastic in PET beverage bottles at 25% and 30% from 2025 to 2030, respectively (EC, 2019b).

In terms of quality that is based on legislation, food-grade plastics can be limited to non-food applications after recycling (Eriksen and Astrup, 2019; Erselius, 2021; Schmidt and Laner, 2021). This follows the EU Directive 1616/2022, which states that only separately collected food-grade plastics that are not mechanically sorted can be recycled for food applications (EC, 2022). However, the European Food Safety Authority allows a limited share of non-food packaging as input for recycling food-grade packaging. A limit of 5% is set for PET, while much lower limits are implied for PE and PP (Franz and Welle, 2022). Nevertheless, separate collection of such packaging is a necessity, and it can be done either through an additional recycling bin or through inclusion in the deposit-return system, which currently only includes PET bottles. The latest developments in marker-based sorting can also be used in this regard to separate packaging based on food or non-food applications (Larder and Hatton, 2023). Such an extended collection portfolio intended for plastic packaging can increase both the quantity and quality of fractions entering the recycling facilities (Feil et al., 2017; Roosen et al., 2022). Based on the detailed characterization in this study, more than half of the incorrectly sorted plastic packing in mixed MSW constitutes food-grade applications that potentially can be dealt with by such structural changes to the current separate collection system. Maintaining the value of food-grade packaging through close-loop recycling can lead to better substitution of primary plastics that undergo strict and tedious manufacturing processes.

4.2. The role of extended waste characterization in managing mixed MSW

Waste characterization is an established tool for municipalities and other entities monitoring household waste composition within their geographical areas (Bisinella et al., 2017; SWM, 2019). In Sweden, the guidance for waste characterization has evolved over the last decades. It has progressed from method descriptions in individual studies (Dahlén et al., 2007; Dahlén and Lagerkvist, 2008) to a comprehensive manual provided by Swedish Waste Management (Rousta et al., 2016; SWM, 2020). The results of annual waste characterizations also contribute to national waste statistics in Sweden. While these studies offer insights into the overall material composition of household waste, they are insufficient for developing strategies to improve the resource-efficiency of specific material flows, such as plastic packaging.

As exemplified in this study, an extended waste characterization of plastic packaging contributed to determining the potential material resources that currently occur in the mixed MSW bound for incineration. In particular, the increased knowledge about the material characteristics of this plastic packaging facilitated the identification of tangible measures and strategies to increase the material recycling rate. The extended waste characterization also provided a quantified understanding of the recycling potential of the plastic packaging in mixed MSW, enabling comparisons among different strategies and measures in terms of their potential impact on the recycling rate.

It is acknowledged that variation in material characteristics can occur considering different sampling conditions, but it is the type of information gathered through extended characterization that is highlighted in this study. When it comes to the transition to a circular economy, a comprehensive understanding of the material characteristics of plastic packaging found in various waste flows will be essential for developing administrative and economic measures that stimulate circulation with a high retained resource utility of plastic packaging. For example, the effectiveness of the extended producer responsibility involving eco-modulation of fees based on packaging design needs to be monitored and evaluated. That is, creating a form of feedback loop to assess the extent to which such differentiated fees are reflected in the composition of plastic packaging across various waste and recycling streams. Conducting detailed waste characterization studies of plastic packaging in both mixed MSW and separate collection could provide valuable insights into the effectiveness of such design policies in terms of improved sorting and recycling. For instance, whether the packaging designed for enhanced recycling is more consistently and correctly recycled than others can be monitored.

