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DISSERTATION

Packaging Waste Management and its Recycling Potential in Vienna: Historical Developments, Current Challenges and Future Opportunities

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Vienna, February 2025

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such. I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Vienna, February 2025

Lea Gritsch

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Abstract

To meet EU recycling targets for packaging waste, it is crucial to collect sufficient quantities of packaging in appropriate quality. While separate collection has proven effective, densely populated urban areas face challenges in this regard. This thesis investigates packaging waste management in Vienna, using it as a case study to explore these challenges and potential solutions. A time series of packaging waste flows from 2006 to 2020 was created using Material Flow Analysis to assess the impact of past waste management measures on quantities, separate collection rates, and sorting rates. Additionally, a detailed characterization of non-beverage plastic bottles and paper-based packaging in mixed municipal solid waste and separate collection was conducted through manual sorting analysis to evaluate critical packaging properties for recovery and recycling, including residues and dirt, and to identify untapped potential for separate collection.

The results show that packaging waste flows increased for materials such as glass, paper and aluminum, while the generation of plastics such as PET and HDPE and ferrous packaging decreased. The study also found a wide range of separate collection rates, from 14% for aluminum packaging, to 19% for non-beverage plastic bottles, 21% for paper packaging, 55% for glass packaging and 80% for corrugated board, indicating that a significant amount of certain packaging waste is lost to mixed municipal solid waste and not yet recycled. However, the results also show that key measures such as the commingled collection of plastic bottles, beverage cartons and metals or the automatic sorting of mixed municipal solid waste and incineration bottom ashes can significantly improve the supply of secondary raw materials, especially for metals.

The research highlights how packaging design significantly affects separate collection rates and calls for reducing packaging variety to improve collection efficiency. It also emphasizes the importance of effective communication and knowledge transfer to simplify waste separation for consumers. The study further uncovers that residues and dirt in packaging waste contribute substantially to the gross mass of waste, affecting material flow data and recycling efficiency. Therefore, improved packaging design to facilitate complete emptying and increased consumer awareness about product waste reduction are recommended. Further research into the behavior of packaging waste during processing and large-scale sorting tests is also suggested to refine recycling strategies.

In conclusion, a holistic approach -including simplified packaging designs, enhanced consumer education, and optimized collection systems- is needed to improve secondary raw material provision and meet recycling targets in urban areas.

Kurzfassung

Um die Recyclingziele der EU für Verpackungsabfälle zu erreichen, müssen Verpackungen in ausreichender Menge und Qualität gesammelt werden. Während dafür die getrennte Sammlung grundsätzlich ein etabliertes System ist, stellt sie in dicht besiedelten städtischen Gebieten eine Herausforderung dar. Die vorliegende Arbeit untersucht daher die Schwierigkeiten und potenzielle Lösungen des Abfallwirtschaftssystems für Verpackungsabfälle anhand der Fallstudie Wien. Mittels Materialflussanalyse wurde eine Zeitreihe der Verpackungsabfallströme von 2006 bis 2020 erstellt, um die Auswirkungen abfallwirtschaftlicher Maßnahmen auf Mengen, Erfassungsgrad und Sortierrate darstellen und analysieren zu können. Zusätzlich wurde zur Qualitätsbewertung eine detaillierte Charakterisierung von Kunststoffflaschen und papierbasierten Verpackungen im Restmüll und in der getrennten Sammlung mittels manueller Sortieranalyse durchgeführt. Dabei wurden verwertungs- und recyclingrelevante Verpackungseigenschaften einschließlich Produktresten und Verunreinigungen untersucht und daraus ungenutzte Potenziale für die getrennte Sammlung ermittelt. Die Fallstudie zeigt, dass die Verpackungsabfallströme bei Glas, Papier und Aluminium zugenommen haben, während das Aufkommen an Verpackungen aus Kunststoffen wie PET und HDPE sowie aus Eisen zurückgegangen ist. Die Ergebnisse zeigen außerdem eine große Bandbreite an Erfassungsgraden, von 14% für Aluminiumverpackungen, über 19% für Kunststoffflaschen, 21% für Papier-, 55% für Glas- und 80% für Wellpappeverpackungen, was verdeutlicht, dass teilweise erhebliche Anteile an Verpackungen im Restmüll landen und derzeit für das Recycling verloren geht. Die Ergebnisse zeigen aber auch, dass bestimmte Maßnahmen wie die gemischte Sammlung von Kunststoffflaschen, Getränkekartons und Metallen oder die automatisierte Sortierung von Restmüll und Müllverbrennungsaschen die Bereitstellung von Sekundärrohstoffen aus Verpackungen deutlich verbessern können. Die Arbeit zeigt, dass das Verpackungsdesign einen großen Einfluss auf den Erfassungsgrad hat, weshalb eine Reduzierung der Verpackungsvielfalt notwendig wäre, um die getrennte Sammlung für die Konsument:innen einfacher und somit effizienter zu gestalten. Dazu sind auch eine effektive Kommunikation und Wissensvermittlung von Bedeutung. Darüber hinaus wurde festgestellt, dass Produktreste und Verunreinigungen erheblich zur Bruttomasse von Verpackungsabfällen beitragen können, was bei abfallwirtschaftlichen Berechnungen berücksichtigt werden muss. Daher werden einerseits eine verbesserte Restentleerbarkeit von Verpackungen, und andererseits eine verstärkte Sensibilisierung der Konsument:innen für Produktverschwendung empfohlen. Ergänzend sollten Großversuche zur Sammlung und automatisierten Sortierung von Verpackungsabfällen durchgeführt werden. Zusammenfassend lässt sich sagen, dass ein ganzheitlicher Ansatz - einschließlich verbesserten Verpackungsdesigns, verstärkter Konsument:innenaufklärung und optimierter Sammelsysteme - erforderlich sind, um die Bereitstellung von Sekundärrohstoffen in städtischen Gebieten zu verbessern und die Recyclingziele zu erreichen.

Contents

List of abbreviations

Al-BP	aluminum beverage packaging
Al-OP	aluminum other packaging
Al-P	aluminum packaging
BC	beverage carton
Fe-P	ferrous packaging
G-P	glass packaging
HDPE	high-density polyethylene
IBA	incineration bottom ash
LPW	lightweight packaging waste
MC	moisture content
MSW	municipal solid waste
PCCC-P	paper/cardboard/corrugated cardboard packaging
PET	polyethylenetherephthalate
PP	polypropylene
RDC	residues and dirt content
SCR	separate collection rate
SRM	secondary raw material

List of figures

Published articles and contributions

This doctoral thesis is based on three peer-reviewed journal articles, published in high quality journals, which can be found in the appendix of this thesis.

Paper I

Gritsch, L., Lederer, J., 2023. A historical-technical analysis of packaging waste flows in Vienna. *Resources, Conservation and Recycling* 194, 106975. https://doi.org/10.1016/j.resconrec.2023.106975.

Contribution: Data curation, Formal analysis, Methodology, Investigation, Visualization, Literature research, Writing – original draft.

Paper II

Gritsch, L., Breslmayer, G., Rainer, R., Stipanovic, H., Tischberger-Aldrian, A., Lederer, J., 2024. Critical properties of plastic packaging waste for recycling: A case study on non-beverage plastic bottles in an urban MSW system in Austria. *Waste management* (New York, N.Y.) 185, 10–24. https://doi.org/10.1016/j.wasman.2024.05.035.

Contribution: Conceptualization, Methodology, Investigation, Data curation, Visualization, Literature research, Writing – original draft.

Paper III

Gritsch, L., Breslmayer, G., Lederer, J., 2025. Quantity and quality of paper-based packaging in mixed MSW and separate paper collection – a case study from Vienna, Austria. *Resources, Conservation and Recycling* 215, 108091. https://doi.org/10.1016/j.resconrec.2024.108091.

Contribution: Conceptualization, Methodology, Investigation, Data curation, Visualization, Literature research, Writing – original draft.

1 Introduction

1.1 Packaging and packaging waste

Packaging tends to be perceived negatively by the general public as a 'necessary evil' and is often directly associated with waste (Robertson, 2012). People often do not realise that it is an essential part of today's economy and fulfils important functions, which can be summarized as containment, protection, communication and convenience (Emblem, 2012a). First of all, packaging represents a 'containment', a container for the proper transport and storage of goods. The second, and perhaps most important, function of packaging is protection. It protects the product from adverse external influences such as light, oxygen, micro-organisms or shocks, thus preserving the integrity of the product and preventing spoilage. The protective function of packaging is therefore essential for the shelf life of products (Emblem, 2012a). In most cases, the environmental impact of the packaging is significantly lower than that of the product (Emblem, 2012b; Robertson, 2012). Packaging therefore plays a very important role, especially in terms of preventing food loss and waste (Wohner et al., 2019a). Packaging also provides important information, including barcodes, filling volume, ingredients and other legally required information, as well as voluntary information such as preparation instructions or health claims (Emblem, 2012a). In addition, the packaging acts as a 'silent salesman' (Emblem, 2012a). Its individual design allows it to stand out from other packaging at the point of sale and contributes significantly to the recognition value of a brand (Clement et al., 2013; Spence, 2016). The fourth essential function of packaging is to make the handling of the product as easy, convenient and safe as possible for the consumer. This can be summarised under the term 'convenience' and covers a wide range of applications. Typical examples include easy-open and easy-close features, pre-portioning, boil-in pouches or carrying handles (Emblem, 2012a).

Despite its necessity and usefulness, packaging is a commodity with a very short life span and a significant environmental impact (EC, 2022a). On the one hand, it has a high raw material demand, with 40% of plastic and 50% of paper being used for packaging and primary raw materials being used predominantly (EC, 2022d; Plastics Europe, 2022). On the other hand, packaging, especially plastic packaging, is responsible for significant environmental pollution (Beaumont et al., 2019; EC, 2022a; Hale et al., 2020); it accounts for about half of marine litter and thus contributes significantly to the formation of microplastics, the potential negative impacts of which are still largely unexplored (EC, 2022a; Hale et al., 2020; Qi et al., 2020). In addition, the volume of packaging in the EU, especially single-use packaging, is constantly increasing. Packaging waste in the EU has increased by more than 20% in the last decade and is projected to increase further (EC, 2022a). There are many reasons for this, both social and socio-demographic. For example, the number of one-person, two-person and elderly households is increasing, which means that smaller packaging sizes are being purchased and packaging consumption is rising (UBA, 2020). Changes in consumer habits are also leading to more out-of-home consumption, on-the-go consumption and ready-to-eat products, delivery services and online retailing, and therefore higher packaging consumption, and additional functions for greater convenience are leading to higher packaging unit weights (UBA, 2020).

Packaging has therefore been identified by the European Commission as one of the areas for action in the first 'EU Action Plan for a Circular Economy' (EC, 2015), which was adopted for the first time in 2015 and aims to implement a sustainable product policy and promote waste prevention. Aspects such as durability, reusability, reparability and recycling should therefore be taken into account at the product development stage. The second 'Circular Economy Action Plan' was adopted in 2020 (EC, 2020). This Action Plan is in turn a key part of the European Green Deal, which aims to pave the way for a climate-neutral, sustainably growing Europe (EC, 2019b). As part of this action plan, (i) the directive on the reduction of the impact of certain plastic products on the environment was adopted (Single-Use Plastics Directive), which is primarily aimed at combating the littering of the (marine) environment by plastic products (EC, 2019c), (ii) the EU Waste Framework Directive has been revised, which inter alia stipulates the separate collection of certain waste streams (bio waste by 2023, textile waste by 2025), defines a recycling target for municipal solid waste (65% by 2035), and also includes a new (output-based) calculation method for recycling rates (EC, 2019a; EPC, 2018), and (iii), the EU Packaging and Packaging Waste Directive has been amended, with the core element of the amendment being the setting of recycling targets for packaging waste in general (70% by 2030) and for individual packaging waste streams in particular (EC, 2018). Accordingly, 30% of wood packaging, 55% of plastic packaging, 75% of glass packaging, 85% of paper packaging, 80% of iron and 60% of aluminum packaging must be recycled by 2030. In 2022, the European Commission then presented a proposal for a corresponding regulation, the Packaging and Packaging Waste Regulation, to replace the directive and make the requirements for packaging and packaging waste more binding for member states (EC, 2022b). The regulation was adopted in December 2024, came into force at the beginning of 2025 and will be binding until mid-2026. The aim of the regulation is to reduce waste, promote the circular economy and increase the safety and sustainability of packaging. Specific requirements include a 15% reduction in packaging waste by 2040 compared to 2018, a reduction in the weight and proportion of empty space in packaging, a mandatory content of recycled material, harmonisation of separate collection and mandatory recyclability of packaging by 2030 (EC, 2022b). Recyclability refers to the entire life cycle of packaging. Accordingly, the basic existence of a disposal and recycling structure is a minimum requirement, as is the technical sortability of packaging and the absence of packaging components and properties that hinder recycling (ZSVR, 2023).

1.2 Separate collection of packaging waste

In order to achieve the required recycling targets, it is essential that sufficient quantities of packaging waste are collected and that it is of sufficient quality to be recycled. Separate collection is a long-established and proven method to achieve this (Cristóbal García et al., 2022). Since its beginnings in the 1970s, it has been the foundation of all modern waste management and thus the main backbone of the circular economy in Europe (Barles, 2014; Tallentire and Steubing, 2020). There are currently different collection systems for packaging waste in the EU (Seyring et al., 2016), depending on what packaging waste is collected ('target fractions'), and how this packaging waste is collected ('service level'). In terms of target fractions, there are single stream collections, where only one material is collection, as is almost always the case for waste paper (Seyring et al., 2016). However, there are also commingled collections of several packaging materials, which has a positive impact on collection yields and is often the case for plastics and metal packaging (Cristóbal García et al., 2022; Seyring et al., 2016; Tallentire and Steubing, 2020). The service level, on the other hand, describes the distance that consumers have to walk until the disposal site. A distinction is made here between collections via (i) the curbside system, also called 'door-to-door' collection (Seyring et al., 2016), with collection containers directly on the property, (ii) collection points, where the collection containers are located within walking distance of the home in public spaces, and (iii) recycling centers, which are large, closed and supervised collection points where many other types of waste can be disposed of (Schuch et al., 2023; Seyring et al., 2016). As far as the collection of packaging waste is concerned, recycling centers exist in addition to the collection systems (i) and (ii) and are not used exclusively (Schuch et al., 2023). Collection points are typical for the separate collection of glass, while waste paper collection is usually organized as curbside-collection (Seyring et al., 2016). Another form of separate packaging collection is the collection of packaging charged with a deposit through reverse vending machines, which is the state of the art for returnable glass bottles (Seyring et al., 2016) and is already established for disposable beverage packaging in some European countries (GS1 in Europe, 2024). This form of separate collection can achieve very high collection rates of well over 90% (GVM, 2022; Martinho et al., 2024).

Different collection systems can exist not only at EU level, but also at national level. In Austria, for example, five different target fractions as well as all three service levels and combinations of these have been implemented for plastic packaging collection until nationwide standardisation in 2023 (BML, 2014; Schuch et al., 2023). An EU-wide simplification of separate collection for consumers through improved communication and information is planned according to the Packaging and Packaging Waste Regulation and is to be achieved through standardised labelling of waste containers and packaging (EC, 2022b).

The success of separate waste collection largely depends on citizen participation, which can vary greatly due to many influencing factors (Barles, 2014). In addition to technical factors (e.g. service level, target fractions, waste charges, design of collection containers, etc.) and socio-demographic factors (e.g. age, education, household size, income, etc.) there are many other factors that can influence separate collection, such as moral norms, habits, knowledge, motivation, information, and environmental awareness (Briguglio, 2016; Cristóbal García et al., 2022; Miafodzyeva and Brandt, 2013; Varotto and Spagnolli, 2017). While the influence of the socio-demographic factors is controversially discussed in the literature, it seems to be confirmed that a convenient, easily accessible infrastructure and simple, understandable information have a positive impact on the success of separate collection of waste (Cristóbal García et al., 2022; Rousta et al., 2017).

However, separate collection depends not only on external conditions but also on the packaging itself and its characteristics, such as material, size, packaging type, decoration, product residues, etc. (Gritsch et al., 2025; Gritsch et al., 2024). For example, waste paper is better collected separately than other packaging materials, as is large and heavy packaging, while soiled packaging tends to be disposed of in mixed MSW (Gritsch et al., 2024; Nemat et al., 2022; Seyring et al., 2016; Thoden van Velzen et al., 2019).

Cities and urban areas play a special role in separate waste collection. They have to deal with more difficult framework conditions than rural areas, such as high population density and limited space reserves in public and private areas, which makes separate collection less successful in terms of the separate collection rates achieved (Miafodzyeva and Brandt, 2013; Rispo et al., 2015; Schuch et al., 2023; Seyring et al., 2015). Therefore, where separate collection reaches its limits, subsequent recovery from mixed MSW or incineration bottom ash (IBA) must also be considered as an option for recovering packaging waste for recycling (Cimpan et al., 2015; Seyring et al., 2016), although, material-dependent quality losses must be accepted, especially for paper and plastics, and less so for metals (Blasenbauer et al., 2024; Lederer et al., 2022; Miranda et al., 2013).

2 Case study description

This work uses Vienna, the capital of Austria, as case study. The following section explains why Vienna was chosen as a case study.

About 2.02 million people live in Vienna, which is about 22% of the Austrian population (Statistik Austria, 2024). As Austria's largest agglomeration, Vienna faces more difficult conditions for separate waste collection, which is reflected in significantly lower collection rates compared to the other federal states and the national average (Schuch et al., 2023). Vienna, for example, produces about 20% of Austria's MSW, but collects only 10% of the recyclables (BMK, 2024).

Compared to other European capitals, however, Vienna performs very well and is among the European leaders (Seyring et al., 2015). One success factor is likely to be the fact that waste management in Vienna is entirely in municipal hands. The city is not only responsible for the disposal of mixed MSW, but as a contractor for the collection and recycling systems also for the collection of packaging waste (Seyring et al., 2015). Mixed MSW and all recyclables (waste paper, lightweight packaging, metals, biowaste, glass) from households are collected via containers, which are emptied into a collection vehicle on site (Huber, 2024). In addition, the city's 13 recycling centers offer the opportunity to dispose of problematic materials, hazardous and bulky waste (Huber, 2024).

The city of Vienna has a very good database on its entire waste management system: strategically important waste treatment facilities are built and operated by the city itself, including waste processing, incineration, composting and biogas plants, and landfills for IBA (Huber, 2024; Seyring et al., 2015). In addition, the city has extensive waste sorting analyses carried out at least every six years, and therefore has comprehensive knowledge of the composition of mixed MSW and collected recyclables. These show that although the amount of mixed MSW per capita has decreased from 310 kg/cp/yr in 2003 to 262 kg/cp/yr in 2022, the general composition of mixed MSW has remained largely the same over the years and still has a high proportion of recyclable materials at around one fifth (Huber, 2024). While metals can be recovered relatively easily and automatically from the IBA of mixed MSW, which is done and can be taken into account when calculating recycling rates (EC, 2019a), this is not the case for plastics and paper. In view of the fact that Vienna has a significant impact on the achievement of national recycling targets, special attention needs to be paid to characterizing and assessing the potential for separate collection and recovery of these two packaging materials prior to incineration.

3 Objectives and thesis structure

Against the background presented in the introduction and the associated problems, this thesis is dedicated to a detailed investigation of packaging waste, especially plastic and paper-based packaging waste, based on the case study of Vienna, with the aim to identify untapped potentials in mixed MSW and separate collection, and to find measures to improve separate collection in order to make more high quality secondary raw material (SRM) available for mechanical recycling. For this purpose, the following research questions were analyzed.

Analysis of packaging waste flows in general:

1) Which measures in separate collection of post-consumer packaging waste and technical sorting of mixed MSW and IBA have been implemented?
2) How have post-consumer packaging waste flows of different materials evolved?
3) What shares of these have been provided as SRM for recycling?
4) What are the future perspectives to increase SRM provision for recycling?

Analysis of specific packaging waste flows, non-beverage plastic bottles:

5) What is the composition of the non-beverage plastic bottles regarding polymer and packaging characteristics?
6) What is the residues and dirt content of the non-beverage plastic bottles, and what factors influence it?
7) Which quantities of non-beverage plastic bottles are generated annually and which share thereof represents a high-quality SRM?
8) What is the separate collection rate of the non-beverage plastic bottles, and what factors influence it?

Analysis of specific packaging waste flows, paper-based packaging:

9) What are the material flows of paper-based packaging waste in Vienna at paper type level (paper, paperboard, corrugated board, paper composite)?
10) What packaging types and qualities for separate collection and recycling are present in these material flows?
11) Which separate collection rate can be derived at packaging type and quality level?
12) What separate collection rate can be achieved by advertising packaging suitable for separate collection and recycling?

In the first part of the thesis, a knowledge base on packaging waste flows in the case study city was established. For this purpose, the material flows of glass, metal, paper, beverage cartons and plastic (PET beverage bottles, HDPE packaging) packaging waste in Vienna for the period of 2006-2020 were modelled using material flow analysis, and the separate collection rates (SCR) and sorting rates per packaging flow were calculated. This information was combined with a historical content analysis of the public reports of the municipal waste management department (MA 48) in order to evaluate the impact of past measures in the waste management system on the change of packaging waste streams and their SRM provision. The related research questions 1-4 were addressed in Paper I (*A historical-technical analysis of packaging waste flows in Vienna; Gritsch and Lederer, 2023*).

The second part of the thesis is dedicated to the quality assessment and estimation of the untapped potential of the two packaging materials plastic and paper, as separate collection is a particularly critical point in their value chain as SRM, since recovery from mixed MSW is currently still difficult and recovery after incineration is impossible.

Achieving national recycling targets will require special efforts, particularly for plastic packaging. In order to reach the target of 55% by 2030, the recycling rate has to be doubled (Schuch et al., 2023). Legal measures such as a deposit refund system on plastic beverage bottles (BMK, 2023c) and the nationwide standardization of the lightweight packaging collection (BML, 2014) are the first steps in this direction. Due to this planned introduction of a deposit on certain packaging, the focus of the work was placed on the plastic packaging remaining after the introduction of the deposit and a detailed analysis of non-beverage plastic bottles was carried out as an example. In addition to plastic beverage bottles, these have been established target fractions for separate collection for many years and represent a significant proportion of lightweight packaging waste (LPW) and mixed MSW (Gritsch et al., 2024). For these non-beverage plastic bottles, quality-determining packaging characteristics such as polymer, color, decoration, product category, filling volume, etc. were determined by manual sorting, assisted by FTIR spectroscopy, and the residues and dirt contents were determined by washing and subsequent drying, from which also the net quantity indicator could be calculated. These analyses were carried out both for non-beverage plastic bottles in mixed MSW and for separate collection (yellow-blue container, yellow-blue bag), which also allowed the calculation of packaging-specific SCR. The results allowed a detailed analysis of the composition and a precise description of the quality. It was then possible to estimate the recyclability and the untapped potential of non-beverage plastic bottles. The related research questions 4-8 were addressed in Paper II (*Critical properties of plastic packaging waste for recycling: A case study on non-beverage plastic bottles in an urban MSW system in Austria; Gritsch et al., 2024*).

In addition to plastic packaging, paper packaging also requires special attention: various trends, such as increasing online retail or out-of-home consumption, are leading to an increase in packaging volumes (Benoit et al., 2016; BMK, 2024; Ratchford et al., 2022), but the increasing use of paper composite packaging as a substitute for plastic packaging is leading to recycling problems in standard paper recycling processes (4evergreen, 2024; Cayé and Marasus, 2023; Schmidt and Laner, 2021). Overall, there is a downward trend in recycling rates and it is not yet certain that the 85% recycling target for 2030 will be achieved (BMK, 2024). Therefore, the composition and quality of paper-based packaging in the separate paper collection and mixed MSW was analyzed using manual sorting analysis, and the quantities, SCR, untapped potential and measures to improve separate collection were investigated. Composite packaging was analyzed in terms of packaging type and composite type, and its composition was determined by manual separation of the sub-components. For paper and paperboard packaging, an analysis of packaging types and product types was carried out, with a focus on food packaging and product contamination. This was used to identify packaging suitable for separate collection and recycling, as well as packaging that is particularly easy to communicate, and to calculate scenarios for an improved separate collection of this packaging. The related research questions 9-12 were addressed in Paper III (*Quantity and quality of paper-based packaging in mixed MSW and separate paper collection – a case study from Vienna, Austria; Gritsch et al., 2025*).

4 Methods

4.1 Material flow analysis

According to Brunner and Rechberger (2016) material flow analysis is a systematic and descriptive method for visualising and analysing the transport, storage and transformation of material flows in a spatially and temporally defined system. It is often used to analyse anthropogenic systems, such as resource and waste management (Allesch and Brunner, 2015). The basic principle of this method is the conservation of mass principle, according to which the sum of the input flows into a process or the whole system must be equal to the sum of the output flows plus the accumulated stocks (Brunner and Rechberger, 2016). Typical waste management processes are waste generation, collection, treatment or landfilling.

Material flows usually have the unit mass per time and can be represented or calculated at the level of goods as well as subgoods or substances contained in these goods (Brunner and Rechberger, 2016). Goods and subgoods are traded materials, such as mixed MSW or waste paper, and substances are chemical elements and compounds (Brunner and Rechberger, 2016). This allows the system to be analysed at increasingly higher levels of detail, e.g.: level (I): goods, lightweight packaging waste; level (II): sub-goods, plastic bottles; level (III): sub-sub-goods, PET bottles, etc. This allows not only the functioning of a waste management system in general, but also individual qualitative aspects of it to be visualised and assessed (Allesch and Brunner, 2015). For waste management issues, the material flow analysis provides a good basis for calculating circular economy indicators such as collection rates, sorting rates or recycling rates.

Equation 1 shows an example of the mass balance of a process, with $\sum_{kI=1}^{kI=nI} \dot{m}_{kI}$ being the sum of $kI = nI$ input-material flows, $\sum_{kO=1}^{kO=nO} \dot{m}_{kO}$ being the sum of $kO = nO$ output-material flows, and $\dot{m}_{storage}$ describing the material flow entering or exiting a storage in the process.

$$\sum_{kI=1}^{kI=nI} \dot{m}_{kI} = \sum_{kO=1}^{kO=nO} \dot{m}_{kO} \pm \dot{m}_{storage} \quad (1)$$

In practice, the mass flows of the goods are usually calculated first and then the mass flows of the subgoods are calculated via the concentration in the goods, as shown in Equation 2, which describes the material flow of a good $\dot{m}_i$ and the concentration c_{ji} of a subgood j in the good i. The material flow of the subgood j in the good i is described as $\dot{m}_{ji}$.

$$\dot{m}_{ji} = \dot{m}_i \times c_{ji} \quad (2)$$

The material flow analysis method was used in Paper I and Paper III.

4.2 Separate collection rate and sorting rate

The separate collection rate (SCR) is a common indicator to describe the success of separate collection (Cristóbal García et al., 2022; Schuch et al., 2023). It describes the proportion of a waste fraction i that is collected via separate collection $m_{in\ SC,i}$, compared to the total amount of this waste fraction generated $m_{in\ SC,i} + m_{in\ mixed\ MSW,i}$ according to equation 3 (Huber, 2024).

$$SCR_i\ [\%] = \frac{m_{in\ SPC,i}}{m_{in\ SPC,i} + m_{in\ mixed\ MSW,i}} \cdot 100 \tag{3}$$

In the scientific literature mainly the term 'separate collection rate' is used (Bertanza et al., 2021; Cristóbal García et al., 2022; Gritsch and Lederer, 2023; Haupt et al., 2018; Lederer et al., 2022; Schuch et al., 2023; Thomassen et al., 2022) or simply 'collection rate' (Brouwer et al., 2020; Miranda et al., 2011; Van Eygen et al., 2018; Warrings and Fellner, 2019), but also 'capture rate' (Antonopoulos et al., 2021; Seyring et al., 2016; Tallentire and Steubing, 2020), 'separate delivery rate' (Wang et al., 2020) or 'collection yield' (Thoden van Velzen et al., 2019; Thoden van Velzen et al., 2013).

Rural areas tend to have higher SCR than urban areas (Schuch et al., 2023). The SCR can also vary considerably depending on the waste material, e.g. in Vienna it varies between 6% and 77% for the separately collected waste factions (Huber, 2024). When evaluating or comparing SCR, it is important to note which masses were used for the calculation. As the gross collection volume contains a significant proportion of missorted waste, dirt and residues, the net mass should be preferred for the calculation (Thoden van Velzen et al., 2019).

Automatic sorting is the next crucial step in providing SRM for recycling after the collection of packaging through separate collection (Feil and Pretz, 2020). The technological effort and efficiency of sorting depends on the quality of the plant input (Antonopoulos et al., 2021; Feil and Pretz, 2020). The output of automated sorting and sent to recycling in relation to the total waste generated in a specific area is referred to as the 'sorting rate' (Van Eygen et al., 2018). Automated sorting is particularly important for metals, as these can be separated from mixed waste and IBA with comparatively little technological effort using magnetic and eddy current separation (Astrup et al., 2016; Cimpan et al., 2015).

While the SCR was calculated in all three Papers (I, II, III), the sorting rate was only calculated in Paper I.

4.3 Quality assessment

4.3.1 Packaging design

Packaging design determines the fate of packaging throughout its life cycle, from (1) separate collection, (2) mechanical sorting to (3) recycling, and therefore has a major impact on recyclability (RecyClass, 2022b). It is therefore very important to analyse the packaging design with regard to the packaging properties. Thus, for example, conclusions can be drawn about consumer behaviour during separate collection or estimates can be made about technical processes such as automated sorting or mechanical recycling.

While large labels, full-body sleeves, dark colours, contamination from paper fibres or other polymers, and packaging smaller than 5 cm are among the main challenges for LPW sorting and plastic packaging recycling or have a quality-reducing effect (Borealis AG, 2019; Faraca and Astrup, 2019; Gabriel et al., 2023; Gürlich et al., 2022; RecyClass, 2022a), in the case of paper packaging, it is mainly organic contamination, contaminants from inks and adhesives, and paper composites that cause problems during recycling (EN 643, 2014; Peters et al., 2019; Pivnenko et al., 2015; Runte et al., 2016; ZSVR and UBA, 2023).

A detailed examination of packaging design and its quality assessment was carried out in Papers II and III by means of manual sorting analysis (partly supported by FTIR for the determination of polymers) using a pre-developed sorting catalogue. Various packaging characteristics were considered, the selection of which was strongly based on the criteria of relevant guidelines for the design for recycling of packaging (4evergreen, 2024; EN 643, 2014; Gürlich et al., 2022; RecyClass, 2022a; ZSVR, 2023).

4.3.2 Moisture content and residues and dirt content

As well as various characteristics of the packaging design, the consideration of moisture, contamination and residues is of significant interest for the quality assessment and recyclability of packaging waste (Bauer et al., 2021; Gürlich et al., 2022; Jepsen et al., 2019; Liu et al., 2018; Miranda et al., 2011; Pauer et al., 2019; RecyClass, 2022a; Wohner et al., 2019b). Not only can they significantly affect quality and lead to additional technological and monetary costs (Borealis AG, 2019; Liu et al., 2018; Miranda et al., 2011), but they can also alter masses in a way that falsifies mass-based calculations and evaluations (Gritsch et al., 2024; Thoden van Velzen et al., 2019). In addition, contamination means that consumers are more likely to dispose of packaging in mixed MSW than in separate collection (Nemat et al., 2022; Thoden van Velzen et al., 2019; Wikström et al., 2016), which makes recovery for recycling more difficult.

In addition to cross-contamination from other waste components, for example attached biowaste or cigarette butts in cans, product residues are often responsible for contamination of packaging. The amount of residues depends on several factors, such as packaging geometry, product rheological properties, and consumer behavior (Wohner et al., 2019b). These residues can adversely affect automatic sorting processes (Gabriel et al., 2023; Gürlich et al., 2022; Nemat et al., 2022), make recycling processes more expensive (Liu et al., 2018; RecyClass, 2022a) and may lead to undesirable odors, colors or mechanical properties, negatively affecting recyclate quality (Borealis AG, 2019; Faraca and Astrup, 2019; Jepsen et al., 2019). Moreover, residues contribute to food losses and food waste (Pauer et al., 2019; Williams et al., 2012; Wohner et al., 2019a), leading to unnecessary resource consumption and significant environmental impact (Rathore et al., 2023; Wikström et al., 2014; Wohner et al., 2020; Wohner et al., 2019b). While few studies on technical emptiability (ante-consumer) exist (Klein et al., 2024; Rathore et al., 2023; Wohner et al., 2020; Wohner et al., 2019b), there are scarce recent studies on actual residues in post-consumer packaging waste and their implications (Roosen et al., 2020; Thoden van Velzen et al., 2019).