Given its importance, future work on extended waste characterization should consider method improvements. While the characterization of manually separable items, such as caps, provides information on the polymer composition of the sample, it is also essential to account for their fate in the sorting and recycling facilities to present a more comprehensive picture of the flows of multi-layer packaging (Eriksen and Astrup, 2019). In this study, caps (4% of the sample, dry-weight basis) were separated from the main packaging, introducing imprecise input/output in the sorting process. While the flows can be corrected in which caps are sorted together with the main packaging, a similar recycling rate is expected, as caps are also captured in the subsequent recycling process. Moreover, the visual approach used to assess the material characteristics in this study presents challenges in terms of time requirements and uncertainties related to unlabeled plastic packaging (Larder and Hatton, 2023). It was also assumed that there is only a negligible error on polymer labels. Such uncertainties can partly be overcome by consistent characterization procedures and expertise in plastic packaging. However, additional methods for material characterization are recommended such as FTIR spectroscopy used by Eriksen and Astrup (2019) for rigid plastic packaging from separate collection, and by Roosen et al. (2020) for sorted plastic fraction from MRF. Moreover, advancements in enhanced package labeling, such as photoluminescent markers under UV–vis, IR, and X-ray or even digital labels can further improve the accuracy of characterization for better sorting in the future (Larder and Hatton, 2023). Digital labeling is the future of extended characterization following the proposed digital product passports in the EU (EC, 2023). It aims to improve sustainability and circularity by improving data access on material characteristics and other information along the life cycle. However, it is still in its infancy, and a long timeline is foreseen before its broad implementation.

5. Conclusions

This study demonstrates the usefulness of extended waste characterization for identifying and evaluating measures for increased circularity and resource-efficiency. By applying this method on plastic packaging in mixed MSW, the detailed material characteristics influencing the recycling potential of this currently misplaced material flow were determined. Our findings reveal that 53% of the plastic packaging in mixed MSW in the case city can be recycled when successfully diverted from energy to material recycling. This translates to an additional 28% improvement from the current 31% recycling rate, thus fulfilling the EU target of 55% by 2030 adopted at a city level. Although limited to a case, the selected city is a common case in Sweden with more than half of plastic packaging is disposed of in mixed MSW, and that annual characterization of mixed MSW is performed. In this regard, improvement measures elicited in this study also apply to other cities to achieve the recycling targets on the national level.

The identified measures needed to further increase recyclability are similar to the ones suggested for separately collected plastic packaging. We thereby confirm the need for orchestrated measures in terms of improved design for recycling, well-functioning separate collection system, and more efficient sorting and recycling processes. Furthermore, our findings underline the importance of correct household separation practices combined with the establishment of MRFs for mixed MSW to ensure high collection rates for material recycling. Without these measures, it will be impossible to meet the new recycling targets set by the EU, irrespective of any upstream or downstream measures. While findings from extended waste characterization serve well as a basis for identifying such potential improvement measures, we suggest that it should also be employed more frequently to monitor the effects of already implemented circular economy measures. For future implementation during cities' annual waste characterization, the use of FTIR is recommended for better identification of polymer types, instead of visual packaging labels. Future studies should expand beyond plastic packaging to cover other potentially recyclable materials in mixed MSW. This will provide a more comprehensive understanding and approach towards circularity and resource efficiency. Additionally, investigating the quality and quantity of materials re-entering the market is essential to assess the true extent of recycling, which currently falls outside the EU's definition of recycling rate.

CRediT authorship contribution statement

John Laurence Esguerra: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Annica Carlsson:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joakim Johansson:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Stefan Anderberg:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data used in this article are accessible in the Supplementary Material.

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Appendix A. Supplementary data

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References

Antonopoulos, I., Faraca, G., Tonini, D., 2021. Recycling of post-consumer plastic packaging waste in EU: process efficiencies, material flows, and barriers. Waste Manag. 126, 694–705. https://doi.org/10.1016/j.wasman.2021.04.002.

Arduin, R.H., Grimaud, G., Martínez Leal, J., Pompidou, S., Charbuillet, C., Laratte, B., Alix, T., Perry, N., 2019. Influence of scope definition in recycling rate calculation for European e-waste extended producer responsibility. Waste Manag. 84, 256–268. https://doi.org/10.1016/j.wasman.2018.12.002.

Bauer, A.S., Tacker, M., Uysal-Unalan, I., Cruz, R.M.S., Varzakas, T., Krauter, V., 2021. Recyclability and redesign challenges in multilayer flexible food packaging—a review. Foods 10. https://doi.org/10.3390/foods10112702.