Papers II and III investigated moisture content and residues and dirt content (RDC). In Paper II, non-beverage plastic bottles with a specific packaging characteristic i were washed in hot water and then dried to determine the adherent dirt and residues content. The difference between the mass before washing $m_{gross,i}$ and the mass after drying $m_{net,i}$, based on the mass before washing, gave the RDC_i [%], which indicates what percentage of the mass of the plastic bottle found in the waste is residues and dirt (see equation 4).

$$RDC_i\ [\%] = \frac{m_{gross,i} - m_{net,i}}{m_{gross,i}} \cdot 100 \tag{4}$$

In Paper III, the moisture content of packaging made of the hygroscopic material paper was determined for each waste stream i according to DIN 6730:2017, which consisted of drying in an oven until a constant weight was reached. The difference between the mass before drying $m_{gross,i}$ and the mass after drying $m_{dry,i}$ in relation to the mass before drying gave the MC_i [%] (see equation 5).

$$MC_i\ [\%] = \frac{m_{gross,i} - m_{dry,i}}{m_{gross,i}} \cdot 100 \tag{5}$$

5 Results and discussion

This chapter summarises the results in three sections corresponding to the three Papers I-III. For the complete results and a detailed discussion, the reader is referred to the full text of the papers in the appendices.

5.1 Packaging waste flows in Vienna 2006-2020 (Paper I)

The time series of packaging waste flows show, that from the year 2006 to the year 2020, the total generation increased for glass from 28 to 32 kg/cp/yr (+14%) and for paper/paperboard/corrugated board from 32 to 35 kg/cp/yr (+9%), but decreased for PET beverage bottles (5.6 to 5.3 kg/cp/yr; -5%), HDPE packaging (1.6 to 1.5 kg/cp/yr; -6%), beverage cartons (4.0 to 3.0 kg/cp/yr; -25%) and metal packaging (6.5 to 5.8 kg/cp/yr; -11%). However, the latter decrease is only due to the decrease in ferrous metal packaging (4.1 to 3.1 kg/cp/yr; -24%), while aluminum packaging increased (2.4 to 2.6 kg/cp/yr; +8%). These trends correspond to national data for glass, aluminum packaging, paper packaging and PET packaging (BMK, 2023a; Van Eygen et al., 2018). There are no comparable data for BC for Austria, but for the Netherlands, where the per capita amount is quite similar. For Fe-P and HDPE-P higher comparable data were found, the reason for which is currently unclear and needs to be further investigated (BMK, 2023a; Van Eygen et al., 2018).

Furthermore, the content analysis of annual reports showed that in the period under review, the following technical measures in the MSW management in Vienna were implemented (see Figure 1): In 2008, a new MSW incineration and IBA treatment plant went into operation, the latter removing ferrous and non-ferrous metals. From 2009 on, plastic bottles and beverage cans have been sorted out from public bins regularly. And in the same year, curbside collection of LPW was started in selected single-family-house areas and gradually expanded. In 2012, a new splitting plant for mixed MSW was introduced, which unlike the old plant, only recovered ferrous but not non-ferrous metals. In 2018, the curbside collection of beverage cartons was ceased and from then on, they were collected together with plastic bottles. A year later, in 2019, additionally also metal packaging was collected with them in the new yellow-blue container/bag, which got a new emblem depicting some of the main target packaging. In the same year, improvements of the IBA processing plant were made to increase the recovery of non-ferrous metals.

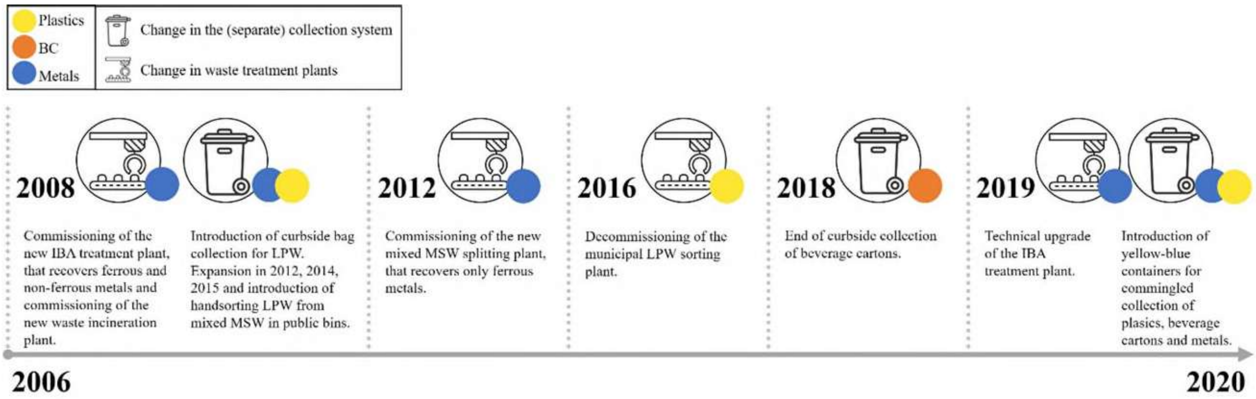

Figure 1: Timeline of the most important changes in MSW management in Vienna from 2006 to 2020, colored dots representing waste fractions mostly affected by these changes.

For packaging that was not affected by these measures, there was no major impact on the SRM provision by these technical measures observed, as for glass, where SCR and sorting rate only increased slightly from 53 to 55% (see Figure 2). For paper, paperboard and corrugated cardboard packaging (PCCC-P) its SCR and sorting rate decreased slightly from 62% in 2006 to 59% in 2020, with corrugated board contributing more to the SCR than paper and paperboard, which has a considerably lower SCR. As there is currently no recovery from mixed MSW or sorting before recycling, SCR and sorting rate are identical for paper and glass. However, there have been significant changes in the SRM provision for the packaging affected by the measures: For beverage cartons, the commingled collection with other LPW has led to a doubling of the SCR from (9% to 18%), but due to sorting losses, the overall sorting rate remains at the same level as before commingled collection was introduced, at around 10%. For plastic packaging, small increases in SCR were observed after the introduction of curbside bag collection and the sorting of plastic bottles from public waste bins, while the largest increase in SCR was, as for beverage cans, due to the introduction of the yellow-blue container. In general, the SCR for plastics increased significantly from 20% in 2006 to 35% in 2020, but after sorting only about 29% remain as SRM.

For metals, the yellow-blue container led also to an increase in the SCR for aluminum packaging from about 9% to about 14%, but not for ferrous packaging, which SCR decreased to 16%. However, as the only packaging, in the case of metals, automatic sorting from mixed MSW and IBA showed a high impact, so for aluminum packaging the sorting rate was nearly 58% in 2020, and for ferrous packaging it was even 94%.

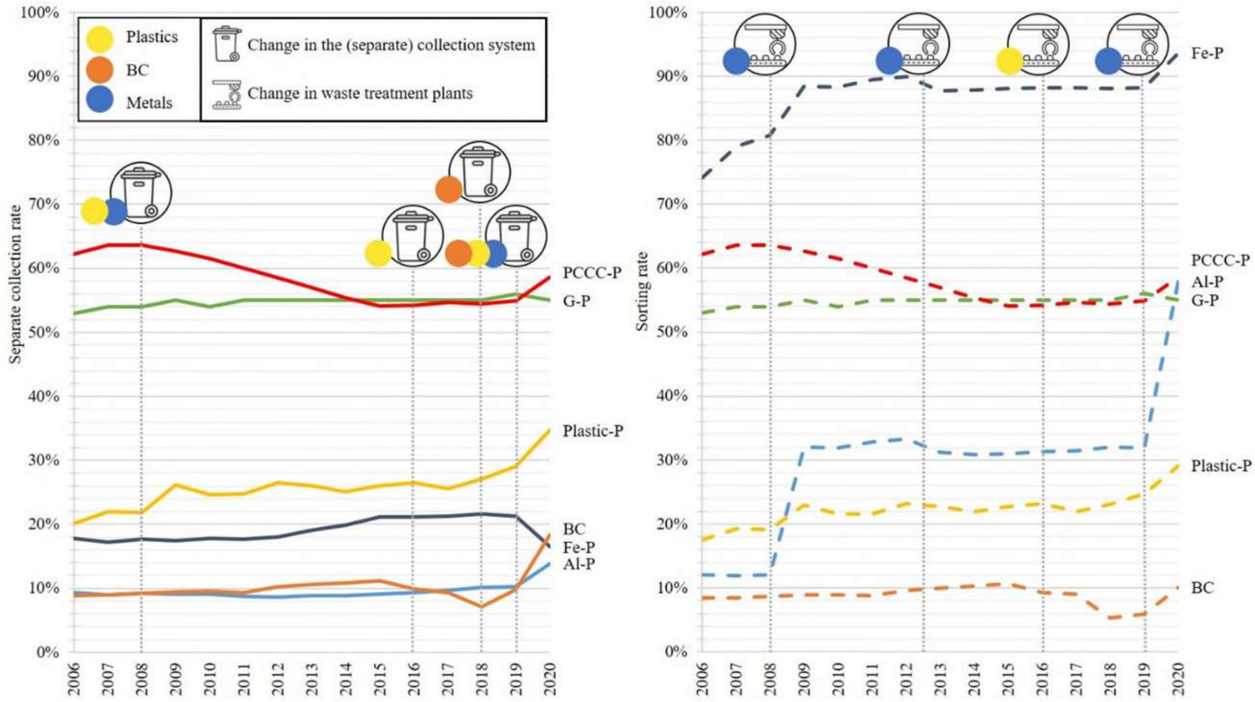

Figure 2: Separate collection rate and sorting rate for selected packaging waste, 2006-2020, with icons highlighting changes or adaptions in waste treatment plants (sorting from a conveyor belt) or changes in waste collection (waste bin) and colored dots representing the respective packaging waste mostly affected by these changes (blue: metals; yellow: plastics; orange: beverage cartons), (Al-P, aluminum packaging; BC, beverage cartons; Fe-P, ferrous metal packaging; G-P, glass packaging; PCCC-P, paper/cardboard/corrugated cardboard packaging; Plastic-P, plastic packaging), (Figure 6 in Paper I).

The results show, that commingled collection has positively influenced the SCR of the regarding packaging waste (beverage cartons, plastic, metals). This probably can be explained by increased convenience for consumers due to simpler storing of waste at home (only one fraction instead of three) and due to an increased number of collection containers and consequently shorter disposal routes (Brouwer et al., 2019; Dahlén et al., 2007; Rousta et al., 2015; Thoden van Velzen et al., 2019). Therefore, one option to further increase SRM provision could be the curbside collection of LPW for further reduced distance and more convenience for the consumers, like it was also implemented in Nottingham and Brescia (Bertanza et al., 2021; Wang et al., 2020). However, as this may lead to more missorted waste and means higher efforts in costs and emissions, this must be carefully planned (Haupt et al., 2018; Wang et al., 2020). Moreover, the results show that the pictorial representation of the target fraction as easily accessible and easy to understand information seems to considerably influence the SCR (Cristóbal García et al., 2022; Rousta et al., 2015). While it increased for packaging depicted on the container (HDPE packaging, beverage cartons, aluminum beverage packaging), it decreased for packaging that were not any more depicted on the new emblem of the yellow-blue container (aluminum other packaging, ferrous packaging). Therefore, such specific information on collection containers is advisable, but as the effects are not fully understood yet, further investigation is needed. Finally, upon the high impact proved for SRM provision technical sorting should be emphasized and further improved. On the one hand an improvement of the LPW sorting technology would be required to reduce sorting losses (Antonopoulos et al., 2021), and on the other hand upgrading the existing mixed MSW splitting plant to a technical sorting plant that also recovers aluminum, plastic and paper would be one option and is suggested where separate collection of combustible packaging waste may have reached its saturation level, however the quality of the produced materials has to be assessed before implementation (Cimpan et al., 2015; Feil et al., 2017). In addition, improving the technical sorting from IBA is recommended for non-combustible packaging material, as this is the last chance to recover SRM for recycling before landfilling, especially for metals, but also glass recovery seems to have a potential (Astrup et al., 2016; Mühl et al., 2023; Šyc et al., 2020). In both cases of technical sorting, it is important to investigate the achieved quality and potential market before implementation, as always a deterioration of quality must be considered (Biganzoli and Grosso, 2013; Gökelma et al., 2021; Mehr et al., 2021).

5.2 Quality assessment and untapped potential of non-beverage plastic bottles (Paper II)

Non-beverage plastic bottles account for 10% of LPW and 1.02% of mixed MSW. The results of the analysis of non-beverage plastic bottles show, that the distribution of polymers is similar in all three waste streams analysed: PET is predominant (41-46%), followed by HDPE (28-37%), PP (19-27%) and other polymers (1-2%). These findings align with those of Eriksen and Astrup (2019), who analyzed post-consumer rigid plastic waste in Copenhagen. The analysis of the quality-determining packaging characteristics showed that the filling volume of 0.5 < x ≤ 1.5 L was the most common for PET, HDPE and PP bottles, with shares between 23-59%. For all three polymers, the most common decoration technology was 'label' (60-85%). Full-body plastic sleeves were also very common and, like large labels, can present a challenge to the LPW sorting process, which is usually carried out using near-infrared technology (Gabriel et al., 2023; Gürlich et al., 2022; Ragaert et al., 2017). In terms of product category, 'food' was the most common for PET and PP (37-46%), while 'washing and cleaning agents' was the most common product category for HDPE (41-49%). Colored non-beverage plastic bottles were most common in PP (25-31%), while clear, translucent and white dominated in PET (86-89%) and HDPE (75-77%).

The results of the study also show that a significant proportion of the non-beverage plastic bottles found in MSW are actually foreign materials, as indicated by the net quantity indicator, which is 58% in mixed MSW, compared to 69-72% in separate lightweight packaging collection. Roosen et al. (2020) found quite similar results with 76% for PE and 77% for PP bottles. Beside caps and sleeves, a great share of foreign materials turned out to be residues and dirt. A calculation of the residues and dirt content of each bottle showed that the RDC in mixed MSW is significantly higher at 20% than in separate collection at about 11%, but no significant differences were found between LPW container and LPW bag collection (see Figure 3). This means that packaging with high RDC level was more likely to be disposed of in mixed MSW, which is in line with other studies (Nemat et al., 2022; Thoden van Velzen et al., 2019; Wikström et al., 2016). In terms of product types, personal care products had the highest share of RDC at 20%, followed by food at 15%, which may be explained by a combination of the high viscosity of these products and unfavorable packaging design, but also by consumer wastefulness (Rathore et al., 2023; Schinkel et al., 2023; Wohner et al., 2020). As the findings of this thesis show, also other packaging characteristics appear to have an influence on the RDC, for example differences have been found between low and high filling volumes, or uncolored and colored non-beverage plastic bottles, but further research is needed to understand these effects.

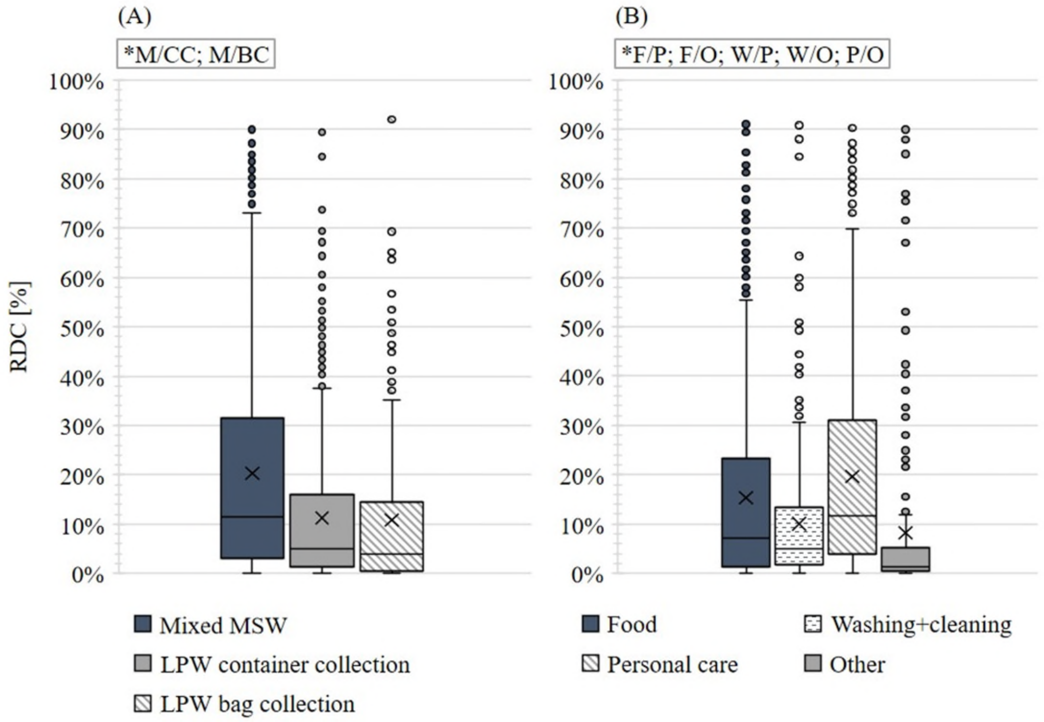

*Figure 3: Residues and dirt content (RDC) of non-beverage plastic bottles per waste stream (A) and product category (B) shown as boxplot; groups with significant difference in RDC according to post-hoc analysis are marked with *, (M, mixed MSW; CC, LPW container collection; BC, LPW bag collection; F, food; P, personal care; O, other; W, washing+cleaning) (adapted from Figure 6 in Paper II).*

The separate collection rate of non-beverage plastic bottles calculated with gross masses is 17.6%, while with net masses it is 19.2%, which can be attributed to the higher RDC values observed in the mixed MSW compared to the separate collection. This demonstrates the impact that the consideration of residues and dirt can have on the results of mass-based indicators (Thoden van Velzen et al., 2019). The analysis also showed, that different packaging characteristics seem to influence the SCR. For instance, the SCR increased with increasing filling volume up to 1.5 L, but then decreased with increasing filling volume. This can be explained partly by the phenomenon, that smaller packaging is more likely to be disposed of in mixed MSW (Nemat et al., 2022; Thoden van Velzen et al., 2019), and partly by the small openings of the collection containers, which prevent the disposal of bulky waste. For polymer, decoration, color, product category, packaging type, viscosity of the product and processing method, also effects on the SCR were observed, but are inconclusive.

The rather low SCR shows that over 80% of the bottles are currently lost for recycling through incineration with mixed MSW. This represents an untapped potential of 4,112 t/yr of non-beverage plastic bottles, comprising 1,762 t/yr of PET, 1,123 t/yr of HDPE, 1,130 t/yr of PP and 96 t/yr of other polymers (see Figure 4). 46% of all the non-beverage plastic bottles, which is 1,899 t/yr are clear or translucent and therefore have the highest market value as secondary raw material (Faraca and Astrup, 2019). Other 50% (2,055 t/yr) have white or colored pigments which lowers the value and a total of 4% (158 t/yr) are black and hence are classified as non-recyclable, as they cannot be detected in the sorting process (Brouwer et al., 2020; Faraca and Astrup, 2019). In terms of material grade, at least 30% of the non-beverage plastic bottles are food grade, so it can be assumed that this packaging material meets the highest quality criteria (EC, 2011, 2004; Tonini et al., 2022), followed by personal care and cosmetics, which account for 27% (1,116 t/yr) and also have specific legal purity requirements (EC, 2022c). The remainder of 43% (1,757 t/yr) is likely to have lower quality requirements.

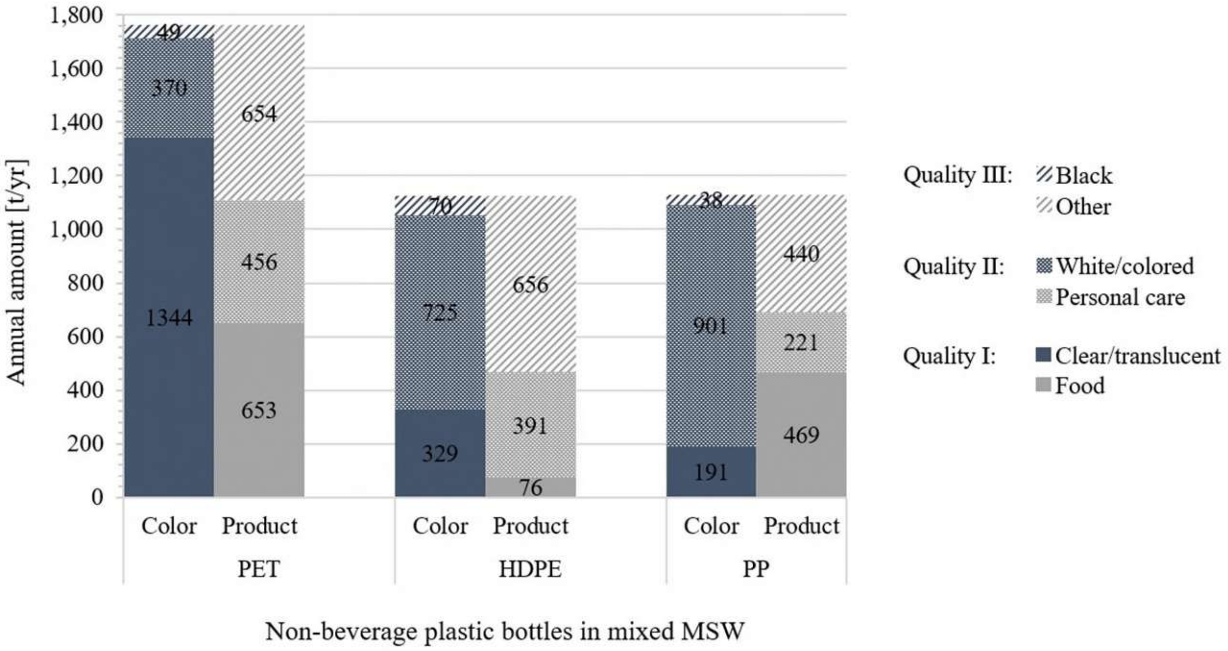

Figure 4: Annual amounts of PET, HDPE and PP non-beverage plastic bottles in mixed MSW by color and product type and by estimated quality grades I-III, where I is highest quality, II is medium quality and III is poor quality, in t/yr dry matter basis (adapted from Paper II).

5.3 Quality assessment and untapped potential of paper-based packaging (Paper III)

The results of the material flow analysis of paper-based packaging reveal that, the annual amount of paper, paperboard and corrugated board packaging in Vienna increased significantly from in total 49,654 t/yr in 2009, to 52,475 t/yr in 2015 and finally 70,028 t/yr in 2022 (see Figure 5). Corrugated board represents the largest material flow but increased the least from 31,418 t/yr in 2009 to 36,358 t/yr in 2022 (+16%), while the largest growth was recorded in paperboard packaging, which increased from 12,590 t/yr to 22,458 t/yr (+79%) and paper packaging, which doubled from 5,646 t/yr to 11,212 t/yr (+100%). Despite increasing volumes, the overall average SCR decreased from 62% in 2009, to 57% in 2015 and 54% in 2022. While corrugated board has a stable SCR of around 80%, paper and paperboard lag far behind and are responsible for the decline: Paperboard reached its highest SCR of 36% in 2009 and has been declining ever since, reaching 34% in 2015 and only 26% in 2022. Similarly, the SCR of paper has been steadily declining from 33% in 2009, to 25% in 2015 and 21% in 2022. Paper composite packaging was analyzed for the first time in 2022, so data is only available for that year, and shows, that a total of 4,707 t/yr was found in mixed MSW and paper collection, with the majority disposed of in mixed MSW at 4,611 t/yr. As it was not targeted for the separate collection at the time of analysis, no SCR was calculated.

Closer examination of paper composite packaging by manual sorting showed that paper composites (2,629t/yr) are slightly more prevalent than paperboard composites (2,066 t/yr) in mixed MSW and separate paper collection. In terms of composite types, fibre-plastic composites clearly dominate over fibre-plastic-metal composites, with the latter proving less separable by hand. Despite the fact, that paper-based composite are becoming increasingly popular as a packaging (Cayé and Marasus, 2023; ZSVR and UBA, 2023), but cannot be recycled in a standard paper mill process (4evergreen, 2024), there is a lack of scientific literature and unclear definitions, whether technical or regulatory, make it difficult to compare data (BMK, 2023b; BML, 2014).

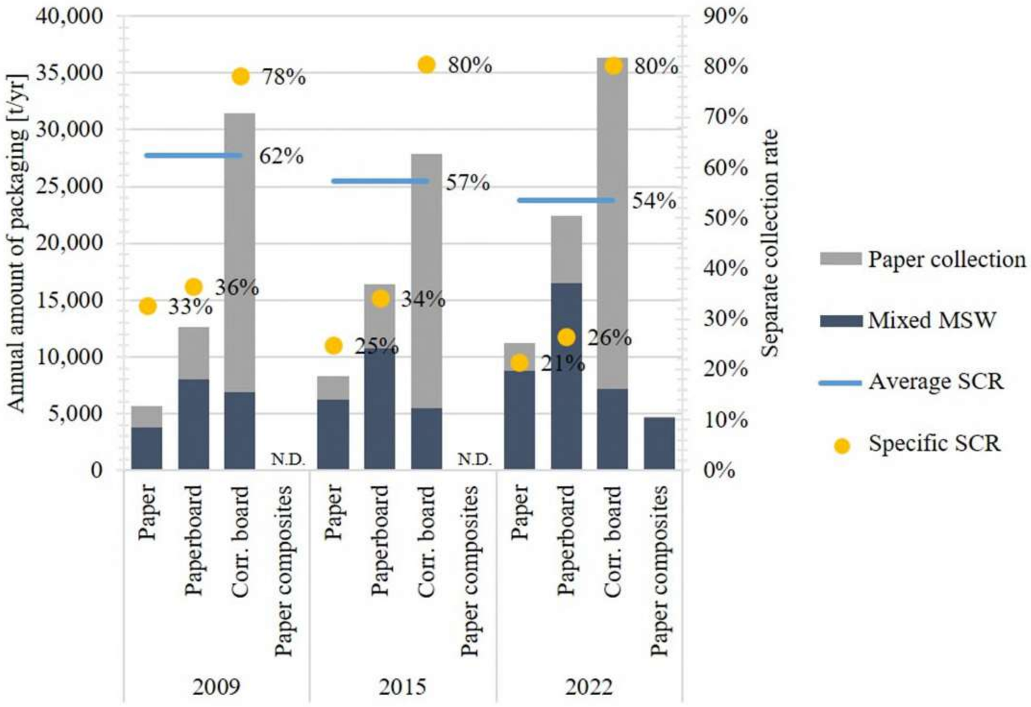

Figure 5: Annual amounts of paper, paperboard, corrugated board and paper composite packaging in Vienna's mixed MSW and paper collection from households for 2009, 2015 and 2022 in t/yr wet matter basis (columns), specific separate collection rates (SCR) per paper-based packaging type (dots) and average SCR for all paper-based packaging for 2009, 2015 and 2022 (lines) in w% wet matter basis, (corr. board, corrugated board; N.D., no data), (Figure 2 in Paper III).

Closer examination of paper and paperboard packaging by means of manual sorting in terms of food compatibility, food contact level and product type of paper and paperboard packaging showed that non-food packaging has the highest share in both mixed MSW and paper collection, with 46% in mixed MSW and 48% in paper collection, followed by secondary food packaging at 31% and 38%, respectively (see Figure 6). For primary food packaging, the share is significantly higher in mixed MSW at 23% (8% oily food, 7% moist food, 6% dry food, 2% liquid food) than in paper collection at 15% (10% dry food, 3% oily food, 2% moist food). This difference could also be reflected in the moisture content, which is more than twice as high in mixed MSW at 17% as in separate paper collection at 7%.

Organic impurities in general, and food in particular is listed under the prohibited substances in paper recycling (EN 643, 2014), thus, only unsoiled packaging is allowed to be disposed of in paper collection. While primary food packaging is, theoretically, likely to be soiled, because it is in direct contact with the packaged food, secondary packaging (contact with packaged food is unlikely but cannot be completely excluded) and non-food packaging should not carry such contamination. This hypothesis was confirmed by a qualitative examination of the packaging for product-related contamination, with the exception of primary packaging for liquid foods, which showed low levels of contamination despite direct contact, probably due to the good emptiability of liquids. According to this, there is a misplaced rate of 85%

unsoiled packaging (for non-food, secondary food, primary liquid food, primary dry food) in mixed MSW, that would be suitable for separate collection and recycling. Similarly, there is a misplaced rate of 5% of contaminated packagaging (for primary moist food, primary oily food) in separate collection, that should have been disposed of in mixed MSW.

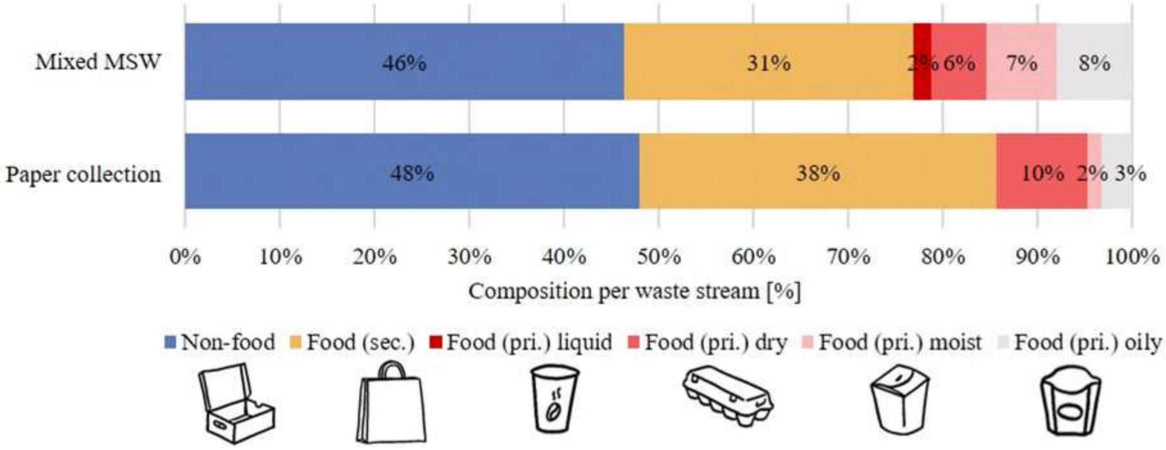

Figure 6: Composition of paper and paperboard packaging in mixed MSW and paper collection regarding food compatibility (food/non-food), food contact level (primary/secondary) and product type (liquid/dry/moist/oily) in w% wet matter basis, and icons showing examples of packaging for each fraction, (sec., secondary; pri., primary), (Figure 3 in Paper III).

The specific SCR at packaging type showed a wide variance (0-45%), with the highest SCR for primary food packaging for dry food (35%), secondary food packaging (30%) and non-food packaging (25%) and the lowest SCR for primary food packaging for liquid (0%), moist (6%) and oily food (11%). Overall, paperboard packaging achieves a slightly higher SCR (26%), than paper packaging (21%).

The specific SCR of paper and paperboard suitable for recycling is 28%, leaving a currently untapped potential of 21,252 t/yr of unsoiled paper and paperboard packaging, consisting of 12,052 t/yr of non-food, 7,218 t/yr of secondary food, 1,448 t/yr of dry food and 534 t/yr of liquid food packaging in mixed MSW (see Figure 7). Improvements of the SCR of only these suitable packaging from the currently 28% to 54% or even 80%, would increase the total SCR of paper, paperboard and corrugated board packaging in Vienna from currently 54% to 65% and 76%, respectively. If improved separate collection only targets paper carrier bags, which have been identified as the most characteristic paper packaging item, and a SCR of 80% is achieved for them, this would still increase the total SCR in Vienna to 60%. The question, however, would be how to achieve improved separate collection. Since the most convenient system, curbside collection, is already in place, an additional support for consumers would be to clearly communicate which packaging is intended for separate paper collection. For example, displaying paper carrier bags on the collection containers would provide clear guidance, as this information is easily accessible and simple to understand (Cristóbal García et al., 2022; Gritsch and Lederer, 2023; Rousta et al., 2015).

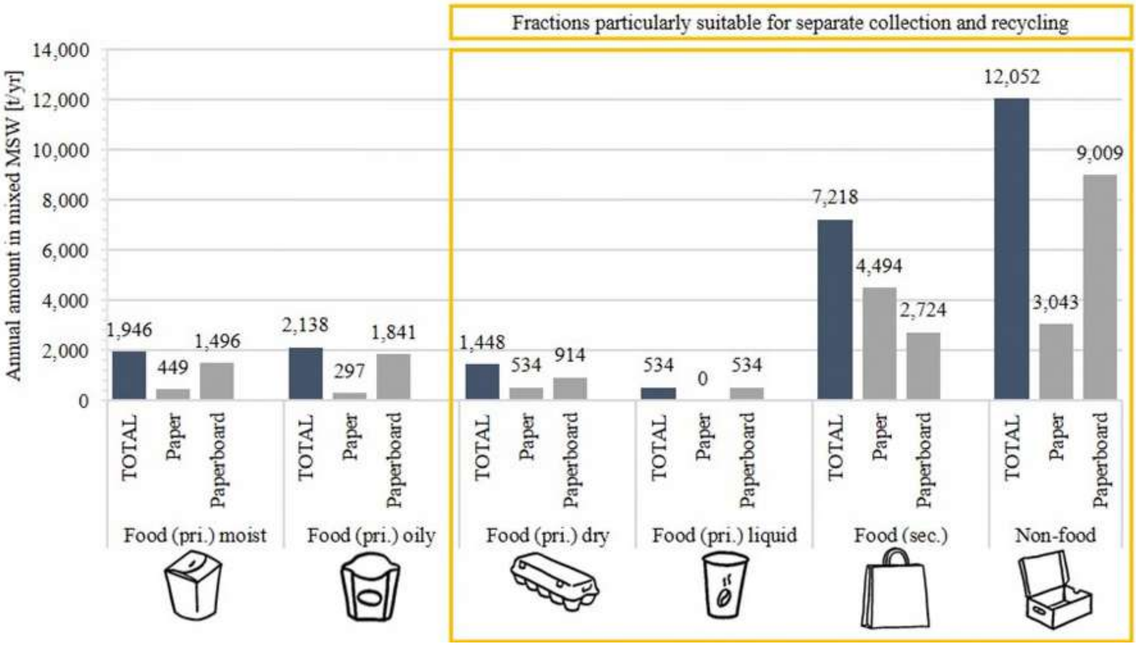

Figure 7: Annual amounts of paper and paperboard packaging in mixed MSW in t/yr wet matter basis, with packaging particularly suitable for separate collection and recycling highlighted in yellow, and icons showing examples of packaging for each fraction, (sec., secondary; pri., primary), (adapted Figure 4 in Paper III).

6 Conclusion

Against the background of the recycling targets to be achieved for packaging waste, the present thesis investigated the packaging waste in the case study area of Vienna, which has particular difficulties with separate collection in a national comparison. For this purpose, a time series of packaging waste flows for the period 2006-2020 was created using material flow analysis, the impact of certain waste management measures was assessed, and a detailed characterization of non-beverage plastic bottles and paper-based packaging was carried out using manual sorting analysis in order to assess the untapped potential and identify measures to improve separate collection. This section summarizes the main findings of the thesis, draws conclusions and outlines the scientific contribution. Firstly, the research questions are briefly answered, and then, the overall conclusions are presented.

1) *Which measures in separate collection of post-consumer packaging waste and technical sorting of mixed MSW and IBA have been implemented?*

   In separate collection, a commingled collection of plastic bottles, beverage cans and metal packaging, a curbside collection of LPW in certain areas and sorting of plastic bottles and beverage cans from public waste bins were introduced. Technical measures also included the commissioning of a new MSW incineration plant, a splitting plant and an IBA treatment plant, and the technical upgrading of the latter.

2) *How have post-consumer packaging waste flows of different materials evolved?*

   While total generation in kg/cp/yr increased from 2006 to 2020 for glass (+14%), paper/paperboard/corrugated board (+9%) and aluminum packaging (+8%), it decreased for PET beverage bottles (-5%), HDPE (-6%) and ferrous packaging (-24%).

3) *What shares of these have been provided as SRM for recycling?*

   In 2020, 55% of glass and 59% of paper/paperboard/corrugated board have been provided as SRM for recycling through separate collection. After sorting, 10% of beverage cartons and 29% of plastics remain as SRM for recycling, 58% of aluminum packaging and 94% of ferrous packaging.

4) *What are the future perspectives to increase SRM provision for recycling?*

   Based on the results, the following measures are recommended to further improve the provision of SRM in Vienna: improved communication with consumers about targeted packaging for separate collection, large-scale introduction of curbside collection of LPW, further improvement of IBA sorting, recovery of more recyclables, including plastics and paper in addition to metals from mixed MSW.

5) *What is the composition of non-beverage plastic bottles regarding polymer and packaging characteristics?*

In terms of polymer, PET predominates (41-46%), followed by HDPE (28-37%), PP (19-27%) and other polymers (1-2%). The most common filling volume for PET, HDPE and PP was $0.5 < x \leq 1.5$ L, and the most common decoration was 'label'. While PET and PP had the highest shares of food, washing and cleaning agents were most common in HDPE. Colored non-beverage plastic bottles were mainly found in PP, uncolored and white dominated in PET and HDPE.

6) *What is the residues and dirt content of non-beverage plastic bottles, and what factors influence it?*

The RDC was significantly higher in mixed MSW (20%) than in LPW collection (11%), with no significant differences between LPW container and bag collection. Certainly, the product influences the level of RDC, and as the results show, personal care products have the highest RDC at 20%, followed by food (15%) and washing and cleaning products (10%), but filling volume, color and other packaging characteristics also seem to have an influence.

7) *Which quantities of non-beverage plastic bottles are generated annually and which share thereof represents a high-quality SRM?*

In 2022, a total of 4,112 t/yr was disposed of in mixed MSW, 946 t/yr in LPW container collection and 35 t/yr in LPW bag collection. In mixed MSW, 46% of the non-beverage plastic bottles can be classified as highest quality by color (uncolored) and 30% by product grade (foodgrade).

8) *What is the separate collection rate of the non-beverage plastic bottles, and what factors influence it?*

The SCR calculated with gross masses is 17.6%, and calculated with net masses is 19.2%, demonstrating the significant influence of residues and dirt. Moreover, size appeared to influence the SCR, with smaller and larger non-beverage plastic bottles having a lower SCR. Other packaging characteristics such as color, decoration, type of packaging and viscosity of the product also seemed to have an effect, but this is not certain and requires further investigation.

9) *What are the material flows of paper-based packaging waste in Vienna at paper type level (paper, paperboard, corrugated board, paper composite)?*

In 2002, 36,358 t/yr of corrugated board, 22,458 t/yr of paperboard, 11,212 t/yr of paper, and 4,707 t/yr of paper composite packaging was disposed of in mixed MSW, separate paper collection and recycling centers in Vienna.

10) *What packaging types and qualities for separate collection and recycling are present in these material flows?*

The highest shares were found for non-food packaging, followed by secondary food packaging and finally, primary food packaging for oily, dry, moist and liquid food. Non-food, secondary food and primary food packaging for dry and liquid food have been identified as suitable for the separate paper collection due to their low levels of contamination, and in particular paper carrier bags.

11) *Which separate collection rate can be derived at packaging type and quality level?*

The highest SCR was achieved by primary food packaging for dry food (35%), secondary food packaging (30%) and non-food packaging (25%), while the lowest SCR have been found for primary food packaging for liquid (0%), moist (6%) and oily food (11%). Overall, paperboard packaging achieves a slightly higher SCR (26%), than paper packaging (21%).

12) *What separate collection rate can be achieved by advertising packaging suitable for separate collection and recycling?*

If the SCR of suitable packaging was improved from currently 28% to 54% or even 80%, the overall SCR of paper, paperboard and corrugated board in Vienna could be increased from the currently 54% to 65% or even 76%. Improved collection of only paper carrier bags with an SCR of 80% would increase the overall SCR to 60%.

Looking to the future, the study showed that despite a sophisticated waste management system, the City of Vienna still needs to increase the provision of SRM and faces significant challenges in the separate collection of waste. Besides successful improvements in the separate collection of LPW with a positive impact on SCR a few years ago, the thesis shows that still significant amounts of high quality packaging waste of any materials, amounting to several thousand tonnes, are currently still being lost for recycling in mixed MSW. The extent to which separate collection has already reached its limits is therefore uncertain and needs to be investigated through sensible and carefully planned large-scale experiments. According to the results of this study, there may still be room for improving convenience for the consumers, either through shorter disposal routes such as an increase in the number of collection points in urban areas or the introduction of curbside collection, or through improved visual presentation of the target fractions on collection containers. Particular attention should be paid to communication and knowledge transfer to consumers, as their influence on waste separation is significant and their cooperation is urgently needed.

The main findings show that the SCR is a suitable and robust indicator for quantifying the success of separate collection systems. It was found, that significant differences in SCR can occur within a packaging group, demonstrating a clear influence of packaging characteristics on SCR. For metals, low SCR can be successfully compensated by automatic sorting of mixed MSW and IBA, which would be the next steps for recovering recyclables. However, this is not currently possible for materials such as paper and plastics, so separate collection of these materials is still essential. The technical feasibility of sensor-based sorting of these materials is already known, and the existing mixed MSW splitting plant could be upgraded for this purpose, although the obstacles at present are the high investment costs and the uncertain purchase options for the sorted material due to the lack of quality assessments and industry standards. However, this study has already provided good results, at least for the type and quality of some specific plastic and paper packaging.

In addition to the challenges and opportunitites in packaging waste management that can be addressed by the City of Vienna itself, there are factors influencing the separate collection that are in the hands of stakeholders outside the City. These include, for example, packaging design, which was addressed by the detailed packaging characterization carried out in the course of this study. It highlights the challenges posed by the wide variety of packaging designs and the resulting heterogeneity, which makes separate collection probably unintuitive for consumers. It is therefore recommended that the diversity of packaging be reduced, which could facilitate recovery and recycling and make it easier for consumers to separate their waste. Although legislation on recyclability, including harmonized collection in the EU, is on its way, developments in packaging design and collection should be monitored in order to identify negative trends at an early stage. In addition, the thesis found that residual contents in packaging contribute significantly to the gross mass of packaging waste, which may have a number of implications, for example for material flow data or on waste management performance indicators. As the thesis did not specifically investigate whether the residues in packaging are due to wasteful consumer behavior or unfavorable packaging design, but finds indications in both directions, both improved packaging design that is easier to empty completely and increased consumer awareness regarding product waste are needed.

Building on the results of the packaging characterizations carried out in the course of this study, further research should be conducted on the detailed characterization of different packaging wastes for a comprehensive sustainability assessment of packaging in order to identify best practice packaging solutions.

Beside the valuable scientific contribution, the thesis has several limitations that need to be taken into account. Firstly, the geographical scope was limited to Vienna, which means that the results may not be fully applicable to other regions of Austria. In order to make more general statements about the quality and quantity of packaging waste on a national level, further research including other waste fractions and conducted at a similar level of detail is necessary. In addition, the study did not take into account seasonal variations. Furthermore, the study focuses only on the quality of packaging waste at the time of collection and does not investigate its behavior during subsequent processing and its quality afterwards. Therefore, large-scale tests in sorting and recycling facilities are needed to assess the real potential for mechanical recycling.

In conclusion, overcoming the current challenges of separate collection in urban areas like Vienna will require a multi-faceted approach to achieve the recycling targets, including measures that can be influenced directly, such as optimized collection systems or consumer education, as well as wider measures that are beyond the city's responsibility, such as improved packaging design. However, this is only one step towards a circular economy. While improving the circularity of products in general and promoting sustainable consumption will remain one of the greatest challenges of our time, I hope that this work has made a small contribution towards a better and more hopeful future.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used DeepL in order to translate and improve readability. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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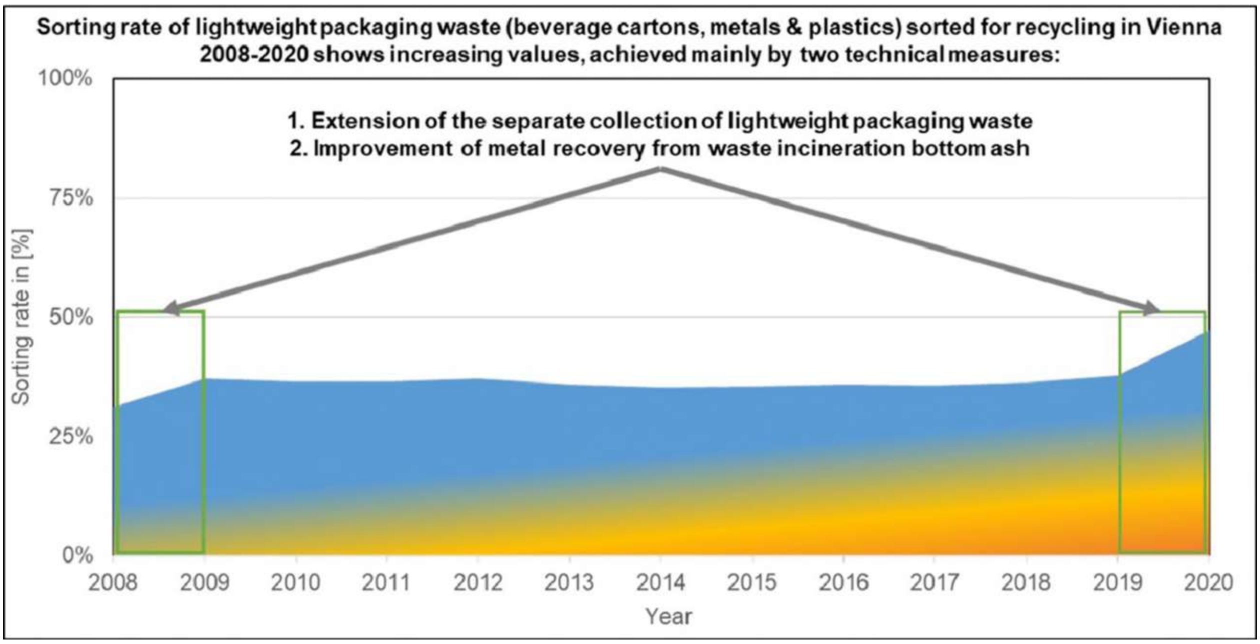
Appendix

Paper I

Gritsch, L., Lederer, J., 2023. A historical-technical analysis of packaging waste flows in Vienna. *Resources, Conservation and Recycling* 194, 106975. https://doi.org/10.1016/j.resconrec.2023.106975.

Graphical abstract



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Full length article

A historical-technical analysis of packaging waste flows in Vienna

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A B S T R A C T

Urban waste management plays an important role in providing secondary raw materials for packaging waste recycling. To assess measures for this provision, material flows of packaging waste for 2006–2020 in Vienna were modeled and evaluated by the separate collection rate and sorting rate. Results showed increasing separate collection rates for the years 2006-2020 for plastic bottles (20%-35%), aluminum beverage packaging (10%-22%), and beverage cartons (10%-18%) achieved by commingled collection and more collection points. Values for other aluminum (6%-5%) and ferrous metal packaging (18%-16%), however, decreased. Glass packaging increased slightly (53%-55%) and paper packaging remained constant (56%). The sorting rate of metal packaging increased significantly due to bottom ash sorting. To increase the provision of secondary raw materials, better communication with consumers and the improvement of technical sorting of mixed waste and bottom ash should be implemented. Door-to-door collection of beverage cartons, metals, and plastics should be carefully tested and evaluated before implementation.

1. Introduction

High resource consumption and its negative consequences can be partially mitigated by a circular economy (CE) (Pearce and Turner, 1990; Fellner and Lederer, 2020). The EU aims to achieve a CE by measures like providing secondary raw materials (SRM) from post-consumer packaging waste (PcPW) in municipal solid waste (MSW) for recycling (EPC, 2018a, 2018b). Urban MSW management plays a key role in this provision of SRM due to the high urbanization of the EU and comparatively low separate collection in urban areas (Feil et al., 2017; Schuch et al., 2023).

Material flow analysis (MFA) can be used to determine the past development, present status, and future potential of urban MSW management contributing to the provision of SRM of PcPW. Many MFA studies illustrate the present status of material flows for one year (Lombardi et al., 2021; Lopez-Aguilar et al., 2022; Schmidt et al., 2020; Schneider et al., 2022). However, a time-series MFA is required to ex-post analyze MSW management and the provision of SRM. Examples exist for states and regions (Brouwer et al., 2019; Buchner et al., 2014, 2017; Thomassen et al., 2022). Therein, Brouwer et al. (2019) analyzed the separate collection of lightweight packaging waste (LPW) and technical sorting of mixed MSW to provide SRM from plastic waste in the Netherlands in 2014 and 2017, while Buchner et al. (2014, 2017) underlined the recovery of aluminum from MSW incineration bottom ash (IBA). The most recent study by Thomassen et al. (2022) focused on the provision of SRM from plastic waste from 1985–2019 in Flanders. What these studies have in common is that they provide valuable insight into MSW management and recycling of selected materials at a national or regional level. What is not included is a historical analysis of technical measures regarding waste collection and treatment technology, in conjunction with material flows and provision of SRM in urban areas, which usually have lower separate collection rates than their rural counterparts, even within one country (Schuch et al., 2023). Rare examples of such studies from Bertanza et al. (2021) and Wang et al. (2020) focus on the development of providing SRM from MSW for recycling in the cities of Brescia and Nottingham, respectively. While

Abbreviations: Al-BP, Aluminum beverage packaging; Al-OP, Aluminum other packaging; Al-P, Aluminum packaging; ARA, Altstoff Recycling Austria; BC, Beverage carton; CC-P, Corrugated cardboard packaging; F, Flow; Fe-P, Ferrous metal packaging; G-P, Glass packaging; HDPE-P, HDPE packaging; IBA, Incineration bottom ash; LPW, Lightweight packaging waste; MA48, Magistratsabteilung 48; MDC, Moisture and dirt content; MSW, Municipal solid waste; MSWI, Municipal solid waste incineration; P, Process; PET-BP, PET beverage packaging; PC-P, Paper & cardboard packaging; PCCC-P, Paper, cardboard & corrugated cardboard packaging; PcPW, Post-consumer packaging waste; SR, Sorting rate; SCR, Separate collection rate; SRM, Secondary raw material; TC, Transfer coefficient.

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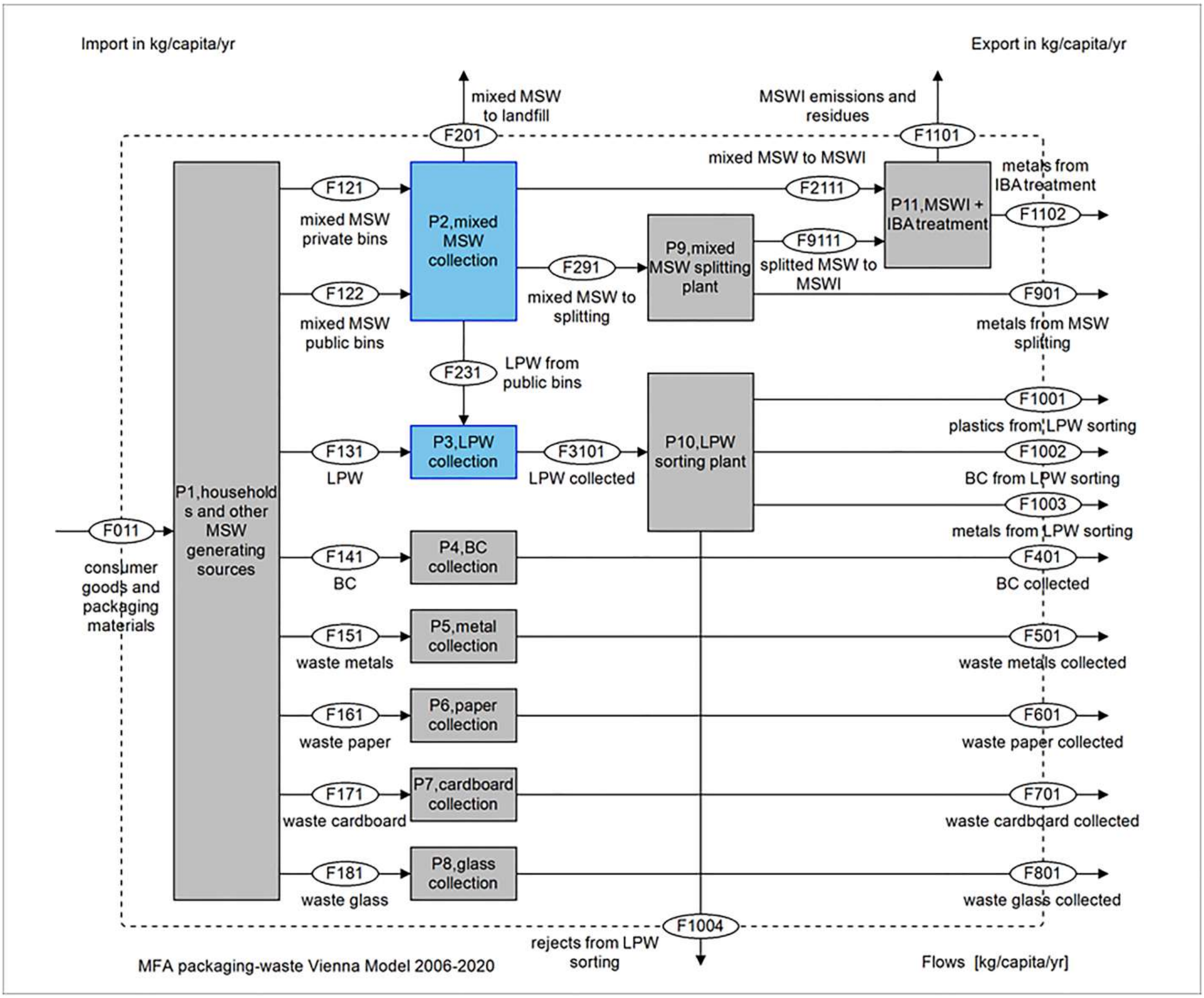

Fig. 1. MFA model of MSW management in Vienna, 2006–2020.

both consider different PcPW streams, they do not distinguish between plastic polymers like PET or HDPE and metals like aluminum and steel, which is essential to evaluate separate collection and recycling efforts as stipulated in EU Directives (EPC, 2019).

To fill these research gaps regarding detailed time series of packaging waste amounts on a detailed material basis together with technical measures of the MSW management in urban areas, this article presents a historical-technical analysis and a time-series MFA of PcPW in a city, considering the most important materials and their provision as SRM for recycling by the separate collection of packaging waste and technical sorting of mixed MSW as well as MSW incineration bottom ash (IBA). Vienna is selected as a case study as it generates more than 20% of the MSW in Austria (BMK, 2023), is larger than the two European cities analyzed by Bertanza et al. (2021) and Wang et al. (2020), and has a well-accessible database provided by the municipal waste management department *Magistratsabteilung 48* (MA48). These data allow material flow modeling and historical analysis to connect changes in material flows of PcPW with causing measures that aimed to achieve a higher provision of SRM. Considering Vienna for the years 2006–2020, the following research questions are asked:

- Which measures in separate collection of PcPW and technical sorting of mixed MSW and IBA have been implemented?
- How have PcPW flows of different materials evolved?
- Which quantities and shares of these have been provided as SRM for recycling?
- What are the future perspectives to increase SRM provision for recycling?

Section 2 presents the methodological background and the data to analyze material flows, secondary raw material provision indicators, and developments of MSW management. Section 3 displays and discusses the results, while Section 4 provides the conclusion.

Details on the data used and results calculated are presented in supplementary-file-1, while supplementary-file-2 shows the MFA results.

2. Methods and materials

The main data sources on MSW flows and information on MSW management were the annual reports of MA48 (MA48, 2021a). The concentration of PcPW materials was taken from Vienna's waste management plans (Ableidinger et al., 2007; Egle et al., 2017; Volk et al., 2012). Additional information was collected by personal communication from MA48 (2021b) and ARA (2021).

2.1. Historical content analysis of MSW management in Vienna

The annual reports of MA48 were objectively and systematically searched for information concerning separate collection and waste treatment technologies in the course of content analysis as described in Titscher et al. (1998), partly as a prerequisite for the MFA and partly to explore explanations for the MFA results.

2.2. MFA of MSW in Vienna

The MFA on MSW, particularly packaging waste, in Vienna was based on Brunner and Rechberger (2016). The MFA system analyzes processes (P) and material flows (F) using the principle of mass conservation. Flows can be calculated for goods (like mixed MSW) and subgoods (materials like packaging waste) contained in these goods. A detailed description of MFA can be found in Subsection S2.2 in supplementary-file-1.

2.2.1. Scope

MSW processes and flows before the actual recycling process are considered, focusing on MSW collection and treatment in Vienna from 2006 to 2020 (Figure S6, supplementary-file-1). Like in Bertanza et al. (2021) and Wang et al. (2020), recycling processes outside of the city were not considered, and like Lopez-Aguilar et al. (2022), Schneider et al. (2022), and Thomassen et al. (2022), neither exports outside of the EU were tracked, nor littering included. Outside of Vienna, only the process of LPW sorting was considered since the LPW sorting plant moved from Vienna to another city in 2017. Goods considered were all MSW flows collected by MA48 and containing the subgoods of packaging wastes. Wastes like biowaste or demolition waste not containing PcPW were not considered. Packaging wastes considered were these separately collected and/or technically sorted for recycling in Vienna, i.e. glass packaging (G-P), ferrous metal packaging (Fe-P), aluminum beverage packaging (Al-BP), aluminum other packaging (Al-OP), paper and cardboard packaging (PC-P), corrugated cardboard packaging (CC-P), beverage cartons (BC), polyethyleneterephthalate beverage packaging (PET-BP), and high-density polyethylene packaging (HDPE-P) (see Figures S1-S5, supplementary-file-1 for images).

2.2.2. System description and calculation of the material flows of goods

The MFA (Fig. 1) was calculated by STAN 2.6 (Cencic and Rechberger, 2008). The numbering of the processes (P) and flows (F) after Lederer et al. (2020) is described in supplementary-file-1, Subsection S2.2.2. Subsystems are blue-colored. Unless otherwise stated, all data came from MA48 (Tables S2-S5, supplementary-file-1).

MSW comes from "households and other MSW generating sources" (P1). The input flow F011 into P1 includes PcPW and was calculated by STAN using the mass balance and data on the output flows, i.e. mixed MSW from private (F121) and public (F122) waste bins and separately collected PcPW (F131-F181). LPW (F131), which consists of plastic bottles, later also BCs and metals, was calculated separately. In contrast, data on BC (F141), waste metal (F151), waste paper (F161), waste cardboard (F171), and waste glass (F181) was readily available (see Table S3 supplementary-file-1). It was assumed that no relevant stock-building takes place in P1, thus consumed goods equals MSW generated.

P2 "mixed MSW collection" contains a subsystem (Figures S8-S10, supplementary-file-1). Some PET-BP and Al-BP from public waste bins are manually collected for recycling (F231). Mixed MSW was landfilled until 2009 (F201) and since then is solely treated in an MSW splitting plant (F291) or incineration plants (F2111).

P3 "separate LPW collection" contains a subsystem. LPWs come from public waste bins (F231) and LPWs (F131), the latter being collected at collection centers (F31321), door-to-door collection from households

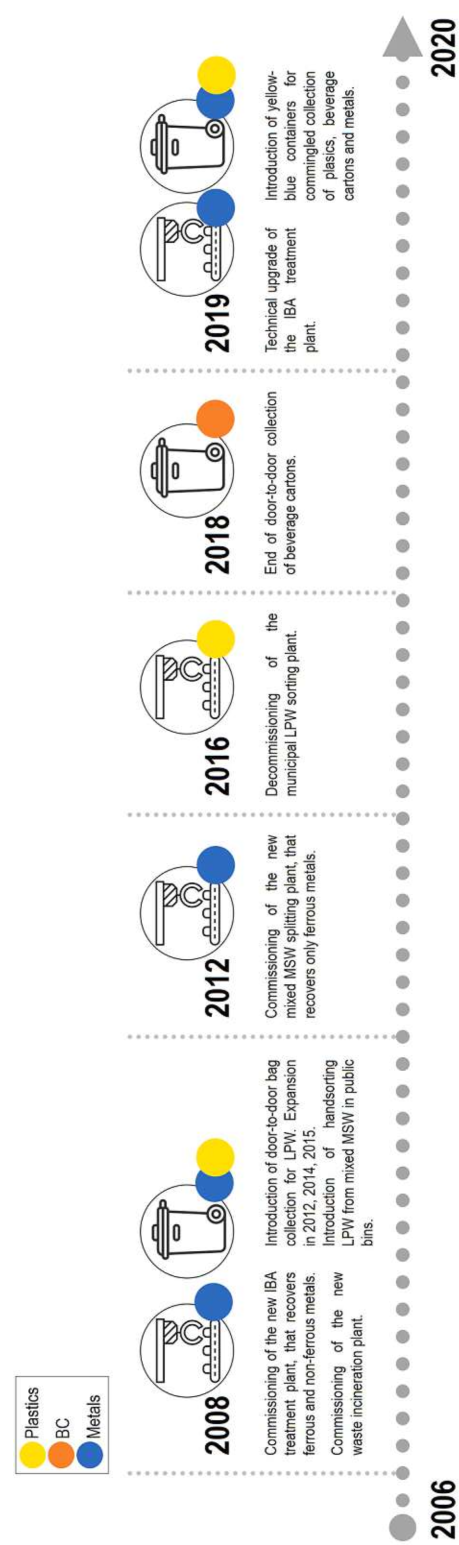

Fig. 2. Timeline of the most important changes in MSW management in Vienna from 2006 to 2020. Icons represent changes or adaptions in waste treatment plants (sorting from a conveyor belt) or changes in waste collection (waste bin). Colored dots represent waste fractions mostly affected by these changes (blue are metals, yellow are plastics, orange are BC).

(F31322) and enterprises (F31323), and collection points (F31324 and F31325) (Figures S11-S14 and Table S2 in supplementary-file-1). F131 and F3101 were calculated in STAN.

P4 is "BC collection", and data came from *Öko-Box* (2014) and ARA (2021) (supplementary-file-1, Table S2 and Figure S17).

P5 is "metal collection" via drop-off points (F501) before sending the material to sorting outside of Vienna.

PC-P and CC-P (F161) are collected by waste paper door-to-door-collection (P6) (supplementary-file-1, Table S2, Figure S19). Bulky waste cardboard consisting of CC-P only (F171) is collected in collection centers (P7). Both are sent to recyclers directly (F601 and F701) (supplementary-file-1, Table S2, Figure S20).

Waste glass (F181) is disposed-off at drop-off points (P8), from where it is sent to recyclers (F801) (supplementary-file-1, Table S2, Figure S21).

The input (F3101) in the LPW sorting plant (P10) is sorted to recyclable plastic (F1001), metals (F1003), BC (F1002), and rejects incinerated outside of Vienna (F1004). Output flows were calculated by STAN, and transfer coefficients (TC) came from ARA (2021) (see supplementary-file-1, Table S1, Figure S24).

From the mixed MSW (F291) treated in the mixed MSW splitting plant (P9), metals are sorted and sent to sorting and recycling outside of Vienna (F901), the rest is incinerated in Vienna (F9111). Data for F291 and F901 came from MA48 (supplementary-file-1, Table S2), and F9111 was calculated using STAN. Mixed MSW from collection (F2111) and splitting (F9111) is incinerated in Vienna (P11). F2111 was calculated in P2 by STAN. The IBA undergoes metal recovery for recycling. The outputs of P11 (emissions and residues F1101 and metals F1102) were calculated by TCs from literature (supplementary-file-1, Table S1 and Figures S25-S26). The different sources for TC were due to the upgrade of IBA treatment in 2009 and 2019 (MA48, 2021a).

2.2.3. *Calculation of material flows of subgoods*

The subgoods for most waste flows were calculated in STAN by multiplying the material flow of goods by the concentration of the subgood in the respective material flow. Data on concentrations were usually not on a net basis, meaning that moisture and dirt contents were not determined and subtracted from the materials. The concentration of the subgoods in material flows F122, F141, F151, F161, F171, F181, F231, F21221, F31322, F31323, F31324 and F31325 came from waste sampling campaigns of MA48 for selected years (MA48, 2021b). For other years they were modeled using best-fit polynomial functions, as shown in Eq. (1).

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_2 x^2 + a_1 x + a_0 = \sum_{k=0}^{k=n} a_k x^k \quad (1)$$

The degree of the polynomial function depends on the number of years for which data were available (see supplementary-file-1, Table S3 for given and Table S4 for modeled concentrations).