Becker, W., Sachsenheimer, K., Klemenz, M., 2017. Detection of black plastics in the middle infrared spectrum (MIR) using photon up-conversion technique for polymer recycling purposes, 2017 Polym 9. https://doi.org/10.3390/POLYM9090435. Page 435 9, 435.

Berglund, C., Söderholm, P., Hage, O., 2022. Recycling, norms, and convenience: a bivariate probit analysis of household data from a Swedish city. Front Sustain Cities 4, 875811. https://doi.org/10.3389/FRSC.2022.875811/BIBTEX.

Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T.H., Astrup, T.F., 2017. Importance of waste composition for Life Cycle Assessment of waste management solutions. J. Clean. Prod. 164, 1180–1191. https://doi.org/10.1016/j.jclepro.2017.07.013.

Blasenbauer, D., Lipp, A.-M., Fellner, J., Tischberger-Aldrian, A., Stipanović, H., Lederer, J., 2024. Recovery of plastic packaging from mixed municipal solid waste. A case study from Austria. Waste Manag. 180, 9–22. https://doi.org/10.1016/j.wasman.2024.02.040.

Briassoulis, D., Hiskakis, M., Babou, E., 2013. Technical specifications for mechanical recycling of agricultural plastic waste. Waste Manag. 33, 1516–1530. https://doi.org/10.1016/J.WASMAN.2013.03.004.

Brouwer, M.T., Thoden van Velzen, E.U., Augustinus, A., Soethoudt, H., De Meester, S., Ragaert, K., 2018. Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. Waste Manag. 71, 62–85. https://doi.org/10.1016/J.WASMAN.2017.10.034.

Brouwer, M., Picuno, C., Thoden van Velzen, E.U., Kuchta, K., De Meester, S., Ragaert, K., 2019. The impact of collection portfolio expansion on key performance indicators of the Dutch recycling system for Post-Consumer Plastic Packaging Waste, a comparison between 2014 and 2017. Waste Manag. 100, 112–121. https://doi.org/10.1016/j.wasman.2019.09.012.

Brouwer, M.T., van Velzen, E.U.T., Ragaert, K., Klooster, R. Ten, 2020. Technical limits in circularity for plastic packages. Sustain. Times 12, 1–29. https://doi.org/10.3390/su122310021.

Brunner, S., Fomin, P., Kargel, C., 2015. Automated sorting of polymer flakes: fluorescence labeling and development of a measurement system prototype. Waste Manag. 38, 49–60. https://doi.org/10.1016/J.WASMAN.2014.12.006.

Brunner, P.H., Rechberger, H., 2016. Handbook of Material Flow Analysis: for Environmental, Resource, and Waste Engineers. CRC Press - Taylor & Francis Group, Boca Raton London New York.

Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN. J Environ Eng Manag 18, 3–7.

Cimpan, C., Maul, A., Jansen, M., Pretz, T., Wenzel, H., 2015. Central sorting and recovery of MSW recyclable materials: a review of technological state-of-the-art, cases, practice and implications for materials recycling. J. Environ. Manag. 156, 181–199. https://doi.org/10.1016/J.JENVMAN.2015.03.025.

Chen, Y., Awasthi, A.K., Wei, F., Tan, Q., Li, J., 2021. Single-use plastics: production, usage, disposal, and adverse impacts. Sci. Total Environ. 752, 141772 https://doi.org/10.1016/j.scitotenv.2020.141772.

Dahlén, L., Vukicevic, S., Meijer, J.E., Lagerkvist, A., 2007. Comparison of different collection systems for sorted household waste in Sweden. Waste Manag. 27 (10), 1298–1305. https://doi.org/10.1016/j.wasman.2006.06.016.

Dahlén, L., Lagerkvist, A., 2008. Methods for household waste composition studies. Waste Manag. 28 (7), 1100–1112. https://doi.org/10.1016/j.wasman.2007.08.014.

Dahlbo, H., Poliakova, V., Mylläri, V., Sahimaa, O., Anderson, R., 2018. Recycling potential of post-consumer plastic packaging waste in Finland. Waste Manag. 71, 52–61. https://doi.org/10.1016/J.WASMAN.2017.10.033.

Ding, Q., Zhu, H., 2023. The key to solving plastic packaging wastes: design for recycling and recycling technology. Polymers (Basel), p. 15. https://doi.org/10.3390/polym15061485.

EASAC, 2020. Packaging plastics in the circular economy. https://easac.eu/fileadmin/PDF_s/reports_statements/Plastics/EASAC_Plastics_Web_complete_6May2020_FINAL.pdf. (Accessed 26 May 2023).

EC, 2018. European commission (EC) directive (EU) 2018/852 of the European parliament and of the council of 30 may 2018 amending directive 94/62/EC on packaging and packaging waste. https://eur-lex.europa.eu/eli/dir/2018/852/oj. (Accessed 26 May 2023).

EC, 2019a. Commission implementing decision (EU) 2019/665 of 17 April 2019 amending Decision 2005/270/EC establishing the formats relating to the database system pursuant to European Parliament and Council Directive 94/62/EC on packaging and packaging waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32019D0665. (Accessed 26 May 2023).

EC, 2019b. European Commission (EC) Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0904, 26.012.23.

EC, 2020. Communication from the commission to the European parliament, the council, the economic and social committee and the committee of the regions — a new circular economy action plan for a cleaner and more competitive Europe. COM (2020) 98 final of 11 March 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0098. (Accessed 5 June 2023).

EC, 2022. Regulation (EU) 2022/1616 of 15 September 2022 on recycled plastic materials and articles intended to come into contact with foods, and repealing Regulation (EC) No 282/2008. ENG. https://eur-lex.europa.eu/legal-content/SV/ALL/?uri=uriserv:OJ.L_.2022.243.01.0003.01. (Accessed 5 June 2023).

EC, 2023. Digital product passport. Call for Proposals. https://hadea.ec.europa.eu/calls-proposals/digital-product-passport_en#description, 12.20.23.

Edjabou, M.E., Jensen, M.B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C., Astrup, T.F., 2015. Municipal solid waste composition: sampling methodology, statistical analyses, and case study evaluation. Waste Manag. 36, 12–23. https://doi.org/10.1016/J.WASMAN.2014.11.009.

Edjabou, M.E., Takou, V., Boldrin, A., Petersen, C., Fruergaard Astrup, T., 2021. The influence of recycling schemes on the composition and generation of municipal solid waste. J. Clean. Prod. 295, 126439 https://doi.org/10.1016/j.jclepro.2021.126439.

Eriksen, M.K., Astrup, T.F., 2019. Characterisation of source-separated, rigid plastic waste and evaluation of recycling initiatives: effects of product design and source-separation system. Waste Manag. 87, 161–172. https://doi.org/10.1016/j.wasman.2019.02.006.

Eriksen, M.K., Damgaard, A., Boldrin, A., Astrup, T.F., 2019. Quality assessment and circularity potential of recovery systems for household plastic waste. J. Ind. Ecol. 23, 156–168. https://doi.org/10.1111/jiec.12822.

Erselius, G., 2021. The climate impact of residual waste: a compilation of calculation data for Stockholm Exergy. In: Swedish "Restavfallets Klimatpåverkan: En Sammanställning Av Beräkningsunderlag för Stockholm Exergi. https://www.stockholmexergi.se/content/uploads/2021/07/Rapport-Avfallets-klimatp%C3%A5verkan-2021.pdf. (Accessed 4 July 2022).

Eurostat, 2023. Packaging Waste by Waste Management Operations. https://ec.europa.eu/eurostat/web/waste/data/database. (Accessed 18 October 2023).