For some waste flows, the subgoods were calculated by TCs coming from Skutan and Brunner (2006) and MA48 (2021b) for metals from MSW splitting (F901), from ARA (2021) for LPW sorting (P10), and from MA48 (2021b) and Huber (2020) for IBA treatment (see supplementary-file-1, Tables S2-S3 for details).

2.3. *Indicators for the provision of secondary raw materials*

The material flows were used to calculate indicators that allow a discussion of the material flows in the context of providing SRM upstream to recycling and thus as a base for a CE. Like in other studies, the indicators used were separate collection rate (SCR) and sorting rate (SR) (Bertanza et al., 2021; Wang et al., 2020). The recycling rate was not considered since the regarding processes are outside of the system boundary.

The SCR was calculated by dividing the sum of the the subgoods collected separately for recycling by these generated, as in Eq. (2)

$$SCR_{j,t} = \frac{\sum \dot{m}_{F\ \text{separately collected},j,t}}{\sum \dot{m}_{F\ \text{generated},j,t}} \times 100\ [\%] \quad (2)$$

whereby $SCRj, t$ is the separate collection rate SCR for subgood j in year t, $\sum \dot{m}_{F\ \text{separately collected},\ j,t}$ is the sum of the material flows $\dot{m}_F$ in year t that contain the subgood j which is collected separately for recycling (in this study $\sum \dot{m}_{F\ \text{separately collected},\ j,t} = \dot{m}_{F3101\,j,t} + \dot{m}_{F141\,j,t} + \dot{m}_{F151\,j,t} + \dot{m}_{F161\,j,t} + \dot{m}_{F171\,j,t} + \dot{m}_{F181\,j,t} + \dot{m}_{F231\,j,t}$), and $\sum \dot{m}_{F\ \text{generated},\ j,t}$ is the sum of the material flows $\dot{m}_F$ in year t that contain the subgood j which is generated (in this study $\sum \dot{m}_{F\ \text{generated},\ j,t} = \dot{m}_{F011\,j,t}$).

The SR was calculated by dividing subgoods collected and sorted for recycling by these generated, as in Eq. (3)

$$SR_{j,t} = \frac{\sum \dot{m}_{F\ \text{sorted for recycling},j,t}}{\sum \dot{m}_{F\ \text{generated},j,t}} \times 100\ [\%] \quad (3)$$

whereby $\dot{m}_F$ is the sorting rate SR for subgood j in year t, $\sum \dot{m}_{F\ \text{sorted for recycling},\ j,t}$ is the sum of the material flows $\dot{m}_F$ in year t that contain the subgood j which is sorted for recycling (in this study $\sum \dot{m}_{F\ \text{sorted for recycling},\ j,t} = \dot{m}_{F1001\,j,t} + \dot{m}_{F1002\,j,t} + \dot{m}_{F1001\,j,t} + \dot{m}_{F401\,j,t} + \dot{m}_{F501\,j,t} + \dot{m}_{F601\,j,t} + \dot{m}_{F701\,j,t} + \dot{m}_{F801\,j,t} + \dot{m}_{F901\,j,t} + \dot{m}_{F1102\,j,t},$), and $\sum \dot{m}_{F\ \text{generated},\ j,t}$ is the sum of the material flows $\dot{m}_F$ in year t that contain the subgood j which is generated (in this study $\sum \dot{m}_{F\ \text{generated},\ j,t} = \dot{m}_{F011\,j,t}$).

This means that the SR consists of the SCR minus losses in sorting separate collected PcPW (for instance in the LPW sorting plant), but plus PcPW sorted from mixed MSW or MSW IBA.

3. Results and discussion

3.1. *Historical content analysis of MSW management in Vienna*

The result of the content analysis is a timeline displaying the history of MSW management in Vienna (Fig. 2) with the most important changes in waste collection, treatment, and technical sorting, including the fractions mostly affected.

In the second half of 2008, before the ban on landfilling of untreated mixed MSW came into force, a new MSW incineration and IBA treatment plant went into operation, the latter removing ferrous and nonferrous metals. In addition, a trial was started to sort out plastic bottles and beverage cans from public waste bins by street cleaning staff, which went into regular operation in 2009. In the same year, door-to-door yellow bag collection of LPW was started in selected areas and gradually expanded.

In 2012, the new splitting plant for mixed MSW replaced the old one, processing MSW for storage and incineration in a fluidized bed (supplementary-file-1, Figures S22–23). Unlike the old plant, the new one recovered ferrous metals, but not non-ferrous metals. Since 2016, LPW sorting was not anymore within but outside of Vienna.

In 2018, the door-to-door collection of BCs (supplementary-file-1, Figure S15) was ceased, and BCs were collected together with plastic bottles. After a successful pilot test in April 2018, the new blue-yellow container/bag was introduced 2019 and provided with a new emblem depicting some of the new main target LPW fractions now commingled collected (PET-BP, HDPE-P, Al-BP, and BC – see supplementary-file-1, Table S2, Figure S16 and S18). For Al-OP and Fe-P, which are also collected with LPW, no emblem was labeled on the containers. In the same year, improvements of the IBA processing aimed to increase the recovery of nonferrous metals.

In addition to these punctual measures, the total number of separate collection containers per capita gradually changed between 2006 and 2020. Consequently, the number of separate collection containers per capita increased for LPW (Al-BP, Al-OP, BC, Fe-P, HDPE-P, PET-BP) but slightly decreased for G-P and PCCC-P. While the relation between amounts separately collected and the number of separate collection containers (both per capita) is shown in Figure S49 (supplementary-file-1), the impacts of both, the punctual measures and the gradual changes, are discussed in the context of SRM provision indicators in Subsection 3.3.

3.2. Material flows of packaging wastes in Vienna 2006–2020

3.2.1. Glass

Glass packaging in MSW (F011) increased between 2006 and 2020 from 28 to 32 [kg/capita/yr]. This trend corresponds with national G-P statistics of 32 to 35 [kg/capita/yr] in 2015 and 2020, respectively (BMK, 2023). The amount of glass packaging in Vienna almost equally distributes between separate and mixed MSW collection (supplementary-file-1, Figures S27-S28).

3.2.2. Metals

Metal packaging in MSW (F011) decreased from 6.5 to 5.8 [kg/capita/yr] between 2006 and 2020, mainly due to a decrease in Fe-P (4.1 to 3.1 kg/capita/yr) (see Fig. 3). Al-P increased from 2.4 to 2.6 [kg/capita/yr] (supplementary-file-1, Figures S29-S35). National statistics contradict this trend reporting an increase in metal packaging from 6.6 to 7.3 [kg/capita/yr] from 2015 to 2020 (BMK, 2023). Therein, Al-P matches quite well (2.7 kg/capita/yr in Austria), while Fe-P does not (4.6 kg/capita/yr in Austria). Results are shown in Fig. 3 for Fe-P.

3.2.3. Paper

PCCC-P in MSW increased between 2006 and 2020 from 32 to 35 [kg/capita/yr] (Fig. 4). The trend is comparable to national statistics, but the total amount is not. BMK (2023) reports 64 and 69 [kg/capita/yr] in 2015 and 2020, respectively. ARA (2022) reports that 64 [kg/capita/yr] of PCCC-P and non-packaging paper were collected separately. The latter fraction is likely included in the national statistics, explaining the difference to this study. In Vienna, the increase was mainly due to PC-P because of increasing e-commerce and delivery services, i.e. during COVID-19 (Ratchford et al., 2022; Szász et al., 2022; Yeo et al., 2017). However, CC-P still dominates PCCC-P with over 60%.

3.2.4. BCs

BCs in MSW (F011) decreased from 4.0 to 3.0 [kg/capita/yr] between 2006 and 2020, an amount equal to the one in the Netherlands (Schneider et al., 2022). The amount separately collected in [kg/capita/yr] remained constant at 0.35–0.38 from 2006 to 2015, dropped to 0.21 in 2018, but increased to 0.55 in 2020 (supplementary-file-1, Figure S43).

3.2.5. Plastics

HDPE-P (1.56 to 1.45 kg/capita/yr) and PET-BP (5.60 to 5.32 kg/capita/yr) in MSW (F011) decreased between 2006 and 2020, but the amount separately collected increased for both (HDPE-P 0.19 to 0.45 and PET-BP 1.25 to 1.87 kg/capita/yr), mainly due to the large increase in 2019–2020 (Fig. 5). Van Eygen et al. (2018) found quite similar amounts of 5 [kg/capita/yr] PET-BP, but higher amounts of 4 [kg/capita/yr] of HDPE-P in Austria. The reason for this difference is unclear and should receive further attention.

3.3. SRM provision indicators versus technical measures in MSW management

Fig. 6 shows the SRM provision indicators SCR and SR. These are discussed for each material in the subsequent subsections.

3.3.1. Glass

Since glass is only extracted for recycling by separate collection, SCR and SR are identical, slightly increasing from 53% to 55% between 2006 and 2020 (supplementary-file-1, Figure S50). In comparison, the SCR in Austria decreased between 2015 and 2020 but from a higher level (BMK, 2023). In Nottingham, the SR started at 31% in 2006 and increased to 59% in 2016, but not taking extraneous materials in separately collected glass into account (Wang et al., 2020). Contrary to Nottingham, where the number of disposal sites for separate glass collection was increased, they were reduced in Vienna on a per-capita basis. At the same time, higher amounts were collected (Figure S49, supplementary-file-1). This effect contradicts the literature, suggesting that the number of collection drop-off points always positively correlates with packaging waste quantities collected (Bertanza et al., 2021; Wang et al., 2020). One explanation is that there is a saturation level for the SCR of glass in Vienna at about 50–60%, after which further changes in the service do not increase the SCR, like in PET-BP collection in Switzerland (Haupt et al., 2018). Furthermore, Seyring et al. (2016) showed that separate collection via drop-off points, as practiced in

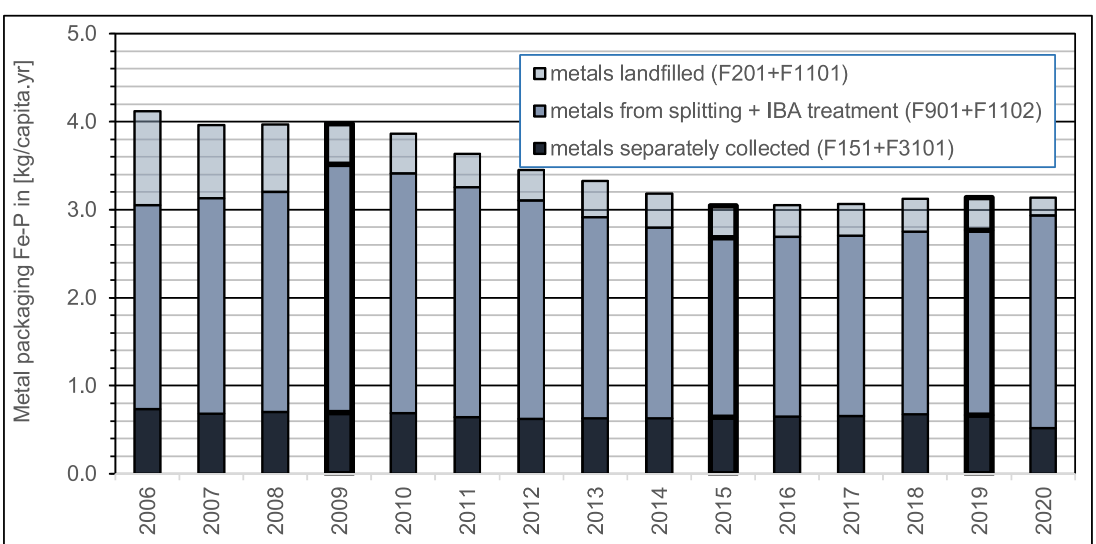

Fig. 3. Distribution of ferrous-metal-packaging (Fe-P) in MSW to different disposal and recycling routes in Vienna, 2006–2020, in [kg/capita/yr]. A bold frame indicates years for which a complete dataset of quantities and concentrations of material flows was available. Data for Al-BP and Al-OP can be found in the supplementary-file-1, Figure S33-S34.

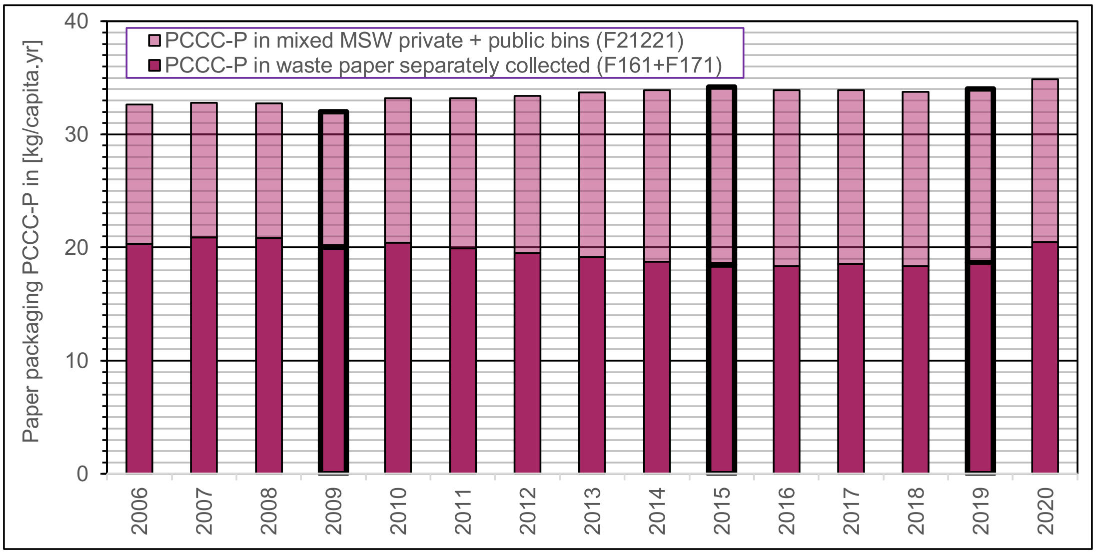

Fig. 4. Paper packaging PCCC-P in MSW in Vienna, 2006–2020, in [kg/capita/yr]. A bold frame indicates years for which a complete dataset of quantities and concentrations of material flows was available. For details of the individual fractions, see supplementary-file-1, Figure S38-S40.

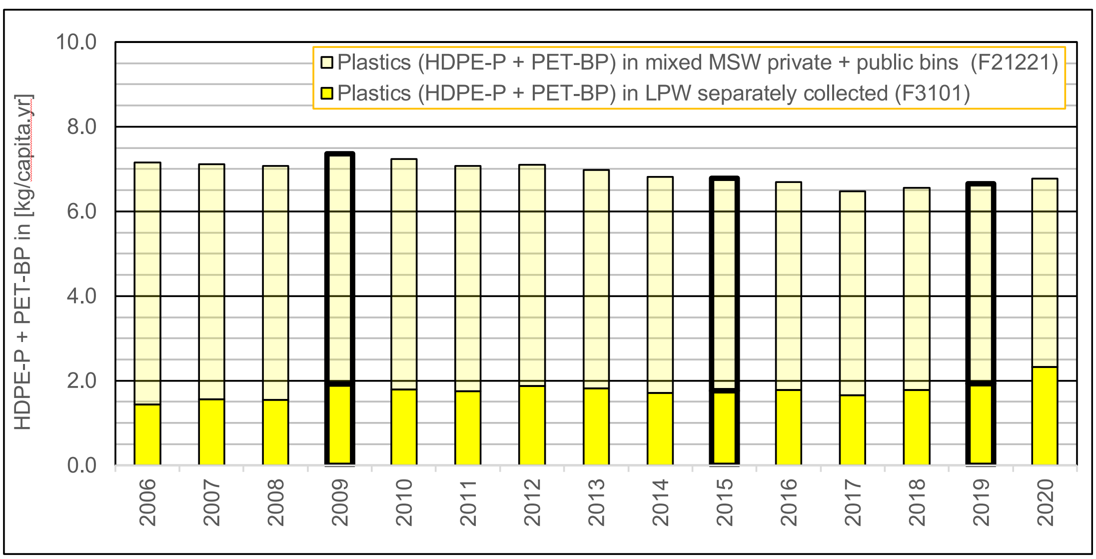

Fig. 5. Plastic packaging HDPE-*P* + PET-BP in MSW in Vienna, 2006–2020, in [kg/capita/yr]. A bold frame indicates years for which a complete dataset of quantities and concentrations of material flows was available. More details can be found in the supplementary-file-1, Figures S46-S48).

Vienna, is the most suitable glass collection technique since door-to-door collection is too noisy (Everett et al., 1998). These results indicate that in order to increase SRM provision, the SR should be increased even if the SCR remains constant.

3.3.2. Metals

Between 2006–2019, the number of separate collection containers per capita for metals at drop-off points slightly decreased before it increased after the inclusion of metals in LPW collection (Figure S49, supplementary-file-1). This last modification positively influenced the SCR of Al-BP, but not of Al-OP and Fe-P, of which the SCR even decreased (Figures S51-S53, supplementary-file-1). A possible explanation is that Al-OP and Fe-P were illustrated on the old metal containers but not on the new LPW containers (see supplementary-file-1, Figures S16 and S18). Furthermore, a saturation level for Al-OP and Fe-P might have been reached, calling for more focus on mixed MSW and IBA treatment to recover these metals (Feil et al., 2017). Recovery of metals from MSW or IBA can have a high impact, as the increasing SR for Al-P and Fe-P between 2006 and 2020 shows (supplementary-file-1, Figures S51-S54). The increases in 2008–2009 and 2019–2020 were due to improvements in the IBA treatment. No such increase was recorded in Nottingham, and the SR dropped from 64.5% in 2006 to 62.2% in 2016 (Wang et al., 2020).

3.3.3. Paper

There is no difference between the SCR and the SR for PCCC-P. Both indicators rely on separate collection (supplementary-file-1, Figure S55). In comparison, in Nottingham and Brescia, the SCR increased to values slightly below and above that of Vienna (Bertanza et al., 2021; Wang et al., 2020). This indicates that introducing door-to-door collection in these cities helped to achieve a similar SCR to Vienna, where the door-to-door collection of PCCC-P has been practiced for many decades.

Some challenges for the SCR of PCCC-P in Vienna exist. The increasing bulkiness of PCCC-P led to the introduction of pictorial instructions on containers to fold the paper waste before disposal

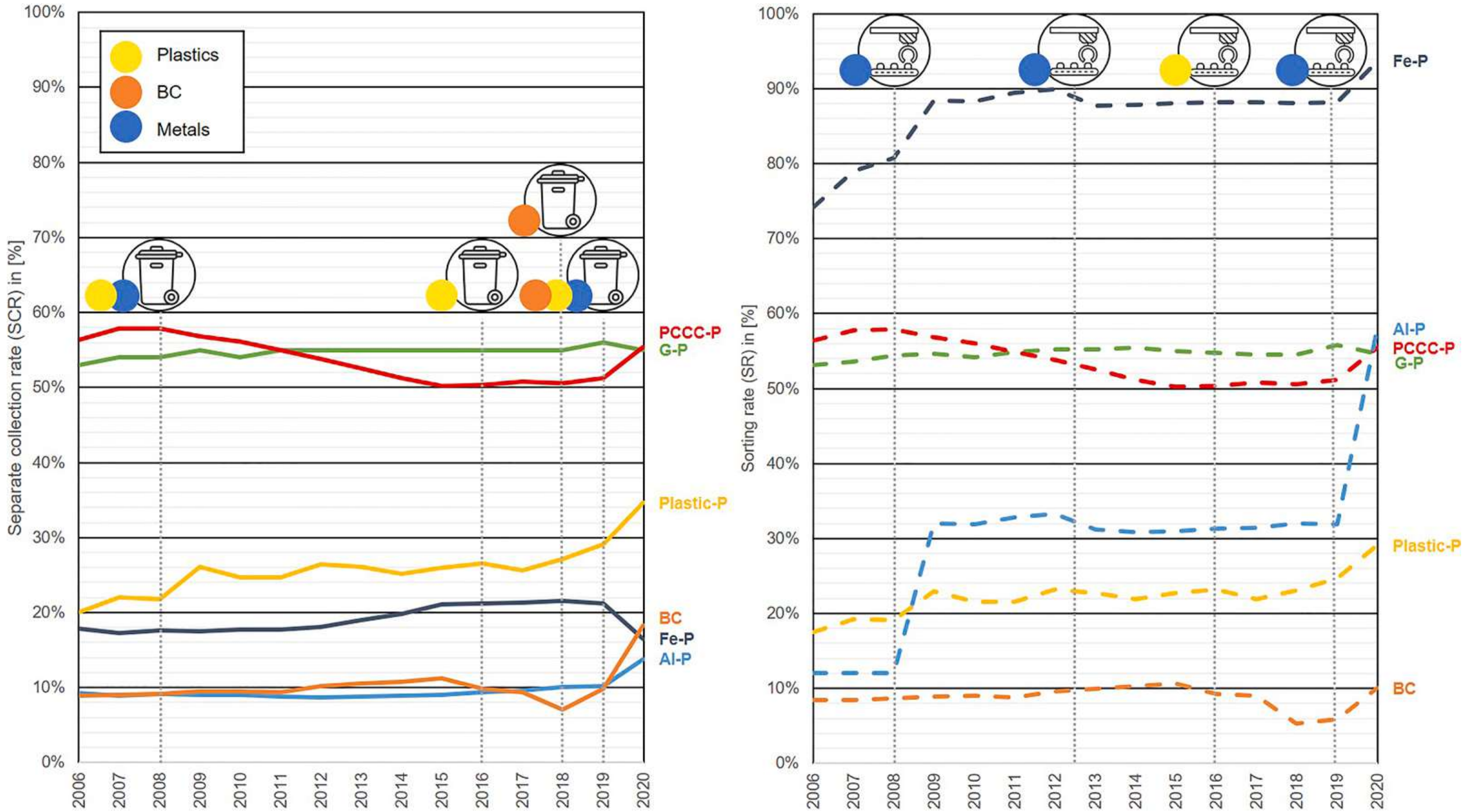

Fig. 6. Separate collection rate (SCR) and sorting rate (SR) for selected packaging waste subgoods in Vienna, 2006–2020. Icons highlight changes or adaptions in waste treatment plants (sorting from a conveyor belt) or changes in waste collection (waste bin). Colored dots represent waste fractions mostly affected by these changes (blue: metals, yellow: plastics, orange: BC).

(supplementary-file-1, Figure S19). Bulky CC-P contributes more to the general SCR of PCCC-P, possibly because they are perceived to be more valuable than the smaller PC-P, which rather end up in the mixed waste (Nemat et al., 2022; Thoden van Velzen et al., 2019).

3.3.4. BCs

SCR and SR (about 10%) were almost identical for BC until 2017, when BCs were collected via door-to-door collection and sent directly to recycling without any sorting losses. After that, the SCR doubled from 9% to 18% in 2020, while the SR remained at 10%. The increase in the SCR was due to more separate collection by the blue-yellow container, but the subsequent LPW sorting now required caused the losses (supplementary-file-1, Figure S56). However, the doubling of the SCR between 2018 and 2020 indicates that the communication with consumers works, and a further increase in the SCR might be possible.

3.3.5. Plastics

The number of LPW containers increased significantly, simultaneously the SCR for PET-BP+HDPE-P (20% in 2006 to 35% in 2020). The first increase from 2008 to 2009 can be explained by sorting out plastic bottles from public waste bins and introducting door-to-door bag collection. However, the latter was only implemented in selected single-family-house areas, which are with only 9% of the population of low quantitative relevance in Vienna (MA23, 2015). The latest and largest increase in the SCR was due to the blue-yellow container in 2019 (supplementary-file-1, Figures S57-S59). Particularly the SCR of fractions with pictorial representation on the collection containers increased (supplementary-file-1, Figures S15-S16).

The SR for plastic was generally lower than the SCR due to the losses in LPW sorting, particularly for HDPE-P and to a lesser extent for PET-BP, indicating a higher sorting efficiency of PET-BP (supplementary-file-1, Figures S57 and S58). Comparing the results to Austria, Brescia, or Nottingham is difficult since these are not on the level of polymers. Establishing a door-to-door collection in order to increase SCR, like in Brescia and Nottingham, is also possible in Vienna, even though it is unclear to which extent extraneous material is present in Brescia and Nottingham.

3.4. Future perspectives to increase SRM provision for recycling from Vienna

The analysis of Vienna's MSW management 2006–2020 shows how organizational and technical interventions can influence the provision of SRM for recycling. Yet, the question is how these and other experiences from urban areas can be used to further increase the provision of SRMs?

3.4.1. Commingled collection of PcPW

The blue-yellow container had a high impact on the SCR of selected LPWs, possibly due to a higher convenience for the consumers who had to collect and store only one instead of three fractions at home, but also since more collection points have been available, reducing the distance to these (Brouwer et al., 2019; Dahlén et al., 2007; Roosen et al., 2022; Rousta et al., 2015; Thomassen et al., 2022; Thoden van Velzen et al., 2019). A further opening to other fractions, including films which was already made mandatory by 2023 by the Austrian Government (Schuch et al., 2023), is inviting. However, from the material fractions in this study, only PCCC-P or G-P would remain to be included in the commingled PcPW collection (Wang et al., 2020). Considering the, if compared to other materials, already high SCR of both materials and the quality deterioration (i.e. higher water content), particularly of PCCC-P in commingled collections (Miranda et al., 2013), it is questionable whether this is advisable.

3.4.2. Extension of separate collection to door-to-door service

For PCCC-P and G-P, introducing a door-to-door collection is not an option since it is already established for PCCC-P but too noisy to be established for G-P. For LPW, it would be possible and an opportunity to further increase consumer convenience by shortening disposal routes (Schuch et al., 2023). Since door-to-door collection means higher efforts (e.g. costs, collection emissions), can lead to higher contents of extraneous materials, and possibly does not increase amounts as expected, it must be carefully planned (Brouwer et al., 2019; Haupt et al., 2018; Thoden van Velzen et al., 2019). This can be done by analyzing past experiences and carrying out large-scale tests. In any case, it must be considered that Austria will make a deposit-refund system for Al-BP and PET-BP in 2025 mandatory (BMK, 2023). The impacts of these changes are not entirely clear and could be investigated in such experiments in addition.

3.4.3. Communication with consumers by pictorial representation

The increase of HDPE-P but decrease of Fe-P in LPW collection in 2019 indicate that pictorial representations likely have a decisive influence on communicating information about the separate collection (Rousta et al., 2015). While this effect is still not fully understood and requires further investigation, including experiments, it would still be an option to increase the SCR of PcPW, which has been little represented in pictures on collection containers so far. This counts for Al-OP, Fe-P, and PC-P.

3.4.4. Technical sorting of mixed MSW

To increase the SR of LPW, an improvement of the LPW sorting technology would be required (Antonopoulos et al., 2021), but this lies beyond the decision of the City of Vienna. Contrary to that, upgrading the existing mixed MSW splitting plant in Vienna to a technical sorting plant that also recovers aluminum, plastic, and paper would be possible and is also suggested for areas where the separate collection may have reached its saturation level. Next to sorting technology, the quality of the produced materials has to be assessed before implementation, particularly for paper (Cimpan et al., 2015; Feil et al., 2017).

3.4.5. Technical sorting of IBA

The differences in the SCR and SR for metals show that IBA treatment increases the SRM provision (Astrup et al., 2016; Šyc et al., 2020). However, considerable losses due to oxidation must be accepted, especially in the case of aluminum, but also a general deterioration of the quality of metals by surface coating (Biganzoli et al., 2014; Biganzoli and Grosso, 2013; Gökelma et al., 2021; Mehr et al., 2021). Therefore, separate collection should be prioritized in order to conserve material for recycling in high quality, and technical sorting, particularly of IBA, should be used as a backup (Lederer et al., 2022). While the technology for metal recovery was and can further be improved, particularly for non-ferrous metals (Grosso et al., 2011; Šyc et al., 2020), other materials can also be targeted, including glass-packaging (Bruno et al., 2021; Mühl et al., 2022).

3.5. Limitations and further research

MFA is always associated with data uncertainties, in the present work regarding the waste quantities and compositions (see supplementary-file-1, Table S7). While data on quantities of mixed MSW and separately collected waste is available annually, the waste composition is only analyzed every five years, similar to other cases (Thomassen et al., 2022). This could be overcome by more frequent data collection on waste composition. The costs of this are usually the inhibiting factor, thus, it is suggested to develop more cost-effective sampling techniques.

In waste composition, statistical and analytical uncertainties must be distinguished. Statistical uncertainties derive from the sample selection and can be calculated if samples were randomly selected. In the present case, this should be guaranteed as sampling was done similarly to the Austrian sampling guideline (Beigl, 2020). These statistical uncertainties are shown in Table S7 in the supplementary-file-1. Analytical uncertainties derive mainly from moisture and dirt content (MDC), which can account for a considerable share of gross mass. For plastics and BCs, values between 3–32% MDC can occur (Calero et al., 2018; Gala et al., 2020; Rodríguez-Liébana et al., 2022; Thoden van Velzen et al., 2013). Consequently, MDC distorts the true mass of packaging materials and requires further investigations in Vienna. These must cover PcPW in mixed MSW, as already practiced in Austria (Beigl, 2020; Schuch et al., 2023), and also PcPW in separate collection.

Having modeled all material flows of PcPW in Vienna, the SCR and the SR were calculated, but not the recycling rate. Even though this might be seen as a limitation of the present work, it is just a consequence of the definition of the scope of this article, which is limited to the geographical area of Vienna. It would have been possible to calculate the recycling rate for PcPW from Vienna using TCs for the recycling processes from literature (Dworak et al., 2022; Schneider et al., 2022; Thoden van Velzen et al., 2013; Van Eygen et al., 2018; Warrings and Fellner, 2021). This, however, would have meant breaking with the principle of this article to mainly use first-hand and hitherto unpublished primary data for MSW management in Vienna. Future works may include these technical processes in order not only to calculate the recycling rate but in addition to estimate the SCR and SR required to achieve the recycling targets in the EU.

4. Conclusion

This work analyzed the history of material flows of packaging waste in Vienna concerning SRM provision for recycling, thus contributing to a circular economy. This is essential to evaluate which measures by municipal authorities have been more or less effective. The basis for this is a sound database, whereby regular and careful data collection on quantities but also qualities of packaging waste is crucial. Even though further improvable, this is a strength of MSW management in Vienna, which should motivate not only other cities to present data of the same quality as Vienna, but also researchers to analyze these data. By doing so, increasing (glass, paper) and decreasing (metals, BC, plastics) volumes of PcPW were found in MSW between 2006 and 2020. Such information is highly relevant in the absence of more detailed production and consumption data of PcPW. The study found that commingled collection of PcPW and increasing the number of collection points increased the SCR of PET-BP, BC, and Al-BP, while the SCR for Al-OP, Fe-P, G-P, and PCCC-P remained constant or decreased. Through technical sorting of IBA, significantly higher shares of metal were provided as SRM for recycling. However, for separately collected plastics and BC, the LPW sorting led to losses compared to SCR. From a future perspective, the study also showed that Vienna still has to increase the SRM provision. While some measures for that lie in the hands of stakeholders beyond the City of Vienna, like deposit-refund systems for Al-BP and PET-BP, uniform separate collection for all plastic PcPW, and improvement of LPW sorting plants, others can be implemented by municipal authorities and companies. These are i) improving the communication with customers, for instance by pictorial representations on separate collection containers, ii) introducing door-to-door collection for LPW, iii) further improving the technical sorting of IBA, and iv) attempting to sort out more metals, but also plastics and possibly paper from mixed MSW. Which of these measures may deliver the best results has to be investigated by ex-post evaluation, large-scale experiments, and subsequent material flow modeling.

CRediT authorship contribution statement

Lea Gritsch: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Jakob Lederer:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.106975.

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Corrigendum

Corrigendum to 'A historical-technical analysis of packaging waste flows in Vienna', Resources, Conservation and Recycling 194 (2023), 106975

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In our article titled 'A historical-technical analysis of packaging waste flows in Vienna', recently published in Resources, Conservation and Recycling 194 (2023), 106975, we erroneously reported the secondary raw material (SRM) provision indicators of the separate collection rate (SCR) and the sorting rate (SR) of paper, cardboard, and corrugated cardboard packaging (PCCC-P) in Vienna as 56% in the years 2006 and 2020 in the abstract. These figures need to be corrected to 62% in the year 2006 and 59% in the year 2020. As a consequence, Fig. 6 in Section 3.3 of the main article and Fig. S55 in Section S3.3.3 of the Supplementary-file-1 also need to be corrected. The corrected Fig. 6 (corrected) is shown below.