Faraca, G., Edjabou, V.M., Boldrin, A., Astrup, T., 2019. Combustible waste collected at Danish recycling centres: characterisation, recycling potentials and contribution to environmental savings. Waste Manag. 89, 354–365. https://doi.org/10.1016/J.WASMAN.2019.04.007.

Feil, A., Pretz, T., Jansen, M., Thoden Van Velzen, E.U., 2017. Separate collection of plastic waste, better than technical sorting from municipal solid waste? Waste Manag. Res. 35, 172–180. https://doi.org/10.1177/0734242X16654978.

Feil, A., Pretz, T., 2020. Chapter 11 - mechanical recycling of packaging waste. In: Trevor, M. (Ed.), Letcher, Plastic Waste and Recycling. Academic Press, pp. 283–319. https://doi.org/10.1016/B978-0-12-817880-5.00011-6. Editor(s).

Franz, R., Welle, F., 2022. Recycling of post-consumer packaging materials into new food packaging applications—critical review of the European approach and future perspectives. Sustain. Times 14. https://doi.org/10.3390/su14020824.

Fråne, A., Schmidt, L., Sjöström, J., Vukicevic, S. och Tapper M., 2015. Knowledge base for increased source sorting of plastic packaging. In: Swedish "Kunskapsunderlag För Ökad Källsortering Av Plastförpackningar. RAPPORT NR B 2247. https://www.ivl.se/download/18.34244ba71728fcb3f3f8b5/1591705067246/B2247.pdf. (Accessed 26 May 2023).

FTI, 2022. Swedish packaging and newspaper collector. Statistics. https://fti.se/en/about-fti/statistics#recycling-rate, 4.13.22.

FTI, 2023. Swedish Packaging and Newspaper Collector. Curbside collection. https://fti.se/en/property-owners/curbside-collection, 10.15.23.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, 25–29. https://doi.org/10.1126/sciadv.1700782.

Goh, E., Esfandiar, K., Jie, F., Brown, K., Djajadikerta, H., 2022. Please sort out your rubbish! An integrated structural model approach to examine antecedents of residential households' waste separation behaviour. J. Clean. Prod. 355, 131789 https://doi.org/10.1016/J.JCLEPRO.2022.131789.

Hage, O., Sandberg, K., Söderholm, P., Berglund, C., 2018. The regional heterogeneity of household recycling: a spatial-econometric analysis of Swedish plastic packing waste. Lett Spat Resour Sci 11, 245–267. https://doi.org/10.1007/S12076-017-0200-3/TABLES/4.

Hahladakis, J.N., Velis, C.A., Weber, R., Iacovidou, E., Purnell, P., 2018. An overview of chemical additives present in plastics: migration, release, fate and environmental impact during their use, disposal and recycling. J. Hazard Mater. 344, 179–199. https://doi.org/10.1016/J.JHAZMAT.2017.10.014.

IVA, 2020. Royal Swedish Academy of Engineering Sciences (IVA). Resource-effective and circular plastics flows – the role of Plastic in a circular society. https://issuu.com/iva-publikationer/docs/202002-iva-rece-branschrapport-plast-english-b/1. (Accessed 4 July 2022).

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (80), 768–771. https://doi.org/10.1126/science.1260352.

Kawecki, D., Scheeder, P.R.W., Nowack, B., 2018. Probabilistic material flow analysis of seven commodity plastics in Europe. Environ. Sci. Technol. 52, 9874–9888. https://doi.org/10.1021/ACS.EST.8B01513/SUPPL_FILE/ES8B01513_SI_003.XLSX.

Knickmeyer, D., 2020. Social factors influencing household waste separation: a literature review on good practices to improve the recycling performance of urban areas. J. Clean. Prod. 245, 118605 https://doi.org/10.1016/J.JCLEPRO.2019.118605.

Lange, J.P., 2021. Managing plastic waste-sorting, recycling, disposal, and product redesign. ACS Sustain. Chem. Eng. 9, 15722–15738. https://doi.org/10.1021/acssuschemeng.1c05013.

Larder, R.R., Hatton, F.L., 2023. Enabling the polymer circular economy: innovations in photoluminescent labeling of plastic waste for enhanced sorting. ACS Polym Au 3, 182–201. https://doi.org/10.1021/acspolymersau.2c00040.

Li, Z., Zhang, T., Sun, Y., Zheng, L., Zhou, H., Wang, H., Chen, T., Yan, J., 2022. Identifying the key policy drivers for behavioral improvement in waste source separation in the Yangtze Delta Region, China. J. Clean. Prod. 351, 131379 https://doi.org/10.1016/j.jclepro.2022.131379.

MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373, 61–65. https://doi.org/10.1126/science.abg5433.

Möllnitz, S., Khodier, K., Pomberger, R., Sarc, R., 2020. Grain size dependent distribution of different plastic types in coarse shredded mixed commercial and municipal waste. Waste Manag. 103, 388–398. https://doi.org/10.1016/j.wasman.2019.12.037.

Nielsen, T.D., Hasselbalch, J., Holmberg, K., Stripple, J., 2020. Politics and the plastic crisis: a review throughout the plastic life cycle. Wiley Interdiscip Rev Energy Environ 9, 1–18. https://doi.org/10.1002/wene.360.

Nordtest, 1995. Municipal Solid Waste: Sampling and Characterization (NT ENVIR 001), Nordtest Method. Finland, Espoo.

Picuno, C., Alassali, A., Chong, Z.K., Kuchta, K., 2021a. Flows of post-consumer plastic packaging in Germany: an MFA-aided case study. Resour. Conserv. Recycl. 169, 105515 https://doi.org/10.1016/J.RESCONREC.2021.105515.

Picuno, C., Van Eygen, E., Brouwer, M.T., Kuchta, K., van Velzen, E.U.T., 2021b. Factors shaping the recycling systems for plastic packaging waste—a comparison between Austria, Germany and The Netherlands. Sustain. Times 2021. https://doi.org/10.3390/SU13126772, 13, Page 6772 13, 6772.

Plastics Europe, 2023. Plastics - the fast facts 2023. https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/. (Accessed 4 December 2023).

Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Manag. 69, 24–58. https://doi.org/10.1016/J.WASMAN.2017.07.044.

Rigamonti, L., Grosso, M., Møller, J., Martinez Sanchez, V., Magnani, S., Christensen, T.H., 2014. Environmental evaluation of plastic waste management scenarios. Resour. Conserv. Recycl. 85, 42–53. https://doi.org/10.1016/J.RESCONREC.2013.12.012.

Roosen, M., Mys, N., Kleinhans, K., Lase, I.S., Huysveld, S., Brouwer, M., Thoden van Velzen, E.U., Van Geem, K.M., Dewulf, J., Ragaert, K., Dumoulin, A., de Meester, S., 2022. Expanding the collection portfolio of plastic packaging: impact on quantity and quality of sorted plastic waste fractions. Resour. Conserv. Recycl. 178, 106025 https://doi.org/10.1016/J.RESCONREC.2021.106025.

Roosen, M., Mys, N., Kusenberg, M., Billen, P., Dumoulin, A., Dewulf, J., Van Geem, K.M., Ragaert, K., De Meester, S., 2020. Detailed analysis of the composition of selected plastic packaging waste products and its implications for mechanical and thermochemical recycling. Environ. Sci. Technol. 54, 13282–13293. https://doi.org/10.1021/acs.est.0c03371.

Rousta, K., Ekström, K.M., 2013. Assessing incorrect household waste sorting in a medium-sized Swedish city. Sustain. Times 5 (4349–4361 5), 4349–4361. https://doi.org/10.3390/SU5104349, 2013.

Rousta, K., Bolton, K., Dahlén, L., 2016. A procedure to transform recycling behavior for source separation of household waste. Recycling 1, 147–165. https://doi.org/10.3390/recycling1010147.