The reason for this confusion of datasets, which goes on behalf of Jakob Lederer, was that the dataset for PCCC-P in the original article included beverage cartons (BCs) in the PCCC-P fraction. The comparatively low separate collection rate and sorting rate of BCs reduced the overall values for the whole PCCC-P fraction. Even though BCs mainly consist of cardboard, they have been shown separately in Fig. 6. Therefore, they have to be excluded from the PCCC-P fraction, as done in Fig. 6 (corrected) and Fig. S55 (corrected) in this corrigendum.

We apologize for any inconvenience caused by this error. A high-resolution and full-size image of Fig. 6 (corrected) will be published along with this corrigendum.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107074.

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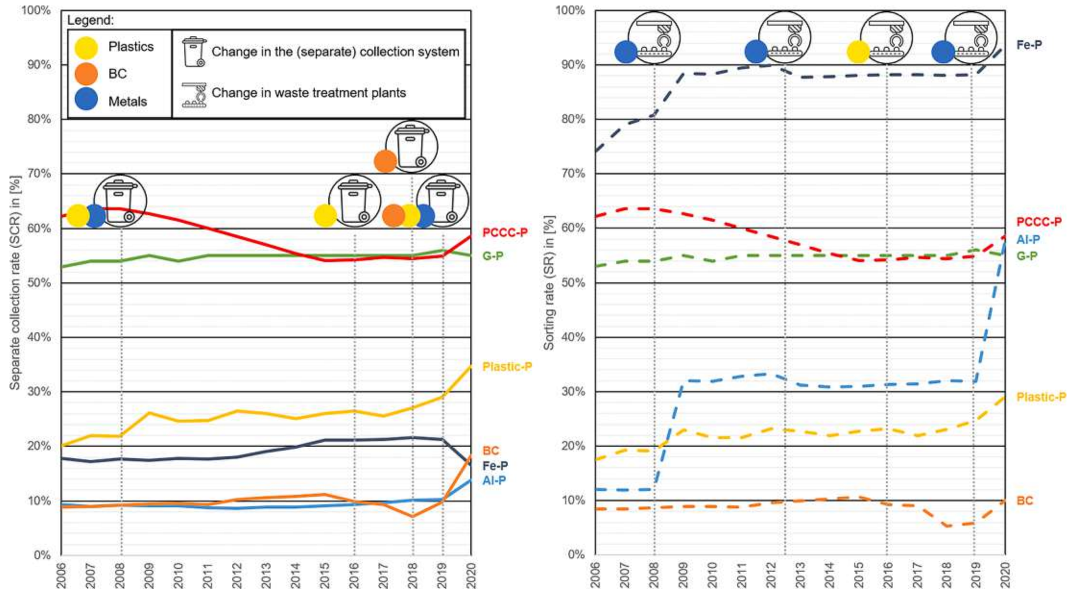
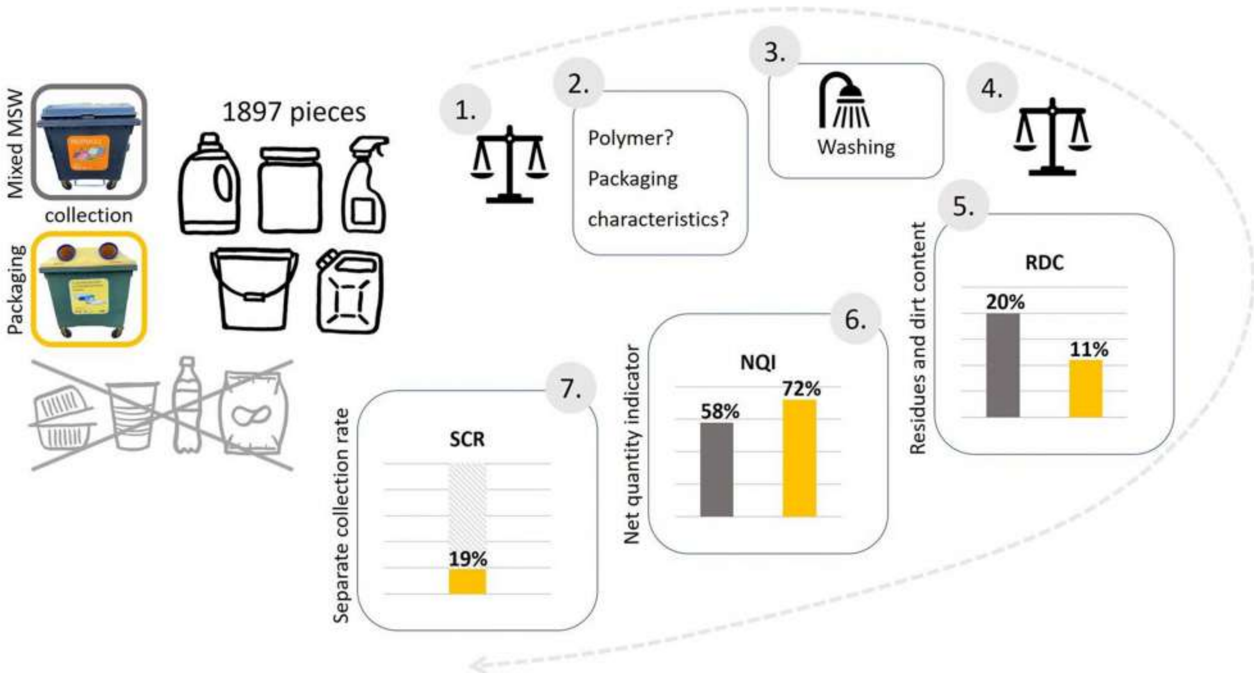


Fig. 6. (corrected). Separate collection rate (SCR) and sorting rate (SR) for selected packaging waste subgoods in Vienna, 2006–2020. Icons highlight changes or adaptions in waste treatment plants (sorting from a conveyor belt) or changes in waste collection (waste bin). Colored dots represent waste fractions mostly affected by these changes (blue: metals, yellow: plastics, orange: BC).

Paper II

Gritsch, L., Breslmayer, G., Rainer, R., Stipanovic, H., Tischberger-Aldrian, A., Lederer, J., 2024. Critical properties of plastic packaging waste for recycling: A case study on non-beverage plastic bottles in an urban MSW system in Austria. *Waste management* (New York, N.Y.) 185, 10–24. https://doi.org/10.1016/j.wasman.2024.05.035.

Graphical abstract



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Research Paper

Critical properties of plastic packaging waste for recycling: A case study on non-beverage plastic bottles in an urban MSW system in Austria

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A R T I C L E I N F O

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A B S T R A C T

The low recycling rate of post-consumer plastic packaging waste (PPW), which is partly due to insufficient separate collection, heterogeneous composition and high levels of contamination, poses a challenge in Austria, where the recycling rate must double in order to meet the target of 55 %. This study analyzes key packaging characteristics of non-beverage plastic bottles influencing recyclability, using Vienna as a case study. Additionally, a net quantity indicator and separate collection rates were calculated. 738 bottles from mixed MSW and 1,159 bottles from separate PPW collection were analyzed. The main polymer's proportion described by the net quantity indicator was higher for bottles from separate collection (69–72 %) than from mixed MSW (58 %), showing that a large share of the foreign materials are residues and dirt, with significantly higher contents in mixed MSW (20 %) than in separate collection (11 %). With a separate collection rate of 19.2 %, the great potential for recycling currently lies in mixed MSW at 4,112 t/yr. Thereof, 46 % is uncolored, 54 % is colored/white and, in terms of material grade, 30 % is food grade. The most common filling volume for PET, PP and HDPE was $0.5 < x \leq 1.5$ L (23–59 %) and the most common decoration technology was label (60–85 %). PET and PP had the highest shares of food-grade bottles (37–46 %), while PP had the highest share of colored bottles (22–31 %). The mechanical recycling potential of bottles depends largely on packaging characteristics, influencing separate collection and also automatic sorting. Harmonized design specifications are therefore crucial for this heterogeneous PPW fraction.

1. Introduction

Modern societies heavily rely on packaging for the transportation and delivery of goods (Robertson, 2012). Paper (36 %) and plastics (34 %) dominate packaging materials, with plastic showing a significant growth since the 1940s due to its cost-effectiveness and versatility (Emblem, 2012a; Shogren et al., 2019). Plastic packaging, which is mainly used for food and beverages, constitutes 39.1 % of European plastic demand (Emblem, 2012b; Plastics Europe, 2022). Plastic packaging has a short lifespan, leading to substantial primary raw material consumption, primarily derived from fossil sources (Huysman et al., 2017; Plastics Europe, 2022; Robertson, 2012; Shogren et al., 2019).

Despite the substantial role of packaging, public perception is often negative (Robertson, 2012). Plastic packaging has gained particular attention in public discourse, fueled by images of ocean pollution and garbage patches (Connan et al., 2021; Emblem, 2012a; Nguyen et al., 2020; Rhein and Schmid, 2020; Ryan, 2014). Improperly managed plastic packaging waste (PPW) not only poses environmental threats but also raises awareness about the need for responsible disposal (Beaumont et al., 2019; Hale et al., 2020; Jambeck et al., 2015; Nguyen et al., 2020; Qi et al., 2020).

Efforts to prevent PPW are underway (EC, 2022a), yet its generation is still expected to rise by 61 % by 2040 (EC, 2022b). Despite recycling initiatives, the current PPW recycling rate in Europe is only 38 % (EUROSTAT, 2022), highlighting the need for enhanced recycling practices to reduce the environmental impacts of PPW. This also counts

Abbreviations: HDPE, high-density polyethylene; LDPE, low-density polyethylene; MA 48, *Magistratsabteilung 48*; MFA, material flow analysis; MSW, municipal solid waste; NQI, net quantity indicator; NB-PB, non-beverage plastic bottle; PB, plastic bottle; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PPW, plastic packaging waste; PS, polystyrene; PVC, polyvinyl chloride; RDC, residues and dirt content; SCR, separate collection rate.

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for countries with a long tradition of separate collection and recycling of PPW, like Austria, which achieves high recycling rates for all packaging waste except plastics, where a recycling rate of only 25.3 % (BMK, 2023a) was achieved in the year 2020 when applying the new calculation method (EC, 2019). Among the different PPW products, beverage bottles, which are mainly made of polyethylene terephthalate (PET), have the highest recycling rates, while other plastic bottles (PB) and hollow bodies show very low separate collection and recycling rates (Antonopoulos et al., 2021; Van Eygen et al., 2018), particularly in urban areas (Schuch et al., 2023).

From 2030, only recyclable packaging will be allowed (EC, 2022a), which requires effective collection, sorting and recycling (EC, 2022a). Design *for* Recycling and Design *from* Recycling go hand in hand here. This means that packaging must be designed to be recyclable, on the one hand, and can be reused as secondary raw material in new packaging, on the other (Alassali et al., 2021). However, plastic recycling currently faces challenges due to the lack of uniform specifications and standards for PPW recyclability (Eriksen and Astrup, 2019; Hahladakis and Iacovidou, 2018). As a consequence, post-consumer PPW, the main input-material for recycling, is very heterogeneous in terms of polymers (PET, PP, PE, etc.), packaging types (bottles, trays, films, etc.), decoration design (direct print, label, plastic sleeve, etc.) and product types (food, cosmetics, cleaning products, ect.) (Feil and Pretz, 2020; Seier et al., 2023; Soares et al., 2022; Vogt et al., 2021) and contains a certain amount of impurities like foreign materials or product residues (Eriksen and Astrup, 2019; Gabriel et al., 2023; Roosen et al., 2020). These packaging characteristics have a strong influence on subsequent processing steps like sorting and recycling and consequently affect the recyclability of PPW. Sorting, which is usually done using near-infrared technology, can be challenging owing to large labels, sleeves or dark colors, and small sizes can also be a challenge (Ding and Zhu, 2023; Faraca and Astrup, 2019; Gabriel et al., 2023; Gürlich et al., 2022; Ragaert et al., 2017). Recycling challenges include issues with added dyes, label fibres and polymer contamination (Borealis, 2019; Madden et al., 2023; RecyClass, 2022a). Residues in packaging can also make proper sorting more difficult and increase the effort required in the recycling process, thus reducing recyclability and requiring further consideration (Borealis, 2019; Gürlich et al., 2022; RecyClass, 2022a; Thoden van Velzen et al., 2019; Wohner et al., 2019).

Each link in the plastic value chain, including packaging design, waste collection, sorting and reprocessing, plays an important role in the quality of the recycled product (Ragaert et al., 2017). Although the various process steps of mechanical recycling can remove many impurities and compensate for undesirable properties, the final quality is highly dependent on the purity of the input stream (Mager et al., 2023; Shamsuyeva and Endres, 2021). Consequently, without knowledge of the key characteristics of PPW that affect quality and recyclability, it can be difficult to recycle and use PPW as a secondary raw material (Hahladakis and Iacovidou, 2018; Seier et al., 2023; Tsochatzis et al., 2022). Waste characterization is therefore the first key to the efficient recycling of PPW for the production of high quality end products and is therefore urgently needed (Eriksen and Astrup, 2019; Faraca and Astrup, 2019; Roosen et al., 2020; Soares et al., 2022).

There is already a large number of papers dealing with post-consumer PPW, with several employing material flow analysis (MFA) on country levels to calculate recycling rates, such as Van Eygen et al. (2018) for Austria, Brouwer et al. (2018) for the Netherlands, Picuno et al. (2021) for Germany and Antonopoulos et al. (2021) for the European Union. Tallentire and Steubing (2020) calculated the recycling rates of different packaging materials, including plastic, for current waste collection in Europe as well as for a best practice scenario, while Thomassen et al. (2022) calculated several improvement scenarios for post-consumer PPW mangement and a retrospective time series of post-consumer PPW, and Roosen et al. (2022) calculated scenarios for various targeted plastic packaging, including collection and sorting efficiencies in Belgium. All of the above studies present the MFA at a polymer level and show that PET, polypropylene (PP), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS) and polyvinyl chloride (PVC) are the most common polymers in post-consumer PPW, often combined in so-called multilayers (Ragaert et al., 2017). Most of the studies also consider packaging types (Brouwer et al., 2018; Picuno et al., 2021; Roosen et al., 2022; Van Eygen et al., 2018).

While PET beverage bottles are almost always treated as a single category in MFAs and studies (Brouwer et al., 2019; Dahlbo et al., 2018; Roosen et al., 2020; Roosen et al., 2022; Schmidt and Laner, 2021; Thoden van Velzen et al., 2019; Van Eygen et al., 2018), the nomenclature for other PPW fractions is not always clear in the scientific literature. While 'flexibles' (Brouwer et al., 2018; Brouwer et al., 2019; Thoden van Velzen et al., 2019), 'soft' (Dahlbo et al., 2018; Eriksen and Astrup, 2019; Nemat et al., 2022), and 'foils'/'films' (Faraca and Astrup, 2019; Picuno et al., 2021; Roosen et al., 2020; Schmidt and Laner, 2021) seem to be common synonyms for packaging films, the term 'rigid' or 'rigids' has become established for non-film packaging, but 'hard' (Dahlbo et al., 2018; Faraca and Astrup, 2019) is also sometimes used and Van Eygen et al. (2018) refer to it as 'hollow bodies'. This waste fraction is more diverse than films in terms of packaging types, which makes it difficult to compare unless a detailed description is provided. Sometimes bottles and trays are even grouped together under the term 'rigid', which makes comparisons difficult, especially when dealing with issues that may differ within these geometrically different forms of packaging. A clear and uniformly applied distinction between all types of packaging is therefore desirable.

Several studies characterize post-consumer PPW in detail by the means of manual sorting analysis. Faraca and Astrup (2019), for example, assessed the recyclability of separately collected plastic waste from recycling centers, including packaging, while Gabriel et al. (2023) analyzed the composition and recycling potential of separately collected rigid PET packaging waste including that from sorting facilities, and Roosen et al. (2020) investigated the composition of and implications for recycling of selected rigid and flexible PPW from the outputs of sorting facilities. Picuno et al. (2021) also analyzed PPW sorting outputs, but additionally also separately collected PPW, taking polymer, application, moisture and dirt into consideration. Eriksen and Astrup (2019) have conducted a comprehensive analysis on the composition of rigid household PPW and modeled scenarios for recycling initiatives in terms of product design and source separation system. They analyzed polymers, product types, colors and also took separability of the packaging components into account.

However, none of these papers analyzed rigid PPW in mixed MSW, which is important to fully capture the quality and potential of this waste fraction and is also a prerequisite for calculating separate collection rates, which have already been calculated for regions and PPW collection systems (Schuch et al., 2023) and at a household level (Thoden van Velzen et al., 2019), but not in terms of specific packaging characteristics. PB, in particular, require separate, detailed consideration. They tend to have more product residues, like other resealable packaging (Schmidt et al., 2024), which is an important part of recyclability assessments. In addition, in Austria, non-beverage plastic bottles (NB-PB) have one of the lowest separate collection and recycling rates of all PPW products (Van Eygen et al., 2018) and Vienna, as the only metropolis in Austria, faces special challenges in waste collection. NB-PB are an important PPW fraction there and they have long been targeted for separate collection, and their importance will increase with the introduction of a deposit system for beverage bottles. In this context, this study clearly addresses NB-PB, providing an in-depth characterization, aiming to enhance the understanding of the composition and quality of this waste fraction in different waste streams. As in the study of Van Eygen et al. (2018), this study also includes other hollow body plastic packaging with similar physical properties to NB-PB, such as three-dimensionality and resealability with a rigid cap, such as jars, canisters and buckets, which are present in MSW in only small quantities relative to NB-PB. To simplify matters, this paper will only use the term

'NB-PB' when referring to the plastic packaging analyzed.

This study pursues the following research objectives, which are to: (1) Explore the composition of NB-PB in terms of polymer and packaging characteristics, (2) investigate the residues and dirt content of NB-PB and the factors influencing it, (3) calculate quantities of NB-PB generated annually and, in particular, the proportion of this waste that has the potential to serve as a high quality secondary raw material and (4) examine the separate collection rate of NB-PB and the factors influencing it.

To answer the research questions implicit to achieving these objectives, household waste of mixed MSW collected at curbside, separate PPW from container collection and separate PPW from bag collection were sampled and the NB-PB therein characterized, using the case study of Vienna, Austria.

2. Methods and materials

2.1. Scope

Vienna, the capital of Austria, has a population of approximately 1.98 million (Statistik Austria, 2023). It is known for its sophisticated waste management, which is run by the municipal waste management department *Magistratsabteilung 48* (MA 48) and provides a sound database for scientific work (Gritsch and Lederer, 2023). MSW is collected separately as mixed MSW and separately collected recyclables, which consist mainly of packaging waste. The collection of packaging waste is organized by *Altstoff Recycling Austria AG* (ARA) and commissioned by MA 48 (Gritsch and Lederer, 2023).

PB, in particular, have been collected separately since 1993 and therefore count as one of the best communicated waste fractions and are usually depicted on collection containers (Ableidinger et al., 2007). When the Packaging Ordinance came into force, all plastic packaging had to be collected separately. However, as Vienna was struggling with a high proportion of mis-sorted waste, collection was reduced to recyclable products and switched to pure PB collection in the household sector (Stadt Wien, 2023), as discussed by Połomka et al. (2020). For this purpose, distinctive collection containers with prominent openings were developed (Stadt Wien, 2023). Since 2019, PB have been collected together with beverage cartons, metal packaging and small scrap in yellow containers located at so-called 'collection points' in public areas or in yellow bags collected directly from single-family homes (Gritsch and Lederer, 2023). Within Austria, Vienna is the most prominent urban region for collecting these waste fractions together (Hauer, 2014; Schuch et al., 2023) and also has the greatest impact, generating 20 % of MSW from households (BMK, 2023a) and therefore showing great potential for increasing the recycling rate of PPW in Austria (Schuch et al., 2023). Therefore, Vienna was chosen as a case study and NB-PB were chosen as the waste fraction for investigation in this study, especially as they have been targeted for separate collection for several years and make up a considerable amount of the collection quantity, currently 10 wt-% in PPW collection and 1.02 wt-% in mixed MSW (MA 48, 2023). Moreover, their importance will grow, notably impacting PPW quality once a beverage bottle deposit has been implemented, as planned in Austria by 2025 (BMK, 2023b).

Explicitly excluded as a subject of this study are PET beverage bottles due to an already existing secondary raw materials market, established material cycles and therefore already high recycling rates (Gabriel et al., 2023; Pinter et al., 2021; Seier et al., 2023; Tsochatzis et al., 2022; Welle, 2011, 2013). Plastic packaging film and trays are also excluded as they have not been targeted for separate collection and were therefore considered to be mis-sorted waste at the time of the analyses and do not, moreover, fall within the scope of the definition above. In addition, trays either lack a separate sorting and recycling route, even if they are monolayer-material, or they are difficult to mechanically recycle due to their multilayer composition and therefore often end up in the residual sorting fraction for thermal recovery (Antonopoulos et al., 2021; Barjoveanu et al., 2023; Eriksen et al., 2019a; Gabriel et al., 2023; Soares et al., 2022). Additionally, there are already studies investigating the composition and recyclability of packaging trays in detail such as Gabriel et al. (2023) and Seier et al. (2022) for Austria, Roosen et al. (2020) for Belgium and Eriksen et al. (2019a) for Denmark. Moreover, parts of this fraction are categorized as restricted single-use plastic packaging in the Proposal for the Packaging and Packaging Waste Regulation (EC, 2022a).

2.2. Sampling and presorting

Data for this study was gathered by means of a large municipal solid waste sampling campaign in Vienna that took place in 2022. Sampling covered mixed MSW and separately collected PPW from yellow containers and bags and was carried out by an engineering company in accordance with technical guidelines (Beigl et al., 2017).

For mixed MSW, 240 L of samples were drawn daily over a period of three weeks from randomly chosen containers at 20 addresses citywide, totaling approximately 3,000–4,000 kg of mixed MSW. The samples were sorted by hand on the same day. In contrast, separately collected PPW samples were obtained directly from collection vehicles using a wheel loader shovel extracting samples of about 100 kg. Each collection vehicle along a randomly selected urban route contributed one sample, with 12 vehicles sampled for container collection (about 1,300 kg sorted) and one for bag collection (about 100 kg sorted). The latter, representing only 9 % of the population in areas with single-family houses, has limited quantitative relevance in the city (Gritsch and Lederer, 2023).

Waste samples from mixed MSW and separate collections were presorted by the engineering company based on a sorting catalogue and supervised by the authors of this study. The NB-PB-fraction was preserved and analyzed for this study, which is described in the next chapter. The samples thus obtained for further analysis included 738 pieces from mixed MSW, 847 pieces from PPW container collection, and 312 pieces from PPW bag collection.

2.3. Characterization of plastic bottles

Fig. 1 provides an overview of the analysis procedure, which consisted of 7 successive steps. Initially, each NB-PB were weighed. Subsequently, a detailed characterization was conducted, followed by a washing step and a final weighing of each NB-PB. The methods are subsequently described in detail.

2.3.1. Polymer

The polymer was determined by means of the Resin Identification Code at the bottom or the neck of the NB-PB. The polymer was determined separately for the body and separable subcomponents (caps, full body sleeves) of the NB-PB. In cases without a code, Fourier-transformed infrared (FTIR) spectrometry was employed. All the samples were measured using an Agilent Technologies Cary 360 FTIR spectrometer performing in the wavelength range of 4000 cm^{-1} to 400 cm^{-1} and attenuated total reflection (ATR) mode resulting in ATR-FTIR spectra. Multiple measurements were taken from both sides of plastic full body sleeves to detect multilayer plastics and from one side for caps and bodies, assuming they are made of one type of plastic. The collected spectra were then compared to the reference spectra from the Polymers and Polymer Additives P/N 30,002 spectrometer database enabling the classification of the samples.

2.3.2. Packaging characteristics

Following circular packaging design guidelines (Gürlich et al., 2022; RecyClass, 2022a) and recent studies (Eriksen and Astrup, 2019; Faraca and Astrup, 2019; Gabriel et al., 2023; Traxler et al., 2024), packaging characteristics influencing recyclability and the resultant quality of collected NB-PB were selected and determined for each packaging piece.

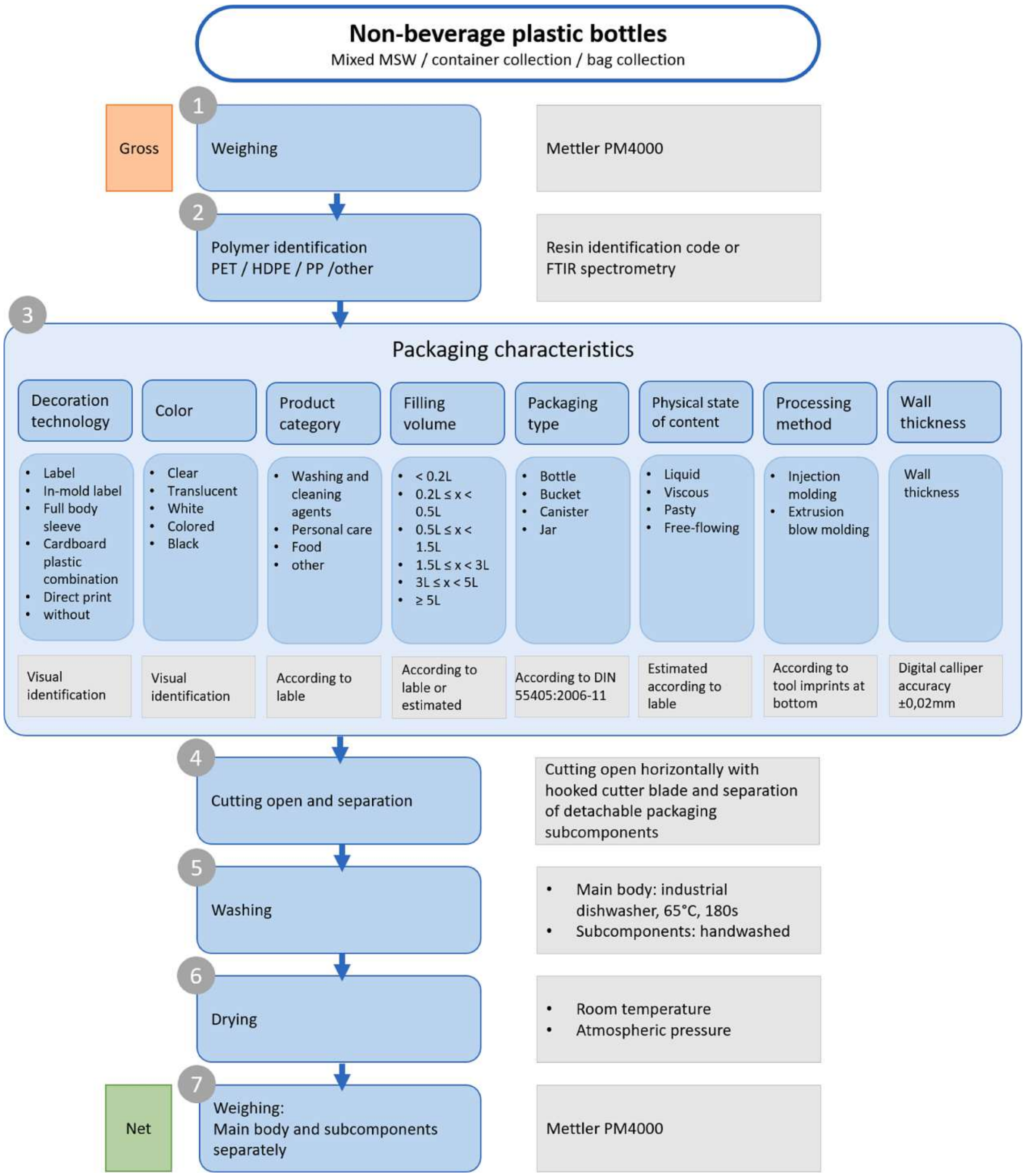

Fig. 1. Manual sorting procedure (1–7) and analysis methods (grey boxes) on non-beverage plastic bottles.

These packaging characteristics include: decoration technology, color, product category and filling volume. Color was determined separately for the body and separable subcomponents like caps. Additional determined characteristics include packaging type, processing method, wall thickness, and the physical state of contents. Fig. 1 provides a concise summary of all analyzed packaging characteristics. Further details and examples for each characteristic can be found in Table S1 and Figs. S1 and S2 in the Supplementary file.

2.3.3. *Residues and dirt content (RDC)*

To analyze RDC, initially the gross mass of each individual NB-PB, inclusive of all subcomponents, was determined from the waste sample. Then it was cut open horizontally using a hooked blade of a cutter. All detachable subcomponents like caps or sleeves were removed simultaneously during this step. Following the cut, the NB-PB underwent washing in an industrial dishwasher at 65 °C for 180 s without detergent and were subsequently air-dried at room temperature and atmospheric pressure. Subcomponents were washed manually with hot water and a sponge. After drying, net mass was individually recorded for both the NB-PB base resin and its subcomponents. The METTLER PM4000 scale with a readability of 0.00 g was used for all weighing operations.

Based on Thoden van Velzen et al. (2017), the RDC was calculated per individual NB-PB i according to the following Eq. (1)

$$RDC_i[\%] = \frac{m_{gross,i} - m_{net,baseresin,i} - m_{net,subcomponents,i}}{m_{gross,i}} \bullet 100 \quad (1)$$

with $m_{gross,i}$ being the mass of the whole NB-PB freshly sampled, $m_{net,baseresin,i}$ being the mass of the base resin washed and dried and $m_{net,subcomponents,i}$ being the mass of the associated subcomponents washed and dried.

For graphical representation and further analyses, negative RDC values were cleansed by replacing them with zero. And a Kruskal-Wallis test was calculated to check whether there was a difference in the RDC values with respect to different groups (e.g. waste stream, packaging characteristics), followed by a Dunn test (with the p-value adjustment method Bonferroni) as a post-hoc test to obtain information about differences within groups.

2.4. Calculation of net quantity indicator, quantities and separate collection rate

2.4.1. Net quantity indicator (NQI)

The recyclable plastic proportion in a target waste stream is critical for processing and mechanical recycling. Additionally, the proportion of the base resin of the NB-PB is decisive as a higher proportion enhances recyclability yield (RecyClass, 2022b). Hence, a NQI was computed per waste stream *i* and polymer *j* following Gabriel et al. (2023). This indicator describes the proportion of the base resin, the main body of the NB-PB, while considering foreign materials like residues, dirt and packaging subcomponents. Subcomponents may not have the same properties as the base resin due to different production processes and additives, potentially compromising the quality of certain base resin recycling materials (Eriksen and Astrup, 2019; Gürlich et al., 2022; Hahladakis and Iacovidou, 2018; Welle, 2005) and are therefore considered as foreign material in this study. However, some subcomponents are mechanically recycled (Akhras et al., 2023; Gall et al., 2020; RecyClass, 2022a). The corresponding Eq. (2) is shown below, with $m_{net,baseresin,i,j}$ being the mass of the base resin, washed and dried, and $m_{gross,NB\text{-}PB,i,j}$ being the gross mass of the entire NB-PB before washing and consisting of the sum of $m_{net,baseresin,i,j}$, $m_{net,subcomponents,i,j}$ and $m_{residues\ and\ dirt,i,j}$.

$$NQI_{i,j}[\%] = \frac{m_{net,baseresin,i,j}}{m_{gross,NB-PB,i,j}} \bullet 100 \quad (2)$$

2.4.2. Quantities

The annual mass of NB-PB was computed per waste stream *i* and polymer *j* for the year 2022 by multiplying the annual mass of waste m_i and the concentration of NB-PB in the waste sample $m_{NB\text{-}PB\ in\ sample,i,j}$ / $m_{sample,i,j}$ according to the following Eq. (3).

$$Annual\ mass\ of\ NB-PB_{i,j}[t/yr] = m_i \bullet \frac{m_{NB-PB\ in\ sample,i,j}}{m_{sample,i,j}} \quad (3)$$

2.4.3. Separate collection rate (SCR)

Furthermore, a total average SCR for NB-PB was calculated as well as per packaging characteristic *i* as a quotient of the separately collected quantity to the total quantity of the NB-PB under consideration according to the following Eq. (4). Whether the SCR was calculated using gross or net masses is stated separately in the results. Data for masses and concentrations have been supplied by Vienna's public waste management provider (MA 48, 2022).

$$SCR_i[\%] = \frac{m_{in\ separate\ PPW-collection,i}}{m_{in\ separate\ PPW-collection,i} + m_{in\ mixed\ MSW,i}} \bullet 100 \quad (4)$$

3. Results and discussion

3.1. Polymer

As illustrated in Fig. 2, PET-NB-PB predominated in all three waste stream samples, followed by HDPE, PP and a minor share of NB-PB made from other polymers. These findings align with those of Eriksen and Astrup (2019), analyzing post-consumer rigid plastic waste in Copenhagen. They reported that over 95 % comprised PET, PE, or PP, with PET being the major component at 37 %, and PP and PE sharing equal portions at approximately 29 %.

In the following sections, the detailed compositions of the main polymer groups PET, HDPE and PP are presented according to the most relevant packaging characteristics. All values are presented in weight percentage (wt-%) on a dry matter basis. The composition of the group of other polymers (Figs. S22 and S23) as well as additional figures on packaging characteristics for PET (Figs. S4–S9), HDPE (Figs. S10–S15) and PP (Figs. S16–S21) can be found in the Supplementary file.

3.2. Packaging characteristics per polymer

3.2.1. PET plastic bottles

The most relevant characteristics of PET-NB-PB are depicted in Fig. 3. The graph illustrates a relatively uniform distribution of the analyzed packaging characteristics across the three waste streams, mirroring a similar pattern observed for all NB-PB in the waste streams (see Fig. S3 in the Supplementary file). The majority of the PET-NB-PB has a filling volume between 0.5 and 1.5 L, followed by the filling volume between 0.2 and 0.5 L and the filling volume between 1.5 and 3 L. PET-NB-PB with a filling volume ≥5 L were most commonly found in mixed MSW, with a share of 8 %. The mean wall thicknesses of PET-NB-PB is 0.46 mm, the median 0.38 mm. Bottles are the predominate packaging type, with PET buckets and canisters being nearly non-existent. Almost all PET-NB-PB showed an injection point at the bottom, which would mean that they are produced by injection molding. However, only the PET preforms are injection molded (Robertson, 2012), the final shape of the packaging is then produced by stretch blow

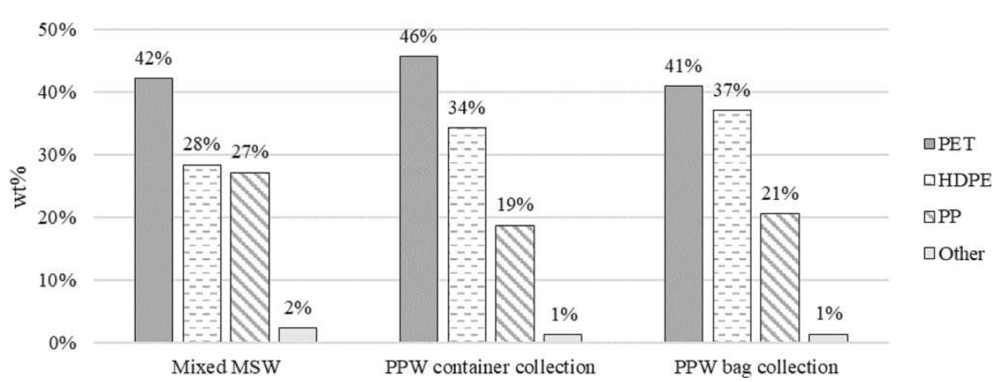

Fig. 2. Composition of non-beverage plastic bottles (incl. packaging subcomponents) regarding polymer in the waste streams of mixed MSW, PPW container collection and PPW bag collection, shown in wt% on a dry matter basis.

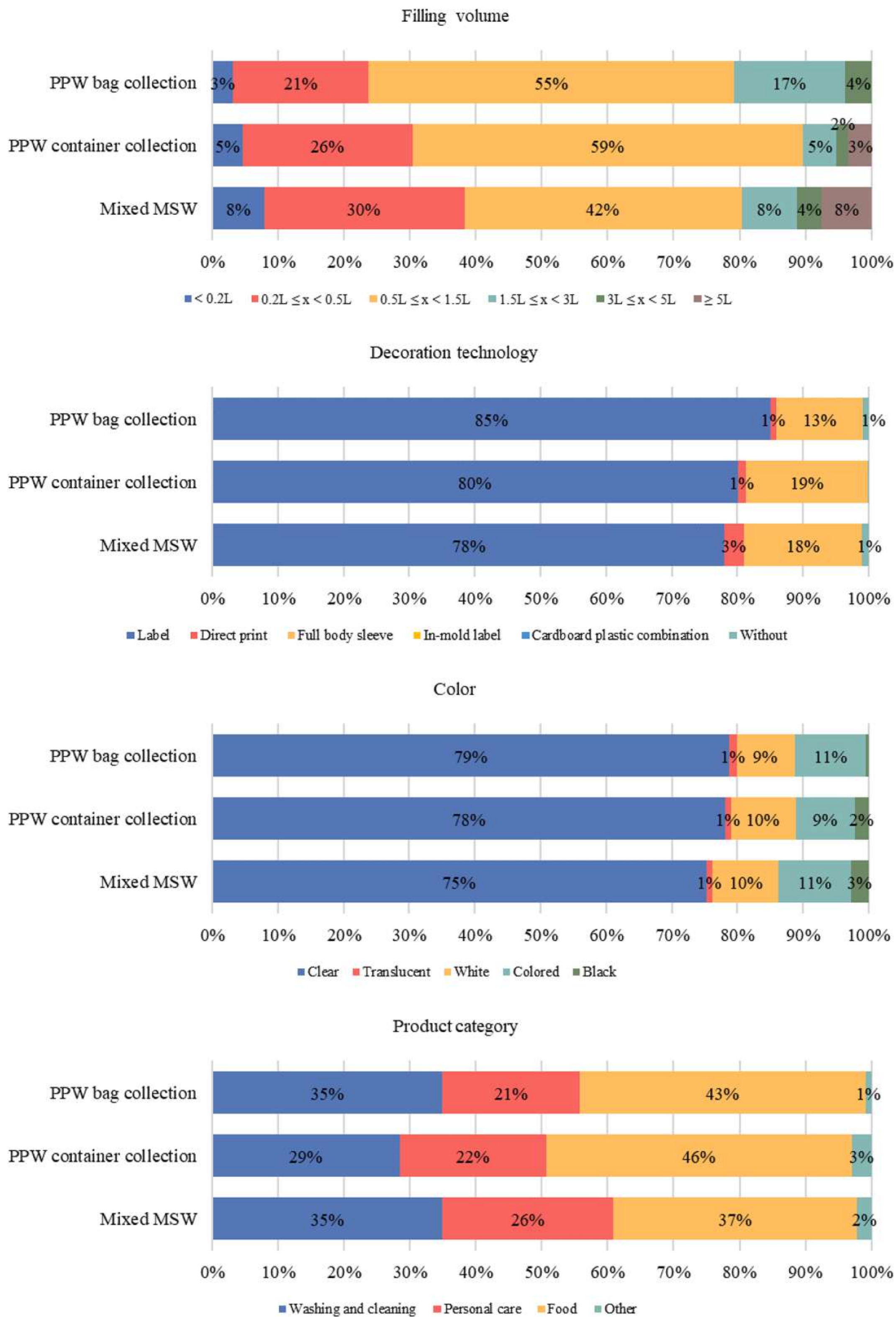

Fig. 3. Composition of non-beverage PET plastic bottles with regard to packaging characteristics 'filling volume', 'decoration technology', 'color' and 'product category' shown per waste stream in wt% on a dry matter basis.

molding (Burgos Pintos et al., 2024).

Labels are the prevailing decoration technology for PET-NB-PB, constituting at least 78 % across all waste streams, followed by plastic full-body sleeves and direct print. Of the PET-NB-PB with labels, 48 % have plastic labels and 52 % have paper labels. Of the PET-NB-PB with full-body sleeves, 58 % have a perforated sleeve, primarily composed of PS (39 %), followed by multilayer PET + PE (32 %) and pure PET (22 %). The remaining sleeves consist of PE + PP, PVC, PVC + PET, or PET + PP, in descending order.

Clear or translucent PET-NB-PB constitute the majority, comprising at least 76 %. These findings align well with Gabriel et al. (2023), who reported approximately 80 % of rigid non-beverage PET packaging

Fig. 4. Composition of non-beverage HDPE plastic bottles with regard to packaging characteristics 'filling volume', 'decoration technology', 'color' and 'product category' shown per waste stream in wt% on a dry matter basis.

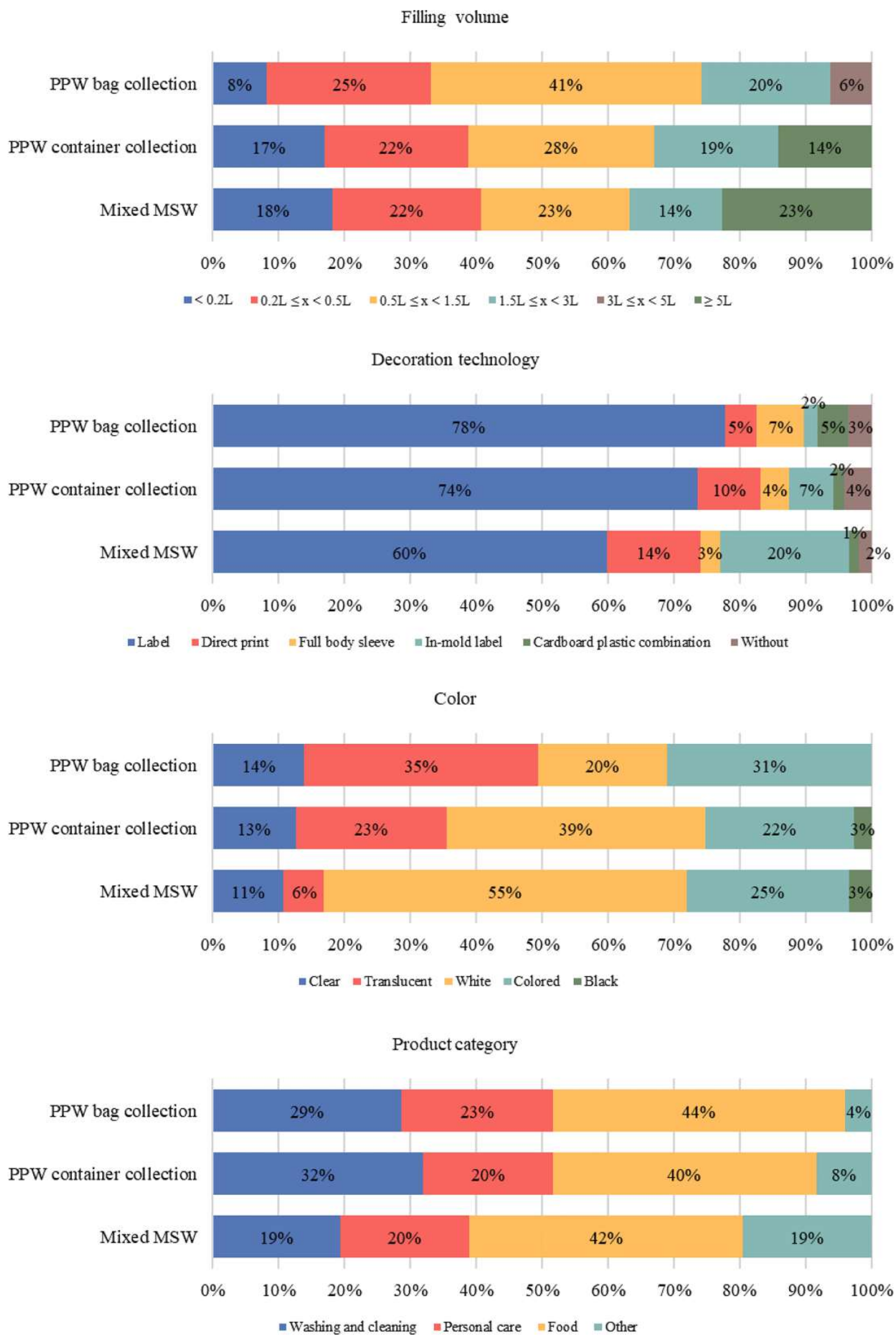

Fig. 5. Composition of non-beverage PP plastic bottles with regard to packaging characteristics 'filling volume', 'decoration technology', 'color' and 'product category' shown per waste stream in wt% on a dry matter basis.

waste being clear. Colored and white PET-NB-PB occur in all waste streams with proportions between 9 and 11 %. Black PET-NB-PB were most commonly found in mixed MSW with a share of 3 %.

The majority of caps are made of PP (78 %), followed by HDPE with a total of 17 % and other polymers with 6 %. 40 % of these caps are white, translucent or clear, 7 % are black and the remaining are various shades of color, with red being the most common at 12 %.

PET-NB-PB used for food applications represent the highest shares, ranging from 37 % to 46 %, followed by washing and cleaning agents and personal care products. Among personal care products, 81 % are rinse-off products and 19 % are leave-on products. With up to 98 %, the majority of PET-NB-PB is filled with liquid or viscous products and only a small proportion with pasty or free-flowing products.

3.2.2. HDPE plastic bottles

Fig. 4 shows the main packaging characteristics of HDPE-NB-PB. It can be seen from the graph that the majority of the HDPE-NB-PB has a filling volume between 0.5 and 1.5 L, closely followed by the filling volume between 0.2 and 0.5 L. The arithmetic mean of the determined wall thicknesses of the HDPE-NB-PB is 0.74 mm, the median 0.72 mm. The most common packaging type is the bottle, with a share between 70 % and 82 %, followed by the canister, with a share between 10 % and 23 %. Buckets do not appear at all. The majority of HDPE-NB-PB (92–97 %) is produced by extrusion blow molding, while only small amounts are produced by injection molding.

By far the most common decoration technology of HDPE-NB-PB in all three waste streams is labels, with shares of at least 81 %, followed by full body sleeves, with shares between 11 % and 14 %. Direct print and HDPE-NB-PB without decoration technology account for smaller quantities. 76 % of HDPE-NB-PB with labels are with plastic label and 24 % with paper label.

About half of the HDPE-NB-PB are white, followed by translucent and colored, with slightly higher shares for the former. With 36–45 %, the most common color among the dyed HDPE-NB-PB is blue, followed by grey (15–24 %). As in the case of PET, black HDPE-NB-PB was most commonly found in mixed MSW, with a share of 6 %.

The majority of caps are made of PP (88 %), followed by HDPE, with a total of 7 %, and other plastics, with 5 %. 45 % of these caps are white, translucent or clear, 8 % are black, the rest is divided among a wide variety of shades, with blue being the most common at 20 %.

The largest share of HDPE-NB-PB was used for washing and cleaning products, with shares between 41 % and 49 %, followed by personal care products, with shares between 27 % and 35 %. As with PET, the majority of the personal care products were rinse-off products (85 %) and only 15 % leave-on products. The share of food-grade HDPE-NB-PB is much lower than for PET at only 7–12 %.

The majority of HDPE-NB-PB is filled with viscous or liquid products (90–93 %), followed by free-flowing products (6–9 %).

3.2.3. PP plastic bottles

The most relevant packaging characteristics of PP-NB-PB are shown in Fig. 5. The majority of PP-NB-PB has a filling volume between 0.5 and 1.5 L, followed by the filling volume between 0.2 and 0.5 L and the filling volume between 1.5 and 3 L. PP-NB-PB with a filling volume ≥5 L was most frequently found in mixed MSW, with a share of 23 %. The arithmetic mean of the determined wall thicknesses of the PP-NB-PB is 0.84 mm, the median 0.73 mm. The most common packaging type is bottles, with a share of 51–72 %, followed by jars, with a share of 18–22 %. Buckets predominate in mixed MSW (31 %), while in separate PPW collection, the share ranges from 1 % to 19 %. Canisters hardly occur at all. Extrusion blow-molded PP-NB-PB predominates in PPW bag collection (77 %) and PPW container collection (55 %), whereas injection molding is the most common processing method for PP found in mixed MSW (54 %).

The most common decoration technology for PP-NB-PB in all three waste streams is labels, with shares ranging from 60 to 78 %, with 79 % of PP-NB-PB being labelled with plastic and 21 % with paper. Direct print accounts for 5 %–14 %. In-mold labels are predominant in mixed MSW, with 20 %.

The majority of PP-NB-PB in mixed MSW and PPW container collection is white, in PPW bag collection translucent is predominant. At 22–31 %, PP-NB-PB has the highest colored content of the polymer streams analyzed. The most common color among the colored PP-NB-PB is red, followed by yellow. The percentage of black PP-NB-PB is a maximum of 3 %.

The majority of caps are made of PP (84 %), followed by HDPE, with a total of 7 %. 31 % of the caps are white, translucent or clear, 8 % are black, and the remaining caps are of various shades, with red being the most common at 14 %.

The share of PP-NB-PB for food applications was similar to that of PET at 40–44 %, followed by washing and cleaning agents and personal care. Slightly more than half are rinse-off products (53 %), and the rest are leave on-products (47 %). The majority of PP-NB-PB were filled with viscous products, followed by pasty and free-flowing product. The lowest share was for liquid products.

3.3. RDC per MSW stream, polymer and packaging characteristics

Fig. 6 (I) displays RDC values as a boxplot per waste stream, revealing a wide dispersion ranging from 0 % to almost 90 % in all three streams. The mean RDC values are 20.3 % for NB-PB from mixed MSW, 11.3 % for container collection, and 10.8 % for bag collection. Schmidt et al. (2024) found a similar value of 8.2 % for bottles from German household PPW, Roosen et al. (2020) reports residue shares between 1.7 and 8.3 % for PP, PET and PP bottles, but on a net packaging weight, and Gabriel et al. (2023) found lower percentages of 4.05 % for nonfood PET bottles from separate PPW collection. In this study, the means are notably influenced by outliers, as indicated by the comparison with the medians (11.4 %, 5.0 %, 3.9 %). These outliers stem from individual packaging with substantial residues, predominantly disposed of in mixed MSW. For instance, 7 % (52 pieces) of the mixed MSW sample (738 pieces) contained over 2/3 of content, while only 0.3 % (4 pieces) of the total 1,159 pieces from separate PPW collection had over 2/3 of content. Descriptive statistical parameters are provided in Table S2 in the Supplementary file.

Accordingly, packaging with high RDC levels are more likely to end up in the mixed MSW, potentially due to consumers deeming it unclean and not worth recycling, aligning with findings in studies by Nemat et al. (2022) and Thoden van Velzen et al. (2019). Wikström et al. (2016) also observed that product residues strongly influence consumers' disposal decisions, with consumers tending to discard packaging with residues in mixed MSW due to perceived difficulty in cleaning. Conversely, packaging in separate collection likely have lower RDC as these are washed and dried for storage at home, minimizing undesirable odors (Williams et al., 2018).

The higher RDC values in the mixed MSW lead to an underestimation of the separate collection rate by about 10 % when calculated with gross masses. The SCR calculated gross is 17.6 %, the calculated net is 19.2 %. However, if people were encouraged to collect more NB-PB separately, the proportion of high residual content packaging would probably also increase, leading to an apparent improvement in quantitative performance indicators such as the SCR, but with a negative impact on the qualitative recycling performance; in addition, it would be difficult to sort this heavy packaging automatically. Nevertheless, since only what is collected separately has a chance of being recycled, it is desirable that all NB-PB, including those with high RDCs, are disposed of in separate collection. However, there is an urgent need to raise consumer awareness about emptying packaging, also to prevent product waste.

As shown in Fig. 6 (II), the RDC levels for PET, HDPE and PP are in a similar range, with arithmetic means of 14.6 %, 15.3 %, and 13.7 %, respectively. As in the case of the comparison of the RDC in the different waste streams, the arithmetic mean and the median are very different.

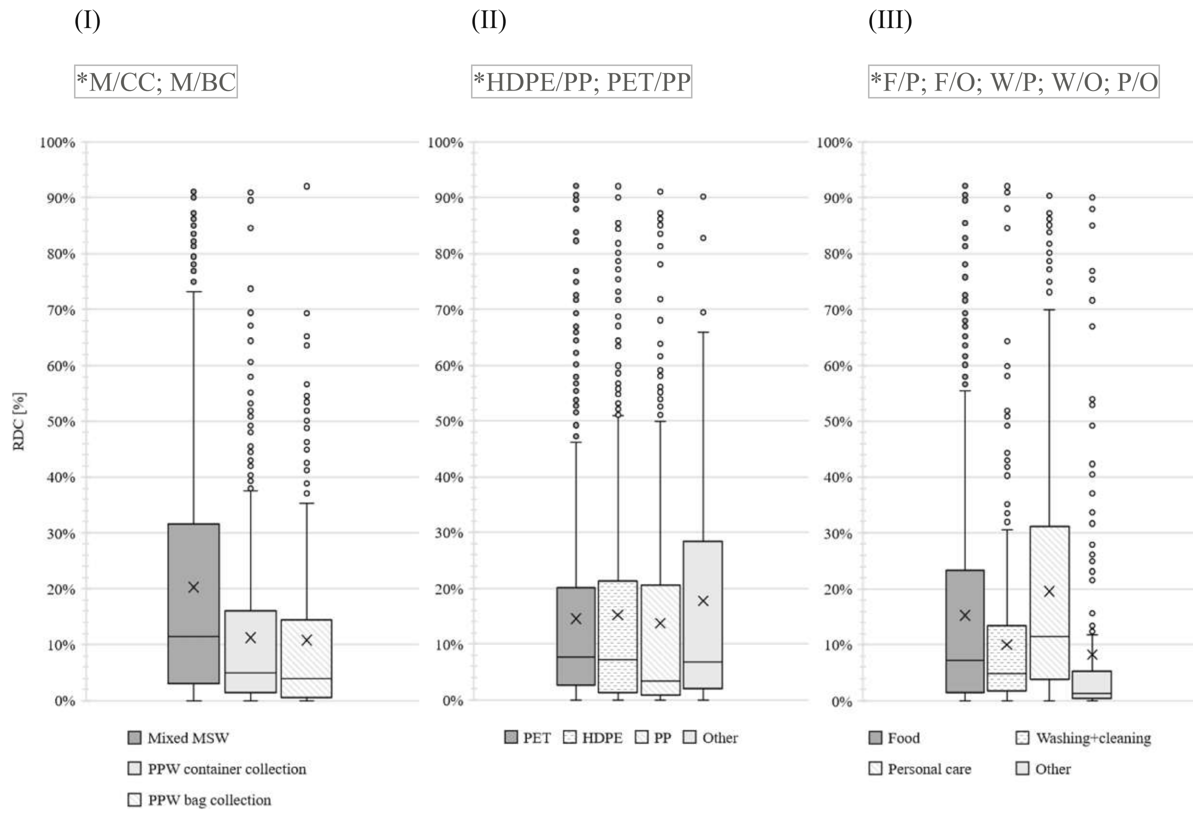

Fig. 6. RDC of non-beverage plastic bottles per waste stream (I), polymer (II) and product category (III) shown as boxplots; groups with significant difference in RDC according to post-hoc analysis are marked with* (M, Mixed MSW; CC, PPW container collection; BC, PPW bag collection; F, Food; P, Personal care; O, Other; W, Washing and cleaning agents).

Other polymers have the highest RDC, with a mean of 17.8 %. However, sample size here is much less than with PET, HDPE and PP. The descriptive statistical parameters are summarised in Table S3 in the Supplementary file. Another study records levels of attached moisture and dirt of 6.4 % for PET bottles, 8.3 % for PE bottles and 1.7 % for PP bottles, but on a dry matter basis (Roosen et al., 2020). Thoden van Velzen et al. (2017) found average moisture and dirt content between 12 % and 15 % for PET and PE bottles and flasks.

Regarding product category (Fig. 6 (III)), personal care and food packaging exhibit the highest RDC levels, averaging 19.6 % and 15.3 %, respectively. Washing and cleaning agents follow with 10.0 %, and other packaging shows 8.2 %. The descriptive statistical parameters are summarised in Table S4 in the Supplementary file. These findings align with similar results in other studies (Rathore et al., 2023; Wohner et al., 2020) and may be explained by the higher viscosity of these products such as also observed by Schinkel et al. (2023), Williams et al. (2012) and Williams et al. (2018).

For all other packaging characteristics than polymer and product category, differences in RDC values have also been observed. These results highlight multiple influencing factors affecting residue and dirt content in NB-PB. The determination of RDC levels indicates that considerable amounts of residues in NB-PB are present in some cases, diminishing the purity of this waste fraction (Faraca and Astrup, 2019). However, the analysis cannot conclusively determine whether these quantities result from unfavorable packaging design or consumer behavior.

The Kruskal-Wallis Test showed a statistically significant difference in RDC between the different waste streams (Chi square = 96.19, $p < 2.2e-16$). Post-hoc analysis showed a significant difference between mixed MSW (Mdn = 11.43) and PPW container collection (Mdn = 5.04) ($p = 8.38e-16$), as well as a significant difference between mixed MSW und PPW bag collection (Mdn = 3.92) ($p = 6.08e-16$). No significant differences were found between PPW container and bag collection. Concerning different polymers, the Kruskal-Wallis Test showed statistically significant differences in RDC (Chi square = 23.478, $p = 3.211e-05$). Post-hoc analysis, however, showed only a significant difference between the polymers PET (Mdn = 7.72) and PP (Mdn = 3.43) ($p = 8.77e-6$), as well as a significant difference between HDPE (Mdn = 7.25) and PP ($p = 0.0248$). No significant differences were found between the other polymers. In terms of product category, the Kruskal-Wallis Test showed statistically significant differences in RDC between the different product categories (Chi square = 161.78, $p < 2.2e-16$). Post-hoc analysis showed significant differences between all product categories except for the categories food and washing and cleaning agents. For all other packaging characteristics (filling volume, decoration technology, color, packaging type, physical state of content, processing method), the Kruskal-Wallis Test also showed a difference in RDC between the different groups. For example, differences were found between low filling volume (<0.2 L) and greater filling volumes ($0.2 \leq x < 0.5$ L; $0.5 \leq x < 1.5$ L; $1.5 \leq x < 3$ L), differences were found between colored and white/translucent or clear NB-PB, and differences were found between jars and bottles and between all physical states. Detailed results on all statistical analyses can be found in Table S5 of the Supplementary file.

3.4. Net quantity indicator, quantities and separate collection rates

3.4.1. Net quantity indicator

As described in the previous section, a notable share of the NB-PB consists of residues and dirt, indicating the inclusion of foreign materials and a reduced share of recyclable main material, as defined by the NQI. Fig. 7 illustrates the NQI per polymer and waste stream. Total NQI was highest for PPW container collection (72 %), followed by bag collection (69 %), with the lowest values obtained for mixed MSW (58

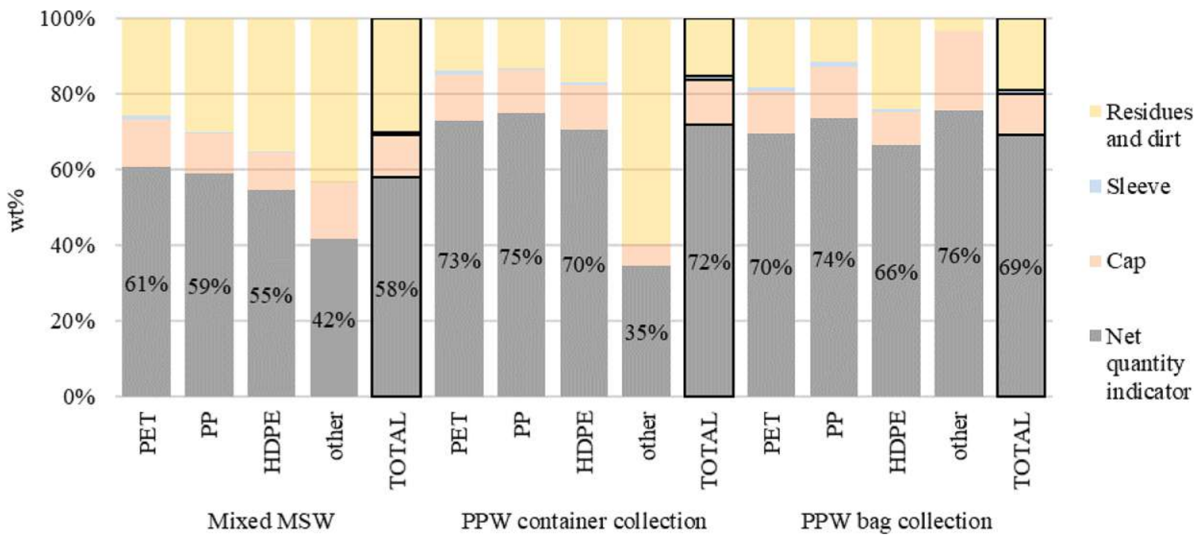

Fig. 7. Net quantity indicator per waste stream and polymer of non-beverage plastic bottles in wt%.

%). Dahlbo et al. (2018) mention a correction factor of 0.56 for hard plastic packaging from mixed MSW, which is quite comparable to the results from this study, while Schuch et al. (2023) used a gross-net factor of 0.813, which in turn is higher. In mixed MSW, PET-NB-PB achieved the highest NQI, with 61 %; in separate PPW container collection, PP-NB-PB achieved the highest NQI, with 75 %. In both waste streams NB-PB from other polymers showed the lowest NQI, with only 35 to 42 %.

Gabriel et al. (2023) analyzed the NQI of rigid non-beverage PET PPW and found an NQI of 84 % for collected and 89 % for sorted PET PPW, which is considerably higher than in this study. However, their PPW consisted mainly of trays and cups and the proportion of total residues was only about 1 to 4 %. For PET food bottles, however, the share of residues was 12.11 % and for PET non-food bottles 4.05 %.

Roosen et al. (2020) also analyzed subcomponents and polymer composition of different waste fractions from a sorting facility and found similar results to this study. They found that PE bottles consist of 77.5 % main body, which is equivalent to the NQI, 11.6 % caps, 2.6 % labels and 8.3 % residues on average. For PP bottles, they obtained values of 76.9 % main body, 12.5 % caps, 2.6 % labels and 1.7 % residues.

3.4.2. Quantities

In 2022, a total of 4,112 t/yr NB-PB was disposed of via the mixed MSW, 946 t/yr via PPW container collection and 35 t/yr via bag collection (dry mass) (see Fig. S24 in the Supplementary file). The majority of the NB-PB, 2,207 t/yr, was made of PET, followed by 1,457 t/yr of HDPE, 1,321 t/yr of PP and 108 t/yr of other plastics (dry mass), with 1,762 t/yr PET, 1,123 t/yr HDPE, 1,130 t/yr PP and 96 t/yr of other polymers being in the mixed MSW. According to the assumptions made by Brouwer et al. (2020), only packaging made of PET, PE or PP can be considered ‘ideal’ for circular recycling.

The significant potential for NB-PB recycling is found within mixed MSW. Therefore, the subsequent evaluation focuses on the quality of these NB-PB in mixed MSW based on the packaging properties critical for recyclability, as outlined in Section 2.3.2. The corresponding Fig. S25 can be found in the Supplementary file.

1,899 t/yr of the NB-PB are clear or translucent and therefore have the highest market value as they offer the greatest flexibility in application (Gürlich et al., 2022; RecyClass, 2022a). Once pigments are added, they can be difficult and costly to remove (Borealis, 2019; Shamsuyeva and Endres, 2021). When pigments are used, white should be preferred as it can be converted to many colors (Faraca and Astrup, 2019). In the case of this study, this refers to 1,370 t/yr in mixed MSW. Colored NB-PB, which amounts to 685 t/yr, therefore have limited applications, at least for packaging, due to the darker shades of the recyclate (Faraca and Astrup, 2019). A total of 158 t/yr are black and should hence be classified as non-recyclable as they cannot be detected in the sorting process, as also assumed by Faraca and Astrup (2019) and Brouwer et al. (2020).

A total of 1,238 t/yr of the NB-PB contained in the mixed waste are used for food purposes, ensuring high material purity in terms of legal material requirements (EC, 2004, 2011; Tonini et al., 2022), as also assumed by other studies (Eriksen et al., 2019b; Eriksen and Astrup, 2019; Faraca and Astrup, 2019; Tonini et al., 2022). Cosmetics also have specific legal purity requirements (EC, 2022c), which would account for an additional 1,116 t/yr of high quality secondary raw materials. The remainder of 1,757 t/yr for detergents and other products is likely to have lower quality requirements than required for food or cosmetics.

With regard to size, the current state of the art makes it difficult or impossible to sort correctly PPW smaller than 5 cm (Antonopoulos et al., 2021; Gürlich et al., 2022; RecyClass, 2022a), which means that a certain proportion of the 529 t/yr of NB-PB smaller than 0.2 L would be considered non-recyclable and would probably end up in a sorting fraction sent to incineration. It is not possible to estimate the exact proportion from the data as the exact dimensions of the NB-PB were not recorded. The remaining 3,582 t/yr are considered easily recyclable due to their size.