Rozenstein, O., Puckrin, E., Adamowski, J., 2017. Development of a new approach based on midwave infrared spectroscopy for post-consumer black plastic waste sorting in the recycling industry. Waste Manag. 68, 38–44. https://doi.org/10.1016/J.WASMAN.2017.07.023.

Sahimaa, O., Hupponen, M., Horttanainen, M., Sorvari, J., 2015. Method for residual household waste composition studies. Waste Manag. 46, 3–14. https://doi.org/10.1016/J.WASMAN.2015.08.032.

Schmidt, S., Laner, D., 2021. The multidimensional effects of single-use and packaging plastic strategies on German household waste management. Waste Manag. 131, 187–200. https://doi.org/10.1016/J.WASMAN.2021.06.003.

SEPA, 2022a. NFS 2022:11 the Swedish Environmental Protection Agency's (SEPA) regulations on determining packaging fees with regard to material recyclability. In: Swedish "Naturvårdsverkets Föreskrifter Om Bestämmande Av Förpackningsavgifter Med Hänsyn till Materialåtervinningsbarhet. https://www.naturvardsverket.se/4afd50/globalassets/nfs/2022/nfs-2022-11.pdf. (Accessed 26 May 2023).

SEPA, 2022b. Sweden's recycling of packaging. In: Swedish "Sveriges Återvinning Av Förpackningar. https://www.naturvardsverket.se/4aaa7a/contentassets/568ba7678ce94e25b99cfc1b02ad7e2a/sveriges-atervinning-av-forpackningar-2021.pdf. (Accessed 30 November 2023).

SME, 2005. Swedish Ministry of the Environment (SME) SFS 2005:220 Ordinance on the return system for plastic bottles and metal cans. In: English "Förordning Om Retursystem För Plastflaskor Och Metallburkar. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-2005220-om-retursystem-for_sfs-2005-220, 1.12.22.

SME, 2020. SFS 2020:614 Waste ordinance. In: Swedish "Avfallsförordning. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/avfallsforordning-2020614_sfs-2020-614. (Accessed 1 December 2020).

Statistics Sweden, 2022. Waste, packaging. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/waste/waste-packaging/, 1.12.23.

Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D.P., Junginger, M., 2022. Plastic futures and their CO2 emissions. Nature 612, 272–276. https://doi.org/10.1038/s41586-022-05422-5.

SWM, 2019. Swedish Waste Management (SWM) Fuel quality - current situation and scenarios for the composition of residual waste by the year 2025. In: Swedish "Bränslekvalitet – Nuläge Och Scenarier För Sammansättningen Av Restavfall till År 2025. https://www.avfallsverige.se/kunskapsbanken/rapporter/rapportera/article/branslekvalitet-nulage-och-scenarier-for-sammansattningen-av-restavfall-till-ar-2025/, 4.13.22.

SWM, 2020. Manual for picking analysis of household food and residual waste. In: Swedish "Manual För Plockanalys Av Hushållens Mat- Och restavfall." Report 2017: 31 Revised in 2020. https://www.avfallsverige.se/rapporter-utveckling/rapporter/2017-31-manual-for-plockanalys-av-hushallens-mat-och-restavfall/. (Accessed 13 February 2023).

Turner, A., 2018. Black plastics: linear and circular economies, hazardous additives and marine pollution. Environ. Int. 117, 308–318. https://doi.org/10.1016/J.ENVINT.2018.04.036.

UNEP, 2022. Historic day in the campaign to beat plastic pollution: nations commit to develop a legally binding agreement. United Nations Environ Program [WWW Document]. https://www.unep.org/news-and-stories/press-release/historic-day-campaign-beat-plastic-pollution-nations-commit-develop. (Accessed 4 November 2022).

Yin, R., 2017. Case Study Research and Applications: Design and Methods. SAGE Publications Inc., pp. 49–50

Stockholm Exergi, 2022. Brista post-sorting facility. In: Swedish "Brista Eftersorteringsanläggning. https://www.stockholmexergi.se/om-stockholm-exergi/bristasorteringsanlaggning/. (Accessed 1 December 2022).