3.4.3. Separate collection rate

Fig. 8 shows the separate collection rates of NB-PB from MSW according to packaging-specific characteristics, as well as the average value. The average SCR of NB-PB is 19.2 %, calculated with net masses, which is comparatively low. This could be attributed to the historical focus on promoting PET beverage bottles for separate collection, with NB-PB only recently being depicted on collection containers (MA 48, 2020).

The SCR calculated for specific packaging characteristics showed that HDPE (23 %) and PET (20 %) reached values above the average (23 %). In contrast, PP and other polymers show a SCR of 14 % and 11 %, respectively.

Notable differences were observed in the SCR based on decoration technology. NB-PB with in-mold labels and direct print exhibited the lowest SCR at 5 % and 10 %, respectively. Conversely, NB-PB without decoration technology, those with full body sleeves and those with labels reached the highest SCR values of 23 %, 22 % and 20 %, respectively.

SCR values varied concerning color, ranging from 5 % for violet and orange to the highest SCR for blue, brown, and grey at 27 %, 26 % and

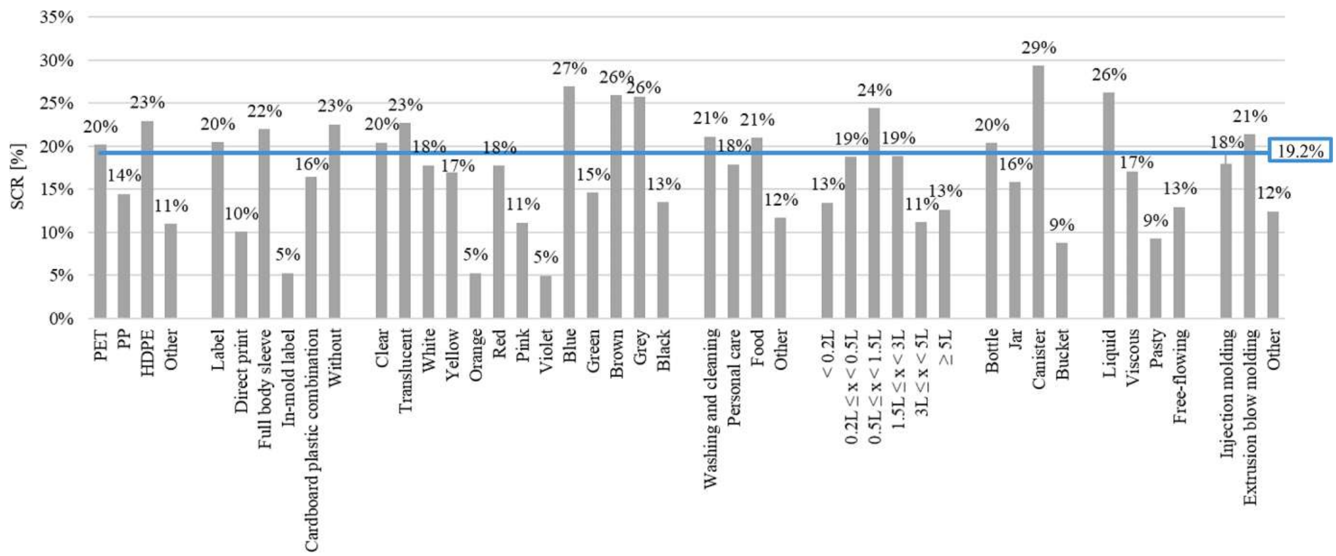

Fig. 8. Packaging characteristic-specific separate collection rates of non-beverage plastic bottles from MSW and average separate collection rate (blue line), calculated on a dry matter basis of the non-beverage plastic bottles incl. packaging subcomponents.

26 %, respectively.

For different product categories, washing and cleaning agents and food both had an SCR of 21 %, followed by 18 % for personal care, with the lowest values for other products at 12 %.

The SCR increased with increasing filling volume, reaching 13 %, 19 % and 24 % for < 0.2 L, $0.2 \leq x < 0.5$ L and $0.5 \leq x < 1.5$ L, but dropped with further increases in filling volume. This might be explained by the small openings of containers for separate collection, preventing the disposal of bulky parts. Studies confirm that large, rigid packaging is more likely to be collected separately, while small packaging has a lower probability of separate disposal (Nemat et al., 2022; Thoden van Velzen et al., 2019).

Canisters demonstrated the highest SCR at 29 %, while buckets exhibited the lowest at 9 %. Jars, bottles and other containers fell in between with 16 % to 20 %. The varying sample sizes, with 23 canisters, 52 buckets, 264 jars and 1,558 bottles and other containers, however, could have significantly influenced results.

NB-PB with liquid content have the highest SCR in terms of physical state, with 26 %, followed by viscous at 17 % and free-flowing at 13 %. Pasty contents resulted in the lowest SCR, with just 9 %, which can possibly be explained by the higher RDC of NB-PB with pasty content, increasing the likelihood of disposal in mixed MSW (Thoden van Velzen et al., 2019).

The SCR of NB-PB formed by extrusion blow molding appeared slightly higher (21 %) than those formed with injection molding (18 %).

Measures to enhance the separate collection rate and amount of NB-PB could involve improving separate collection. This could be done by targeting all plastic packaging for PPW collection instead of only plastic bottles, which would facilitate separate collection for consumers (Roosen et al., 2022; Schuch et al., 2023; Tallentire and Steubing, 2020) or by better communicating separate collection to the public by better advertising the appropriate fractions (Mielinger and Weinrich, 2024). Pictorial representations are a great help for citizens (Rousta et al., 2015), and the illustration of specific product groups could possibly increase the collection rate (Gritsch and Lederer, 2023). Studies indicate that the service level of separate collection significantly influences both quantity and quality (Dahlén et al., 2007; Haupt et al., 2018; Schuch et al., 2023; Thoden van Velzen et al., 2019) and that improved convenience in separate collection leads to greater acceptance (Rousta et al., 2017). Transitioning from collection points to more curbside collection, where feasible, can reduce distances and enhance service levels for citizens. However, this is not possible everywhere due to structural conditions. Environmental and financial aspects should also be taken into account as their influence increases with the number of collection points. Alternatively, sorting of MSW provides an option for automated recovery of recyclable materials, such as metals or plastics, although the quality may be lower (Blasenbauer et al., 2024; Cimpan et al., 2015; Feil et al., 2017; Feil and Pretz, 2020).

4. Conclusion

This study provided an in-depth characterization of NB-PB including all packaging subcomponents in mixed MSW as well as separate PPW collection, including polymer, product category, decoration technology, filling volume, color and more, in order to assess the quality of this waste stream and the potential for recovery and recycling.

This study found that the overall SCR is only 19.2 %, which would still leave a potential of 4,112 t/yr in mixed MSW. If an increase in the SCR cannot be achieved through improved separate collection, recovery from mixed MSW would be a way to increase recycling. The results of this study give a first indication of the qualities that can be expected. The analysis showed that about 46 % of the NB-PB in mixed MSW are clear or translucent and therefore represent a high quality secondary material in terms of color. Approximately 50 % contain white or colored pigments, which reduces the market value, more for colored than for white. At least 4 % of the NB-PB in mixed MSW can almost certainly be classified as non-recyclable due to black colors. In terms of material grade, at least 30 % of the NB-PB is food grade, so it can be assumed that this material meets high quality criteria.

The filling volume of $0.5 < x \leq 1.5$ L was the most common for all three polymer fractions (PET, HDPE and PP), with shares between 23–59 %. The most frequently used decoration technology was ‘label’, with shares of 60–85 %. While ‘food’ was the most common product category in PET and PP (37–46 %), ‘washing and cleaning agents’ was the most frequently found in HDPE (41–49 %). Colored NB-PB were mainly found in the PP fraction, with shares of 22–31 %.

This study confirms that a significant proportion of the NB-PB found in MSW is actually foreign materials. The net quantity indicator in mixed MSW is 58 %, whereas in separate collection it amounts to 69–72 %. A great share of foreign materials is residues and dirt. Statistically significant differences were found in the residues and dirt content of NB-PB in mixed MSW and in separate PPW collection, with the RDC in mixed MSW being significantly higher at 20 % than in separate collection at 11 %. Among the products, personal care products, with 20 %, and food, with 15 %, had the highest share of RDC. And there are certainly other influencing factors that should be further investigated.

The results of this study show that NB-PB is a very heterogeneous fraction. There are a large number of combinations of the different packaging characteristics, which have a wide range of influences on e.g. consumer behavior and on the behavior of the packaging in automated sorting plants, which in turn affects the recyclability in general. Mandatory design specifications for harmonisation are therefore urgently needed in order to successfully collect, sort and mechanically recycle this waste fraction. Specifically, efforts should be made to limit the polymers used and to possibly link them to a product group in order to improve sorting efficiencies and closed-loop recycling of high-quality packaging such as food-packaging. Additionally, the variety of colors, decoration technologies and packaging geometries should be reduced to make it easier for consumers to identify specific packaging and to sort it separately. Even if legal requirements regarding recyclability (EC, 2022a), including harmonized collection (EC et al., 2022), are on their way, developments in the design and collection of PPW should be monitored to identify negative trends at an early stage.

As the level of the RDC can have a number of effects, for example on material flow data or on performance indicators in the waste management sector, it should also be carefully examined in more detail. This study did not specifically investigate whether the residues are due to wasteful consumer behavior or unfavorable packaging design, but finds indications in both directions. Consequently, it is recommended that more emphasis should be placed on the development of easy-to-empty packaging and that consumers should be made more aware of the wastefulness of products, as they obviously also play a decisive role in the fact that packaging is not always emptied completely.

As this study was only carried out as a case study for Vienna and as waste sampling is time consuming, labour-intensive and costly, the results are limited geographically and in terms of the waste fractions analyzed. In addition, seasonal variations were not taken into account. In order to be able to make statements about the quality and quantity of the total PPW on a national level, however, further research with seasonal sampling is required, including other waste fractions and at a similar level of detail as well.

CRediT authorship contribution statement

Lea Gritsch: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Gisela Breslmayer:** Investigation. **Ricarda Rainer:** Investigation. **Hana Stipanovic:** Investigation. **Alexia Aldrian-Tischberger:** Supervision. **Jakob Lederer:** Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used DeepL and ChatGPT in order to translate, shorten sections and improve readability. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Appendix A. Supplementary data

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Paper III

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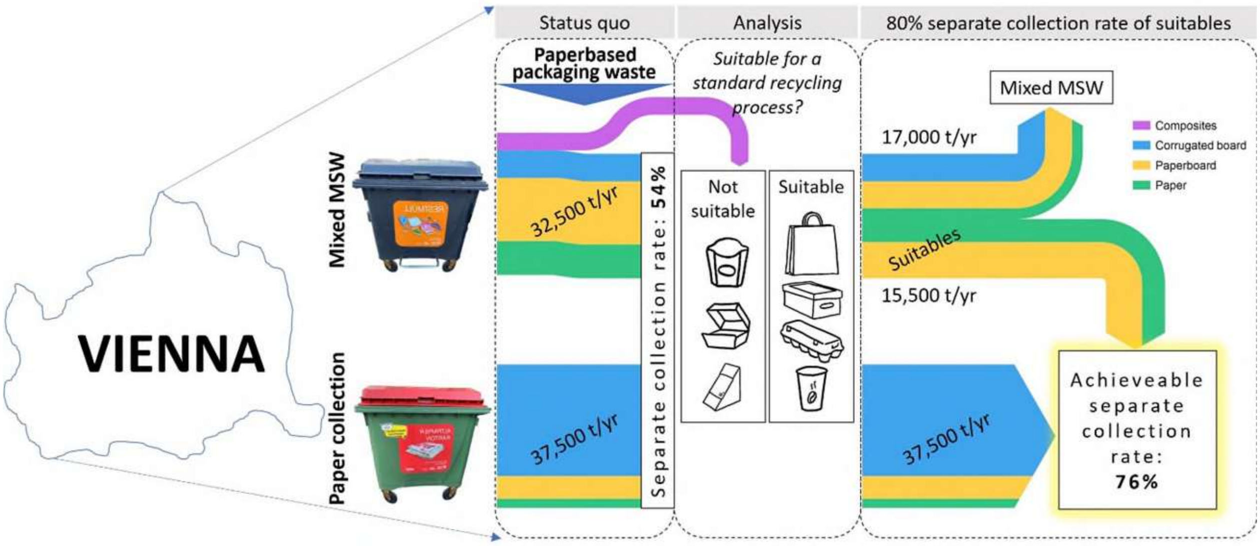
Graphical abstract



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Quantity and quality of paper-based packaging in mixed MSW and separate paper collection – a case study from Vienna, Austria

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ABSTRACT

Given the increasing trend towards paper-based packaging, this study investigated paper, paperboard, and paper-based composite packaging in municipal solid waste (MSW) in Vienna by manual sorting. It identified 25,336 t/yr of paper and paperboard packaging in mixed MSW and 8,335 t/yr in separate paper collection (SPC). Primary food packaging had higher shares in mixed MSW (14–29 %) compared to SPC (8–16 %), while non-food and secondary food packaging dominated both streams. The latter two and dry food packaging deemed most suitable for SPC and recycling due to their low contamination. Improving their separate collection could increase the total separate collection rate from 54 % to 60–76 %. Composite packaging was mainly disposed of in mixed MSW (4,611 t/yr), with fibre-plastic composites dominating over fibre-plastic-metal composites, whereby the latter proved to be less manually separable. The study highlights the need for appropriate disposal methods and effective consumer communication on separate collection to increase recycling of paper packaging.

Abbreviations

LPW	Lightweight packaging waste
MSW	Municipal solid waste
PbPW	Paper-based packaging waste
PW	Packaging waste
SCR	Separate collection rate
SPC	Separate paper collection
RQ	Research question

1. Introduction

Today's modern societies are unimaginable without packaging, enabling global trade and modern consumer marketing (Emblem, 2012; Robertson, 2012). However, packaging has a substantial environmental impact due to the high demand for primary raw materials and is responsible for considerable air and land pollution at the end of its life as packaging waste (PW) (EC, 2022b). PW in the EU has increased by more than 20 % in the last decade, especially single use packaging, and is predicted to increase further (EC, 2022a), but the recycling rate lags behind (EUROSTAT, 2023). This also accounts for paper-based packaging waste (PbPW), which has also constantly increased from 64 kg/capita in 2011 to 73 kg/capita in 2020 (EUROSTAT, 2022). The reasons for the increase are partly the booming online retail sector, the increase in out-of-home consumption, food delivery and associated service packaging, and the substitution of plastic packaging (Benoit et al., 2016; Cayé and Marasus, 2023; Kim et al., 2022; Ratchford et al., 2022; Schmidt and Laner, 2021). At the same time the PbPW's recycling rate in the EU 27 declined from 85.4 % (2016) to 82.5 % (2021) (EUROSTAT, 2024), which is below the recycling target of 85 % to be achieved in 2030 (EC, 2018).

These EU-wide trends can also be observed at national level in Austria, where PbPW volumes increased from 553,300 t/yr (2015) to 603,900 t/yr (2022) while recycling rates decreased from 84 % in 2015 to 79 % in 2022 (BMK, 2021). Although it is not yet clear whether this is due to statistical uncertainties, it is evident that the paper recycling industry has undoubtedly faced significant challenges in recent years. The market for paper for recycling has become increasingly competitive: high-quality graphic papers are becoming scarcer (APA, 2019; Cayé and Marasus, 2023; Fischer, 2024; ORF, 2024; Sung and Kim, 2020), making paper packaging an increasingly important raw material source for recyclers (Bajpai, 2014b; Fischer, 2024). While high quality sources, such as industrial and commercial waste, which are also the easiest to access, have already been largely exhausted, the focus now needs to shift to

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household waste paper, but this has the disadvantage of lower quality due to its heterogeneous composition and high level of impurities (4evergreen, 2023; Bajpai, 2014a; Miranda et al., 2011).

Looking at the regional distribution of recycling rates of packaging in general and PbPW in particular, these tend to be lower in urban than in rural areas (Lederer et al., 2022; Schuch et al., 2023; Seyring et al., 2016). This also counts for PbPW in Austria, where its capital Vienna showed separate collection rates (SCR) for PbPW below the national average (Gritsch and Lederer, 2023). As a consequence, also recycling rates are lower than the national average. Considering this and the fact that Vienna produces 20 % of MSW generated in Austria (BMK, 2023a), there is a large potential in Austria's capital to increase the separate collection and recycling rate of PbPW in the country. However, in order to explain separate collection and recycling rates of PbPW and also to design scenarios for its improvement, not only material flow analyses (MFA) of PbPW are required, as it was done for plastics or metals (Brouwer et al., 2019; Lederer and Schuch, 2024), but also a detailed analysis of quality and characterization of PbPW has to be carried out (Esguerra et al., 2024; Gritsch et al., 2024; Santomasi et al., 2024).

Unfortunately, scientific literature on the quality of paper for recycling is scarce. There are studies focusing on contaminants in PbPW recycling (Peters et al., 2019; Pivnenko et al., 2015, 2016a, 2016b; Pivnenko et al., 2018), studies analysing the impact of increased collection rates and the use of commingled collection systems on the quality of PbPW (Miranda et al., 2011, 2013), and a technical report on the standard qualities of PbPW in Germany, focusing on the technical properties of paper (Krebs, 2019). While the share of paper and cardboard in mixed MSW is usually reported in the course of MSW sorting analyses, with some studies only reporting the share of 'paper and board' (Boer et al., 2010; Denafas et al., 2014) and some studies additionally reporting the share of 'packaging' and 'non-packaging' (Faraca et al., 2019; Liikanen et al., 2016), there are only a few studies reporting a further differentiation, such as Edjabou et al. (2015; 2021), who sorted paper from Danish mixed household waste into several subcategories, or Spies et al. (2024), who analyzed the composition of paper from lightweight packaging waste (LPW), but both did not differentiate PbPW at the product level and did not compare the quality of PbPW from mixed MSW and separate collection. Furthermore, no studies were found that included composite packaging (other than beverage cartons) made of paper and other materials such as plastics and aluminum. This is interesting because this packaging type has become very popular as a substitute for plastic packaging, especially in the food sector, due to the positive consumer image of paper (Nemat et al., 2020, 2022; Nguyen et al., 2020; Otto et al., 2021; Stravens, 2023), but is considered critical in terms of its recyclability and could be partly responsible for the recent decline in recycling rates (Gürlich et al., 2022; Runte et al., 2016; ZSVR, 2023).

Against this background, this study analyses PbPW from household waste, in particular from mixed MSW and from separate paper collection, using manual sorting and material flow analysis (MFA). The aim of this study is to provide insights into the composition, qualities and quantities of PbPW in general, and the unexploited potential and measures to increase the separate waste collection of PbPW in particular, by addressing the following research questions (RQ): (RQ1) What are the material flows of PbPW in Vienna at paper type level (paper, paperboard, corrugated board, paper composite)? (RQ2) What packaging types and qualities for separate collection and recycling are present in these material flows? (RQ3) Which SCR can be derived at packaging type and quality level? (RQ4) What SCR can be achieved by advertising packaging suitable for separate collection and recycling?

The paper is structured in a reasonable order defined by these four research questions (1–4), i.e. the corresponding chapters of the Materials and Methods section (2.1, 2.2, 2.3, 2.4) and the Results and Discussion section (3.1, 3.2, 3.3, 3.4) are numbered accordingly.

2. Methods and materials

2.1. *Material flows of PbPW in Vienna*

2.1.1. *Management of PbPW in Vienna*

SPC in Vienna uses a door-to-door collection convenient to consumers (Stadt Wien, 2024a). Collection containers are provided with a sticker on the front as supporting information for consumers displaying a stack of folded corrugated board boxes and newspapers as examples for the targeted fractions (Gritsch and Lederer, 2023). At the time of analysis these were non-packaging paper and packaging paper like paper bags, folding boxes and corrugated board (Stadt Wien, 2024a), but not paper-based composite packaging that should has been disposed of in the mixed MSW. Large corrugated board should be disposed of at one of the city's recycling centers due to its stiffness and volume (Stadt Wien, 2024a). This study explicitly excludes beverage cartons from paper-based composite packaging, as they are already collected by the LPW collection, separate recovery and recycling processes are already established and their composition is fairly consistent and already known (Feil et al., 2016; Gürlich et al., 2022; Robertson, 2021; Thoden van Velzen et al., 2017).

2.1.2. *Material flow analysis of PbPW in Vienna*

Material flows of PbPW have been calculated by means of MFA, which is a common tool for investigating waste management systems, using the principle of mass conservation (Eq. (1)) to calculate material flows between processes within a defined system (Brunner and Rechberger, 2016). Where, $\sum_{kI=1}^{kI=nI}\dot{m}_{kI}$ is the sum of $kI = nI$ input-material flows, $\sum_{kO=1}^{kO=nO}\dot{m}_{kO}$ is the sum of $kO = nO$ output-material flows, and $\dot{m}_{storage}$ describes the material flow entering or exiting a storage in a process.

$$\sum_{kI=1}^{kI=nI}\dot{m}_{kI} = \sum_{kO=1}^{kO=nO}\dot{m}_{kO} \pm \dot{m}_{storage} \tag{1}$$

Material flows can be calculated for goods, which represent a specific waste flow, and for subgoods, which represent specific types of waste contained in these goods and therefore describe the goods in more detail. Material flows of subgoods are usually calculated through their concentration in the regarding good following Eq. (2), with $\dot{m}_{ji}$ describing the material flow of a subgood j in a good i and c_{ji} describing its concentration in the material flow of good $\dot{m}_i$.

$$\dot{m}_{ji} = \dot{m}_i \times c_{ji} \tag{2}$$

In the case of this study, goods represent all MSW flows from households collected by the MA 48, the municipal waste management department, within the political-administrative boundary of Vienna and containing subgoods of interest (see below) in relevant quantities. These waste flows are mixed MSW and SPC. The LPW collection was excluded from the analysis, because at the time of analysis it was not a target flow of the subgoods analyzed, and therefore the quantities of the subgoods were very low. The annual waste flows for mixed MSW and SPC (in wet masses) have been provided by the MA 48 (MA 48, 2022).

The subgoods contained in the material flows of goods, defined in this study, are paper packaging, paperboard packaging, corrugated board packaging and paper composite packaging, collectively referred to as 'PbPW'. The terms and definitions of paper, paperboard and corrugated board have been defined according to DIN 6730:2017, except for corrugated board where the short form has been used instead of 'corrugated fibreboard' for simplification. According to this standard, paper and paperboard differ mainly in grammage and strength, while corrugated board is precisely defined and consists of at least one corrugated and one flat sheet of paper glued together. The definition of paper composite packaging was according to 4evergreen (2024), a cross-industry alliance of the Confederation of European Paper Industries, which says that composite packaging is “packaging composed of paper and a considerable share of non-paper elements that by design are not separated after use” (4evergreen, 2024). The share of non-paper elements was set at ≥20 % in accordance with the legal requirements of the national Packaging Ordinance (BMLFUW, 2014) and, in line with this, paper packaging coated on both sides were counted as composite, regardless of the ratio of their mass fractions. Some examples of paper composite packaging covered by this definition are listed in the supplementary material (S2.2.3.2); yoghurt cups with paper wrapping were excluded from the analysis, as they are intended to be separated by the consumer.

The annual quantities of these subgoods (in wet masses), as defined above, were calculated by multiplying their concentration in the material flow of goods according to Eq. (2), with the concentrations provided by the MA 48 for 2009, 2015 and 2022 (MA 48, 2022), except for paper composite packaging, for which data only exist for 2022. For calculating material flows of separately collected corrugated board, additionally to the household container collection, also amounts collected via the recycling centers were considered (Table S3-S6 in the supplementary file).

2.2. Types and qualities of PbPW for separate collection and recycling

All subgoods, except for corrugated board, were further analyzed at different levels representing sub-subgoods to determine their composition and quality. Corrugated board was exempted, because amounts collected separately are already high, in contrast to paper and paperboard packaging (Gritsch and Lederer, 2023) and it is usually a very homogeneous waste consisting of large, unsoiled packaging.

2.2.1. Sampling and presorting

The sampling was conducted as part of a large MSW sampling campaign in 2022, where all MSW flows in Vienna were sampled and analyzed, including the target flows for PbPW, SPC and mixed MSW. Sampling was based on the national guideline for waste sorting analyses (Beigl et al., 2019; BMK, 2021), which has been developed in consideration of national standards and European guidelines (ÖNORM S 2097: 2005; EC, 2004). Accordingly, four different strata were considered, representing different settlement structures and purchasing power. When selecting the random samples, the four strata were included in proportion to their share of the total waste volume. Sampling and pre-sorting of goods (mixed MSW and SPC) to subgoods (paper, paperboard, corrugated board, paper composite packaging) was carried out by an engineering office according to the standard characterization defined in the national guideline and a previously defined sorting catalogue (Beigl et al., 2019; BMK, 2021). The distinction between packaging and non-packaging was conducted according to the national Packaging Ordinance (BMLFUW, 2014). MA 48 not only provided this data for modelling the material flows of subgoods (Section 2.1.2), but also the pre-sorted subgoods from the sampling campaign for further in-detail characterization carried out by the authors of this study as described in Section 2.2.2 and 2.2.3.

In detail, during the 15 working day sampling campaign, mixed MSW samples were collected from 20 randomly selected addresses per day throughout the entire area of the city, resulting in 300 addresses over the entire sampling campaign. The daily samples were therefore representative of the city as a whole. In each case, samples of 240 L were taken directly from the waste containers on the day of regular collection or the day before. In total, about 3,000 kg of mixed MSW was analyzed by the engineering company. In each of the three weeks, the same day of the week was selected on which the pre-sorted subgood samples relevant for this study were retained by the engineering company, meaning that the mixed MSW samples from 60 addresses were analyzed in detail. The corresponding sample weight analyzed in detail were 26 kg of paper and paperboard packaging, and 7 kg of paper composite packaging.

For SPC, 180 containers were taken as individual samples from randomly selected addresses across the city and then analyzed as a whole, giving a total sample of about 3,600 kg. Samples were taken on the day of regular collection or the day before. For the paper and paperboard packaging samples, the engineering office retained the sorted partial quantities from every tenth container, and for the paper composite packaging samples from every container, i.e. a total of 33 kg and 11 kg, respectively.

2.2.2. Detailed characterization of paper and paperboard packaging

The paper and paperboard packaging sample was air-dried at room temperature and atmospheric pressure and then manually sorted at four levels (Table S1) and weighed afterwards. This procedure was chosen for practical and health reasons, as sorting took several days, during which time the fresh material would have started to mould. On the first level (I) of sorting there is a distinction in food and non-food packaging, as it is assumed that food packaging is the most critical for the quality of paper for recycling due to contamination with product residues, or food in particular (4evergreen, 2024). However, this depends on the food contact level, which is addressed in step (II) and divides in primary and secondary food contact. In this study, primary contact means packaging that by design is in direct contact with the packaged food, e.g. egg carton, disposable paper cup, flour paper bag, and are therefore likely to carry residues. Secondary contact in this study means indirect contact with the packaged food, where contact and therefore contamination is unlikely but cannot be completely excluded (Burggräf et al., 2023), e.g. cardboard box for cereals in a plastic bag, supermarket paper carrier bags, outer packaging of multipacks. The third step (III) is to differentiate the primary food packaging by product type, i.e. what type of food was packaged. Moist and oily foods are likely to have the greatest product related contamination potential in terms of product residues in the packaging, while liquid foods are easier to empty and dry foods generally have a low risk of leaving product residues in the packaging. To test this, the packaging were qualitatively classified as “clean” and “soiled” in a final step (IV). Only internal, product-related contamination at the moment of disposal was considered, not external contamination, which occurs in mixed MSW due to cross-contamination with other waste components. As an additional point of reference for soiled packaging, the moisture content of paper and paperboard per waste stream (mixed MSW and SPC) was also determined at 105 °C until constant weight as defined in DIN 6730:2017 (details see S2.2.2).

As a result of the manual sorting at the four different levels, the packaging that is suitable for separate collection and recycling have been identified, including characteristic packaging that could represent a good and easy communication tool for an improved separate collection of PbPW.

The resulting composition of paper packaging from manual sorting is presented as proportions of the respective subgood (paper/paperboard) and also as extrapolated annual quantities in wet mass, calculated by inserting in Eq. (2), using the annual quantities of goods and subgood concentrations provided by MA 48 (MA 48, 2022). It has been decided to present all quantities in wet mass as this is the mass in which the paper is handled and delivered to the paper mills and therefore best reflects practice.

2.2.3. Detailed characterization of paper composite packaging

After air-drying at room temperature and atmospheric pressure, the paper composite packaging samples were manually sorted at three levels (Table S2) and weighed afterwards. At the first level (I), a distinction was made between paper, paperboard and corrugated board packaging material. The composites were then categorized according to their composite type (II) into fibre-plastic, fibre-plastic-metal and fibre-metal composites. Fibre in this context means both paper and paperboard. To check a plastic lamination, a tear-off test was carried out. Finally, the composites were disassembled by hand as far as possible and the quantities of the separated subcomponents were weighed (III).

The resulting composition of paper composite packaging from manual sorting is presented as proportions of subgoods and also as extrapolated annual quantities, calculated using the annual amounts of goods and subgood concentrations provided by MA 48 (MA 48, 2022).

2.3. Separate collection rate

SCR was computed for all subgoods and sub-subgoods i targeted for separate collection as a quotient of the separately collected quantity $m_{in\ SPC,i}$ to the total quantity of the regarding PbPW fraction $m_{in\ SPC,i} + m_{in\ mixed\ MSW,i}$ according to the following Eq. (4). As the calculation of the SCR only covers the waste streams of mixed MSW and SPC, but there are certainly other waste streams containing PbPW (Kladnik et al., 2024; Spies et al., 2024), the relevant waste streams have been added as an index to the SCR. To calculate the SCR of corrugated board, the amount of corrugated board deposited at the recycling center was added to the amount collected separately from households with container collection.

$$SCR_{SPC,mixed\ MSW,i}\ [\%] = \frac{m_{in\ SPC,i}}{m_{in\ SPC,i} + m_{in\ mixed\ MSW,i}} \cdot 100 \quad (4)$$

2.4. Scenarios for improved separate collection of PbPW

Based on the PbPW composition, the potential of paper and paperboard packaging in mixed MSW was determined by developing scenarios for improved separate collection of PbPW suitable for separate collection and for recycling. This is critical, as interventions for improved separate collection should only address suitable PbPW for recycling, otherwise a deterioration in quality would be accepted (Miranda et al., 2011). Corrugated board was assumed to be 100 % suitable for separate collection and recycling, while composite paper packaging was assumed not to be suitable because of significantly reduced recycling efficiency (4evergreen, 2024; Gürlich et al., 2022). The scenarios therefore only cover the improved collection of paper and paperboard packaging.

The first scenario assumed that all suitable paper and paperboard packaging, as found after the detailed characterization (Section 2.2.2), were collected at the average SCR of the PbPW in Vienna (see Fig. 2). The second scenario assumed that all suitable paper and paperboard packaging were collected at the highest SCR occuring among all subgoods (see Fig. 2). And the third scenario assumed that only the most characteristic and easily recognizable PbPW (as identified in Section 2.2.2) was collected at the highest SCR occuring among all subgoods.

The impact on the total SCR of paper, paperboard and corrugated board together per scenario i was calculated, according to Eq. (5), with $m_{CB,SPC}$ being the annual mass of corrugated board, $m_{NS,SPC}$ being the summarized mass of the not suitable paper and paperboard fraction and $m_{S,SPC} = (m_{S1} + m_{S2} + \cdots + m_{Sn})_{SPC}$ being the summarized mass of the suitable paper and paperboard fractions in SPC. For scenario 3, the suitable fraction account only for one, namely the most characteristic one. Masses with the index *MSW* are the corresponding masses in mixed MSW. The variable a stands for the respective SCR for each scenario, as described above.

$$SCR_i[\%] = \frac{m_{CB,SPC} + m_{NS,SPC} + a \cdot m_{S,SPC}}{m_{CB,SPC} + m_{NS,SPC} + a \cdot m_{S,SPC} + m_{CB,MSW} + m_{NS,MSW} + (1-a) \cdot m_{S,MSW}} \quad (5)$$

Fig. 1 gives an overview of all the methods and materials used for this study.

3. Results and discussion

The results are presented in the same order as the research questions, starting with the material flows of PbPW (3.1; RQ1), then the types and qualities of PbPW assessed by manual sorting are presented, with the results for paper and paperboard packaging first (3.2.1; RQ2), followed by paper composite packaging (3.2.2; RQ2). The next chapter presents the specific separate collection rates at packaging type and quality level (3.3; RQ3), and the last chapter presents the scenarios for an improved separate collection of suitable PbPW (3.4; RQ4).

3.1. Material flows of PbPW in Vienna

Concentrations of PbPW increased in both, the SPC and mixed MSW. While in 2009 the total PbPW was 23.0 % in SPC and 3.7 % in mixed MSW, in 2015 it was 23.3 % and 4.3 % and in 2022 it was 36.3 % and 6.4 %, respectively. Thus, the total quantities of paper, paperboard and corrugated board packaging increased significantly, from 49,654 t/yr (2009), to 52,475 t/yr (2015) and finally 70,028 t/yr (2022). Simultaneously, the total SCR of paper, paperboard and corrugated board decreased from 62 % (2009) to 57 % (2015), and 54 % (2022). For detailed data see Table S3-S7 in the supplementary file.

This trend of increasing quantities and decreasing SCR can also be observed for paper packaging alone, where amounts doubled from 5,646 t/yr in 2009 to 11,212 t/yr in 2022, while SCR decreased from 33 % to 21 %. Similarly, for paperboard packaging, volumes increased from 12,590 t/yr in 2009 to 22,458 t/yr in 2022, while SCR decreased from 36 % to 26 % (Fig. 2).

Corrugated board represents the largest material flow of all PbPW and there is also a trend for increasing quantities, with 31,418 t/yr in 2009 and 36,358 t/yr in 2022. Of all PbPW, corrugated board has the highest SCR, which, unlike paper and paperboard, has remained constant at about 80 % over time. This is possibly due to the fact that consumers are more likely to collect large packaging separately than small packaging (Nemat et al., 2020; Thoden van Velzen et al., 2019).

In contrast, paper-based composite packaging not only have the lowest amount of 4,707 t/yr in 2022, but are also almost entirely found in mixed MSW at 4,611 t/yr. SPC contains comparatively small amounts of composites with 96 t/yr.

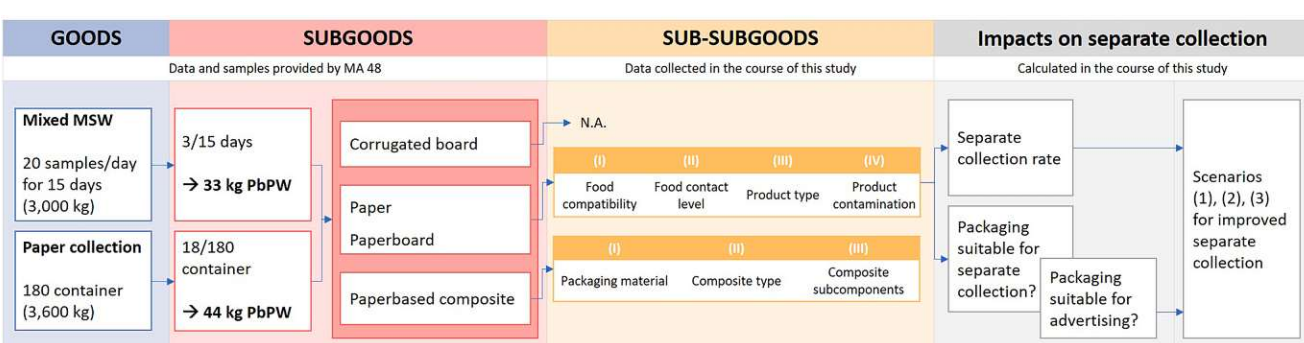

Fig. 1. Overview of the methods and materials used (N.A., not analyzed; MSW, municipal solid waste; PbPW, paper-based packaging waste).

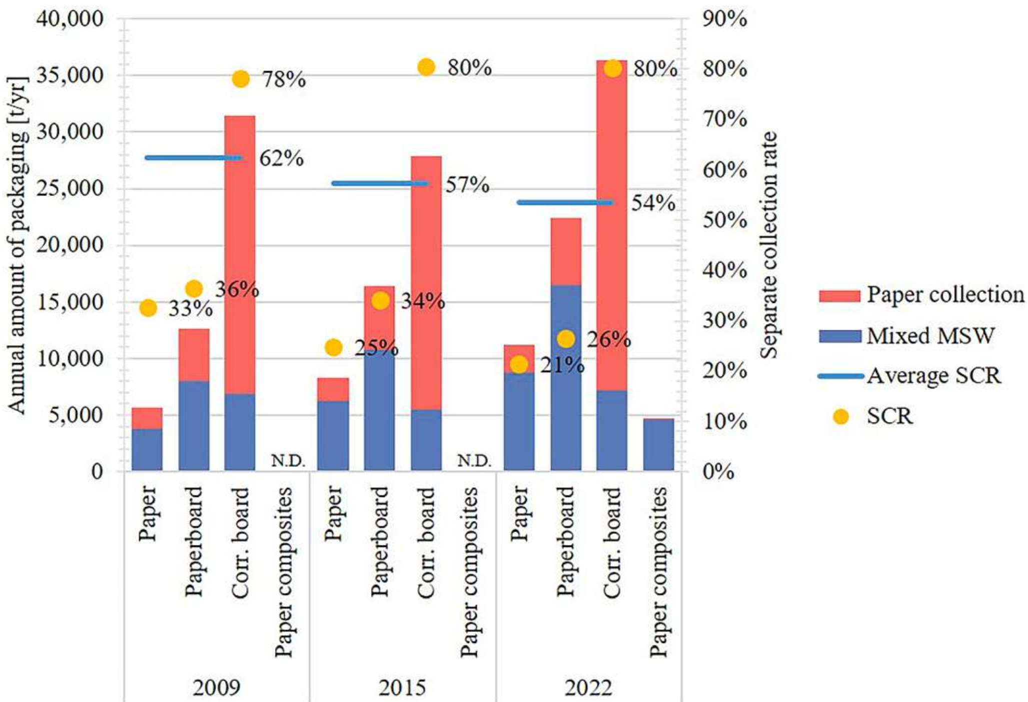

Fig. 2. Annual amounts of paper, paperboard, corrugated board (for 2009, 2015, 2022) and composite packaging waste (2022 only) in Vienna, shown in t/yr (stacked columns), related separate collection rates (SCR) (dots) and average SCR (lines) in w% on a wet matter basis, (corr. board, corrugated board; N.D., no data).

3.2. Types and qualities of PbPW for separate collection and recycling

3.2.1. Paper and paperboard packaging

3.2.1.1. Composition. The results of the characterization of paper/paperboard packaging shown in Fig. 3 indicate that 55 % of the paperboard in mixed MSW is non-food and 16 % is secondary food packaging. In contrast, for paper packaging, secondary food packaging has the highest share with 51 % and non-food packaging accounts for 35 %. Overall, the share of primary food packaging is higher for paperboard at 29 % than for paper packaging at just 14 %. In primary food paperboard packaging, oily (11 %) and moist food (9 %) have the highest shares, liquid food the lowest (3 %). In primary food paper packaging, dry (6 %) and moist food (5 %) have the highest shares (Fig. 3(A)). For pictures of the fractions see the supplementary file Figure S1-S2.

In SPC (Fig. 3(B)), the shares of non-food and secondary food in

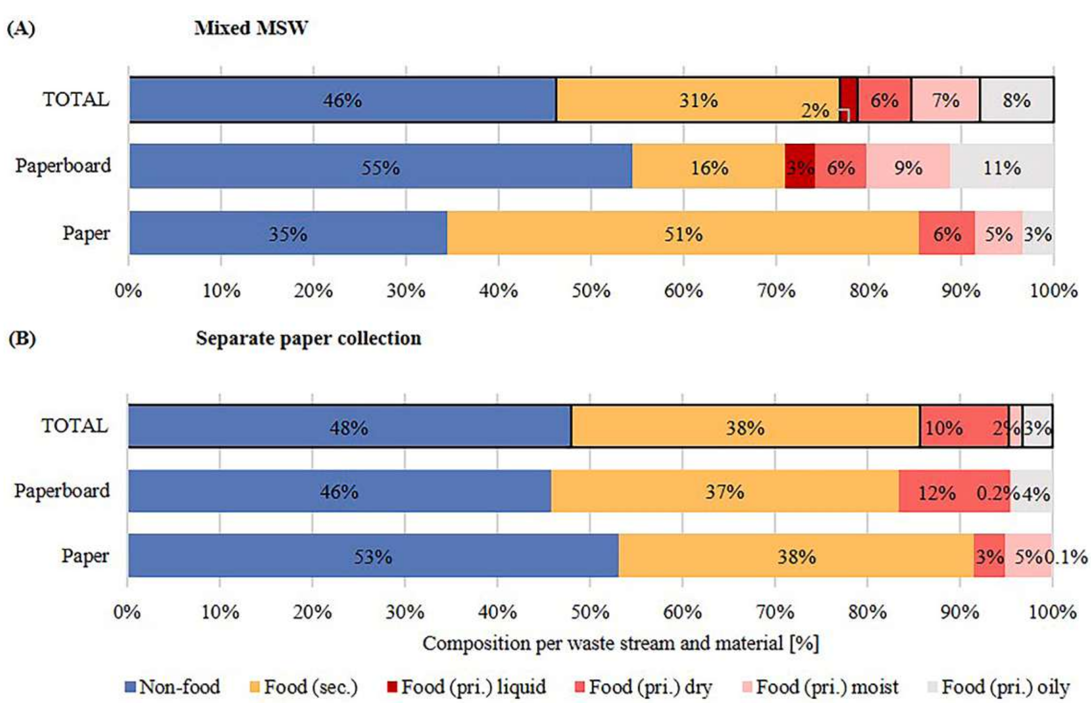

Fig. 3. Composition of paper and paperboard packaging and a mean composition of both (TOTAL) in mixed MSW (A) and the separate paper collection (B), regarding food compatibility (food/non-food), food contact level (primary/secondary) and product type (liquid/dry/moist/oily), (sec., secondary; pri., primary).

paperboard and paper packaging are of the same range with 46 % and 37 % in paperboard and 53 % and 38 % in paper packaging. The shares of primary food packaging are much lower than in mixed MSW, with around 16 % in paperboard and around 8 % in paper packaging. Dry food has the highest share in paperboard packaging, while in paper packaging it is moist food. Packaging of liquid foodstuff was not found at all in SPC.

Overall, the share of potentially contaminated primary food packaging is significantly higher in mixed MSW (23 %) than in SPC (15 %). The share of food packaging for moist and oily foods, which have the highest risk of carrying residues, is even three times higher in mixed MSW (15 %) than in SPC (5 %). This difference could also be reflected in the moisture content found, which is also more than twice as high in mixed MSW (16.6 %) as in SPC (7.2 %). For SPC the moisture content is within the normal range for this grade of paper, which is usually around 10 % (Krebs, 2019; Miranda et al., 2011).

The qualitative analysis of packaging contaminated by the product itself showed that in total in mixed MSW, a considerable higher share of packaging was soiled, with 7 % of paper and 21 % of paperboard, in contrast to SPC, where it was 1 % of paper and 4 % of paperboard packaging. The detailed analysis at product level showed the highest share of soiled packaging in moist (15–100 %) and oily (82–100 %) food packaging, whether in mixed MSW or SPC. The lowest share was found in non-food and secondary food packaging at only 0–1 % and liquid food packaging at 5 % (Figure S3-S4). It can therefore be confirmed, that moist and oily products have the greatest product-related contamination

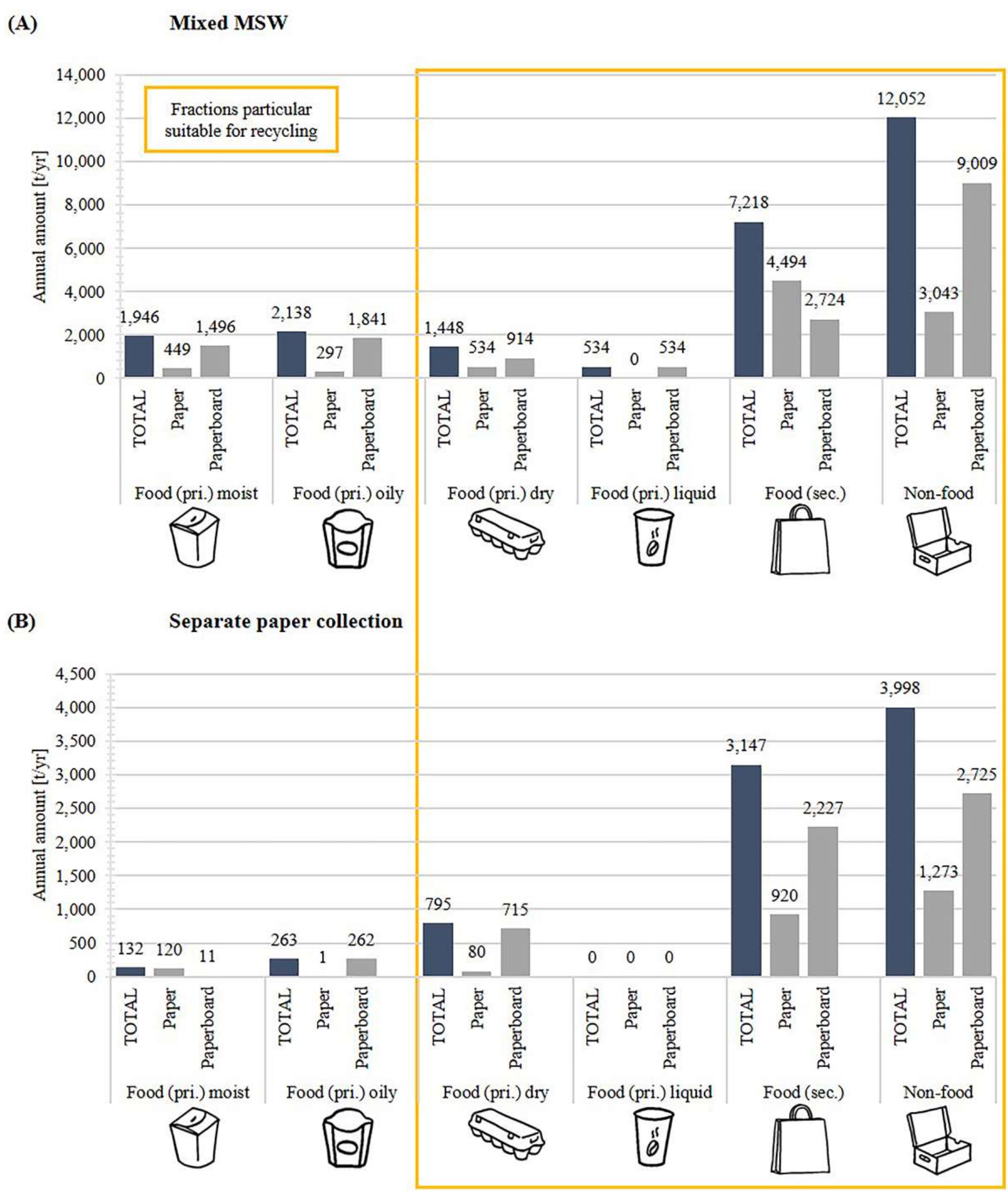

Fig. 4. Annual amounts of paper and paperboard packaging waste in mixed MSW (A) and separate paper collection (B), shown in t/yr on a wet matter basis, packaging suitable for recycling circled in yellow, icons showing examples of packaging for the respective fraction (sec., secondary; pri., primary).

potential and could pose a risk to the transfer of product residues to the recycling process and therefore should be disposed of in the mixed MSW. These, and food material in general, are highly unwanted and are therefore listed as prohibited materials in the European Standard EN 643:2014, as they can lead to excessive microbial growth and increased risk of pests infestation resulting in lower quality and higher production costs (4evergreen, 2024). Therefore, only packaging with low contamination would be suitable for separate collection and recycling, which are food packaging of dry and liquid food, secondary food packaging and non-food packaging. Summarized, at least 5 % of paper and paperboard in SPC was missorted due to contamination and 85 % of unsoiled packaging in mixed MSW was missorted, because it should have been disposed of in SPC (see Fig. 3).

From all suitable paper packaging, paper carrier bags were determined as the most characteristic paper packaging articles (Figure S2). They would represent an easily understandable and depictable packaging article for consumer communication and represent 91 % of the secondary food paper packaging and 54 % of the non-food paper packaging in mixed MSW.

3.2.1.2. Material flows. For material flows of sub-subgoods this means, that in mixed MSW there is an amount of 12,052 t/yr of non-food, 7,218 t/yr of secondary food and 6,066 t/yr of primary food packaging, with oily (2,138 t/yr) and moist (1,946 t/yr) food packaging being the most frequent. In SPC also non-food (3,998 t/yr) and secondary food (3,147 t/yr) packaging have the highest amounts. In contrast, dry food is the dominant primary food packaging with 795 t/yr, oily and moist food are behind at 263 t/yr and 132 t/yr, respectively (Fig. 4).

3.2.2. Paper composite packaging

3.2.2.3. Composition. The results of the characterization of paper composite packaging indicate that paper composites are predominant in mixed MSW (56 %), whereas in SPC there are more paperboard composites (53 %) (Figure S5(A)). Possibly because, from a consumer's perspective, paperboard is considered more valuable for recycling due to its higher weight or size (Nemat et al., 2020, 2022; Thoden van Velzen et al., 2019). Composites with corrugated board are very rare (0.2–5 %). In terms of composite type (Figure S5(B), fiber-plastic composites are predominant in all waste flows (74–75 %), followed by fiber-plastic-metal composites (25–26 %). Most of the fiber-plastic composites in the mixed MSW are made of paper (67 %), whereas the majority of the fiber-plastic-metal composites are made of paperboard (77 %), this is also true for the SPC (Figure S6). The results of disassembling the composites showed, that the proportion of manually inseparable components is the highest for paperboard composites (42–47 %) and for composites composed of fibre-plastic-metal (62–65 %) (Figure S7-S8).

3.2.2.4. Material flows. Although composite packaging was not a target fraction at the time of the analyses this will change in 2023 when all LPW, including composite packaging, will have to be collected separately (EC, 2018; Stadt Wien, 2024b). This means that from mixed MSW and SPC up to 2,629 t/yr of paper composites, 2,066 t/yr of paperboard composites and a maximum of 11 t/yr of corrugated board composites will enter the LPW collection, provided they are disposed of separately. When considering composite types, the largest quantities will be fiber-plastic composites with 3,520 t/yr, followed by fiber-plastic-metal composites with 1,186 t/yr and negligibly small amounts of fiber-metal composites (1 t/yr).

At the national level, a comparison is not possible because Austria does not report the annual amounts of paper-based composite packaging separately (BMK, 2023b), whereas a comparison with the per capita amounts in Germany is possible: Germany reports 279,000 t/yr of paper-based composite packaging in 2021 (Cayé and Marasus, 2023), which corresponds to 3.4 kg/capita (Destatis, 2024), while the 4,707 t/yr of paper-based composite packaging in Vienna corresponds to 2.4 kg/capita (Statistik Austria, 2024) and is therefore in the same range. However, a comparison is difficult, because composite packaging is very heterogeneous and can be defined both technically or according to the Packaging Ordinance (BMLFUW, 2014). Therefore, a large amount of paper-based composite packaging may not even appear in the statistics, because paper-based composites with a content of foreign materials (e.g. plastic, metal) lower than 20 % are licenced as paper mono-packaging (BMLFUW, 2014). However, especially paper packaging with a low content of foreign materials, mainly plastic, is increasing (Burger et al., 2022) and needs to be addressed in the near future.

3.2.3. Separate collection rate

With a total of 32,530 t/yr of paper, paperboard and corrugated board in the mixed MSW and a respective amount of 37,498 t/yr in the SPC (including recycling centers), the current total SCR in Vienna for paper, paperboard and corrugated board together in 2022 is 54 %.

Looking at the packaging-specific SCR of paper and paperboard at the sub-subgood level, the results show a wide variance from 0 % to 45 % (Fig. 5). For food packaging of moist and oily food SCR is rather low with values at 6 % and 11 %, which is desirable and probably a result of recommending dirty paper to dispose of in the mixed MSW by the municipality (Stadt Wien, 2024a). The packaging with the highest SCR are those of dry foods (35 %), secondary food (30 %) and non-food packaging (25 %), which are also among the most suitable for recycling. Together with liquid food packaging, all suitable packaging achieve a weight average SCR of 28 %. In terms of packaging material, paperboard tends to achieve higher SCR (0–45 %) than paper (0–29 %). The SCR of only paper carrier bags, which are included in the non-food and secondary food paper packaging, is 19 %.

3.3. Scenarios for improved separate collection of PbPW

As the current SCR of paper and paperboard suitable for recycling is 28 % on average (Section 3.3), there is currently an unexploited PbPW potential of at least 21,252 t/yr of paper and paperboard packaging in the mixed MSW (12,052 t/yr of non-food, 7,218 t/yr of secondary food, 1,448 t/yr of dry food and 534 t/yr of liquid food packaging). Paper carrier bags alone (which are included in the non-food and secondary food packaging) already account for 5,737 t/yr.

In the first scenario, 54 % of all suitable packaging is collected separately, resulting in an increase of 11 percentage points in the total SCR to 65 % (Fig. 6). If 80 % of all suitable packaging were collected separately, which is the highest SCR of all packaging achieved by corrugated board (Fig. 2), a total SCR of 76 % would be achieved in scenario 2. And if 80 % of only the paper carrier bags, were collected separately, this would still increase the total SCR to 60 %. The result of scenario 2 shows, that theoretically an increase of the SCR by 22 percentage points compared to the status quo state can be achieved in the best case of the given scenarios.

As the SPC is already implemented as the most convenient collection system, improvement of the SCR must be achieved otherwise. Studies showed, that pictograms can help consumers to choose the right container for recyclables (Cristóbal García et al., 2022; Gritsch and Lederer, 2023; Rousta et al., 2015), therefore, one option to enhance SCR would be to display the respective packaging waste on the collection container. However, not every PbPW is equally suitable for depiction, as found in this study. While non-food packaging would represent the highest amount, simplified representation as e.g. a pictogram cannot be realized easily, as this waste fraction is composed of many different small articles, and is therefore very inhomogeneous (Figure S2(A)). Whereas secondary paper and non-food paper fractions are composed of a considerable amount of paper carrier bags, which very well can be displayed as image, as they have a characteristic appearance and are easy recognizable (Figure S2(B)). Moreover, paper carrier bags are made

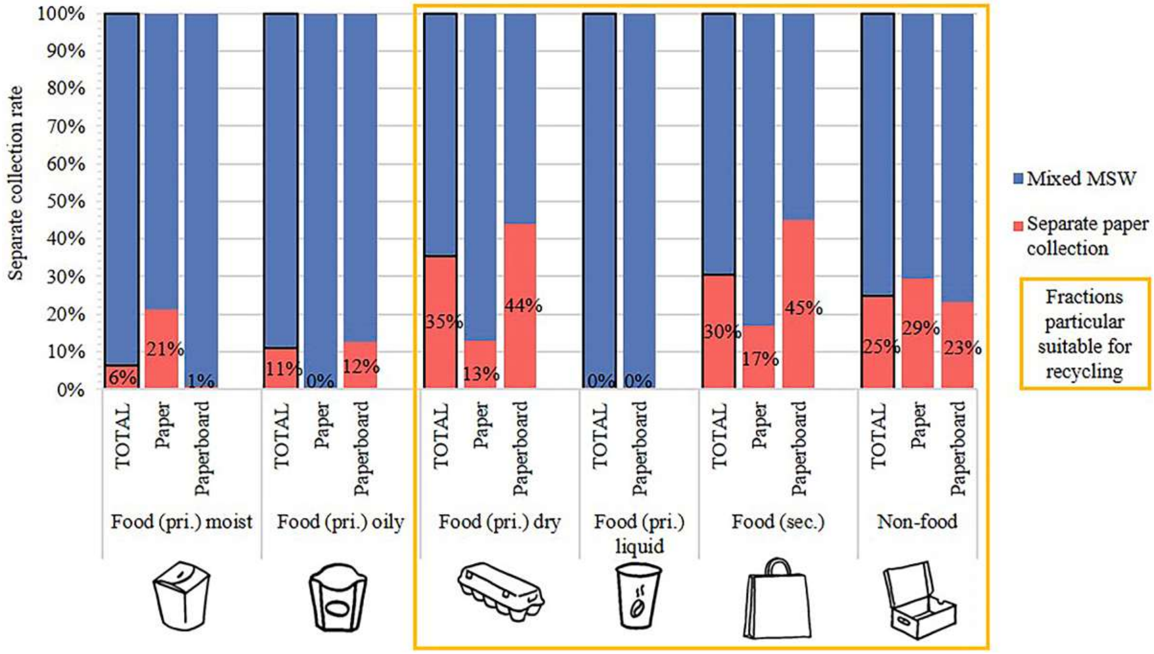

Fig. 5. Separate collection rates (SCR) as percentage of packaging waste in separate paper collection (red bars) in relation to packaging waste in mixed MSW (blue bars), packaging suitable for recycling circled in yellow, icons showing examples of packaging for the respective fraction (sec., secondary; pri., primary).

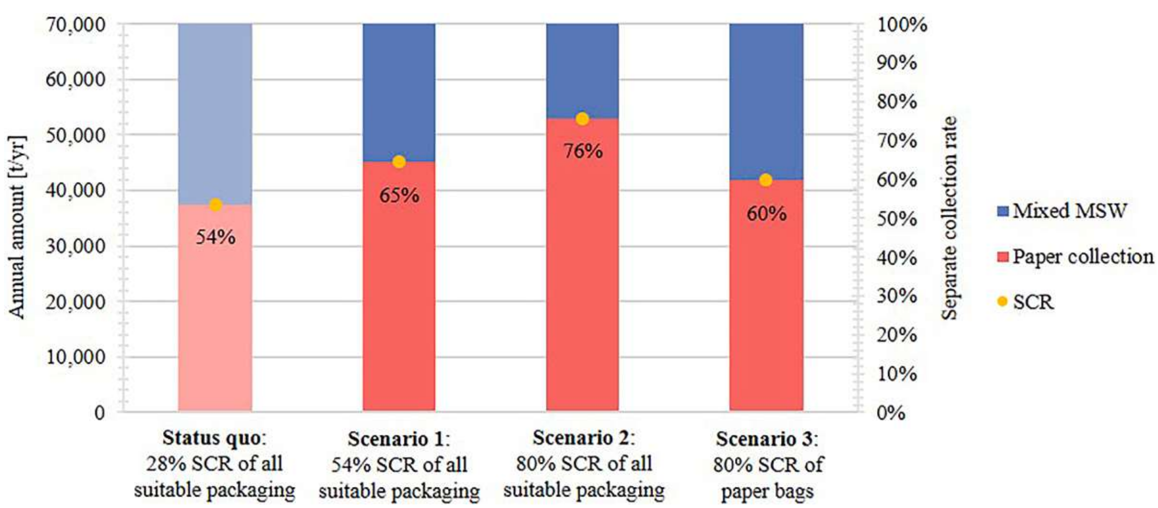

Fig. 6. Status quo of paper, paperboard and corrugated board packaging in mixed MSW and in paper collection and three different scenarios (1–3) for improved separate collection of paper and paperboard packaging. Annual amounts in mixed MSW (blue bars) and separate paper collection (red bars) in t/yr on a wet matter basis and the resulting total separate collection rate for paper, paperboard and corrugated board together in % on a wet matter basis. Scenario 1: 54 % of all suitable packaging is collected separately, scenario 2: 80 % of all suitable packaging is collected separately, and scenario 3: 80 % of the paper carrier bags are collected separately.

of Kraft paper, the strongest fiber type and are therefore considered a high-quality secondary raw material for packaging (Welton Bibby and Barton Ltd, 2005). As an EU-wide harmonization of separate collection, including harmonized sorting instructions on packaging and collection containers (EC, 2022c) is planned by 2028, the possibility of an additional display of locally specific packaging on collection containers is therefore highly recommended.

It is generally known, that separate collection has its saturation limits, which especially counts for urban areas. If improvements in separate collection cannot be achieved by afore mentioned measures, commingled collection with other recyclables could be considered, as already established with plastic and metal packaging waste in Vienna (Gritsch and Lederer, 2023). This facilitates waste sorting for consumers by e.g. saving space in the household (Cristóbal García et al., 2022). However, there will always be a reduction in quality, which must be weighed up (Miranda et al., 2013). The final option for recovering paper for mechanical recycling is automated sorting from mixed MSW. However, there are some limitations to consider: Small packaging is difficult to sort (Tanguay-Rioux et al., 2021), the quality is reduced (Cimpan et al., 2015) and sorted paper is not suitable for use as a food contact material (BfR, 2019). In addition, EN 643:2014 still declares paper from mixed waste collections unsuitable for use in the paper industry. However, with decreasing recycling rates and other current challenges in the recovered paper industry, it would be appropriate to review these restrictions.

3.4. Limitations

Despite the valuable scientific contributions of this study, several limitations should be taken into account. Firstly, it is important to be cautious when attempting to generalise the findings to the wider Austrian context, as this study was conducted as a case study focused on Vienna and the specific demographic and waste management characteristics of Vienna may not fully represent those of other regions of Austria.

Secondly, the sampling procedure, which involved direct collection of waste from bins, presented challenges that may have affected the representativeness of the results. As a result of the considerable effort put into detailed sorting at several levels, the sample size for certain subcategories was relatively small, limiting the ability to draw detailed conclusions at this level. Furthermore, the manual sorting method, although necessary at this level of detail, is inherently prone to error or inconsistency, without further technical support, for example in differentiating between paper mono and paper composite packaging. As a result, this study should be seen as a preliminary effort to understand the composition of paper-based packaging. It is not intended to draw definite conclusions but to provide a basic understanding for future research.

In addition, the study was limited to specific waste streams, such as household waste, and future research should include other sources such as public waste or LPW for a more comprehensive understanding of the composition and recycling potential of PbPW.

Finally, it is recommended that future studies include fibre quality in the sorting methodology, distinguishing between white, grey and brown fibres, to be consistent with industry practice.

4. Conclusion

In this study, paper, paperboard and paper-based composite packaging in MSW from households in Vienna were manually sorted according to packaging and product-related aspects in order to gain knowledge about the specific quality and composition. Suitable packaging for separate collection and recycling was identified and scenarios for an improved separate collection were investigated by calculating SCR.

The results show that in contrast to corrugated board (80 % SCR), only 21 % and 26 % SCR were found for paper and paperboard in this study. Therefore, an amount of 25,336 t/yr of paper and paperboard packaging was still found in mixed MSW and the corresponding amount of 8,335 t/yr in SPC. Specifically, non-food and secondary food packaging were found to have the highest shares, both in mixed MSW and SPC. For primary food packaging, the shares were significantly higher in mixed MSW (14–29 %) than in SPC (8–16 %), which is also supported by the low packaging-specific SCR of liquid, moist and oily food packaging (0–11 %) and is desirable from a paper recycling point of view due to the risk of contamination. In addition, the study identified primary packaging for dry and liquid food, secondary food packaging -particularly paper carrier bags- and non-food packaging as suitable for SPC due to their low contamination levels and easy communication. As a result of their average SCR of only 28 %, the study identified a currently unexploited potential of these suitable PbPW of at least 21,252 t/yr in mixed MSW. By promoting this packaging for separate collection, the actual SCR of paper packaging in general in Vienna (54 %) could be increased to 60–76 %.

The study also found that paper composite packaging, with a total of 4,707 t/yr, is contained in mixed MSW and SPC in much lower quantities than paper and paperboard packaging. It was disposed of almost entirely in mixed MSW (4,611 t/yr), with paper composites (2,589 t/yr) predominant over paperboard composites (2,015 t/yr). The results also show, that in terms of composite type, fiber-plastic composites were the most common, with 3,520 t/yr in mixed MSW and SPC, followed by fiber-plastic-metal composites (1,186 t/yr).

This study confirms that there is a considerable amount of paper-based packaging in MSW, with high amounts in the mixed MSW, which is lost for recycling. With the increasing trend towards paper-based packaging, it is essential to develop appropriate disposal and recycling methods to ensure these materials contribute to a circular economy. Future research should focus on a larger scale, possibly using automated sorting technologies, which would help to provide a more realistic picture of the challenges of paper recovery and recycling. Finally, further research should focus on acceptable levels of product contamination of PbPW, the detailed composition and recyclability of paper-composite packaging and effective consumer communication, as these topics are likely to become increasingly important.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used DeepL in order to translate and improve readability. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

CRediT authorship contribution statement

Lea Gritsch: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Gisela Breslmayer:** Methodology, Investigation, Data curation. **Jakob Lederer:** Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.108091.

Data availability

Data will be made available on request.

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