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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.

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

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 $\dot{m}_i$.

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

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.

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

### 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.

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

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.

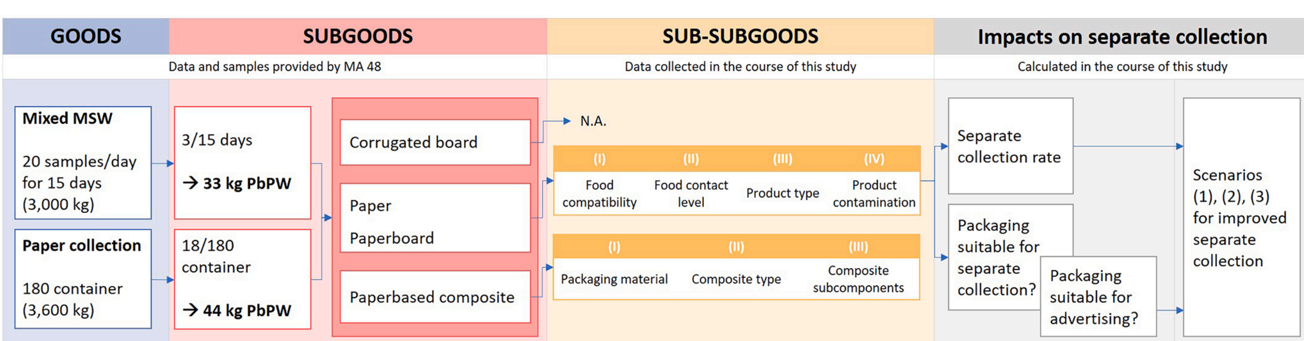


**Fig. 1.** Overview of the methods and materials used (N.A., not analyzed; MSW, municipal solid waste; PbPW, paper-based packaging waste).

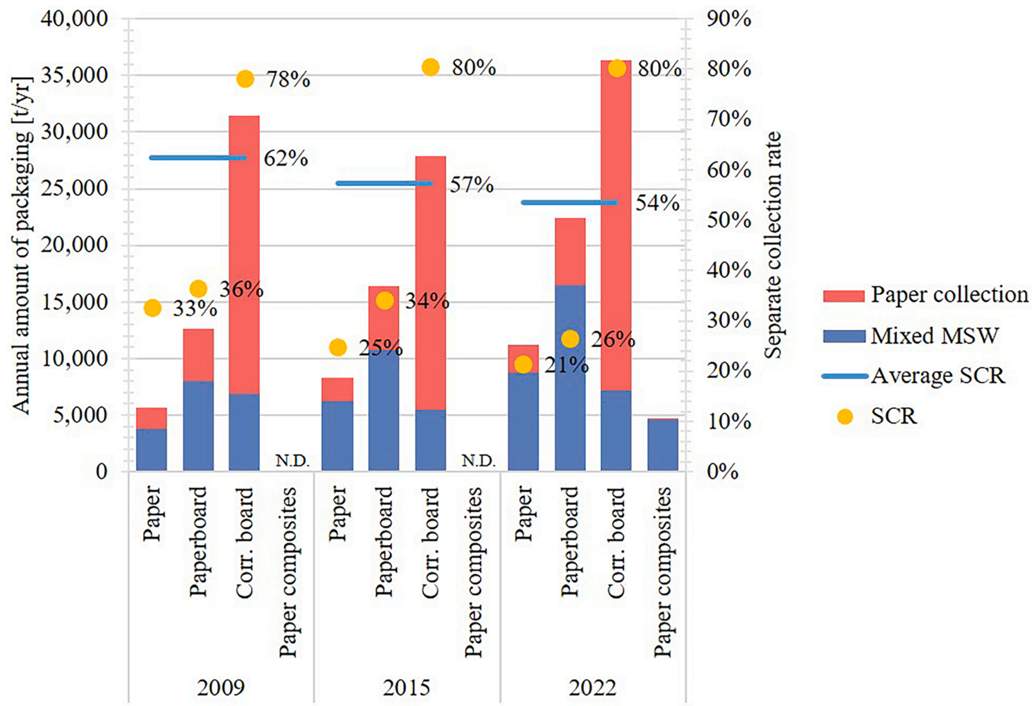


**Fig. 2.** Annual amounts of paper, paperboard, corrugated board (for 2009, 2015, 2022) and composite packaging waste (2022 only) in Vienna, shown in t/yr (stacked columns), related separate collection rates (SCR) (dots) and average SCR (lines) in w% on a wet matter basis, (corr. board, corrugated board; 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

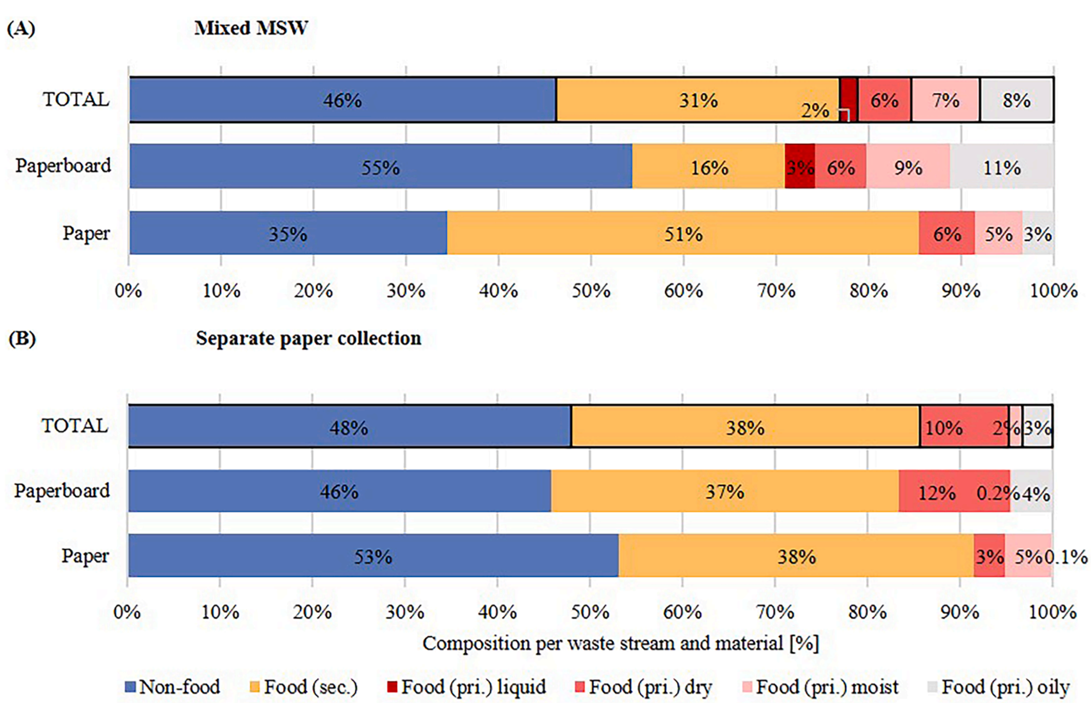


**Fig. 3.** Composition of paper and paperboard packaging and a mean composition of both (TOTAL) in mixed MSW (A) and the separate paper collection (B), regarding food compatibility (food/non-food), food contact level (primary/secondary) and product type (liquid/dry/moist/oily), (sec., secondary; pri.,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

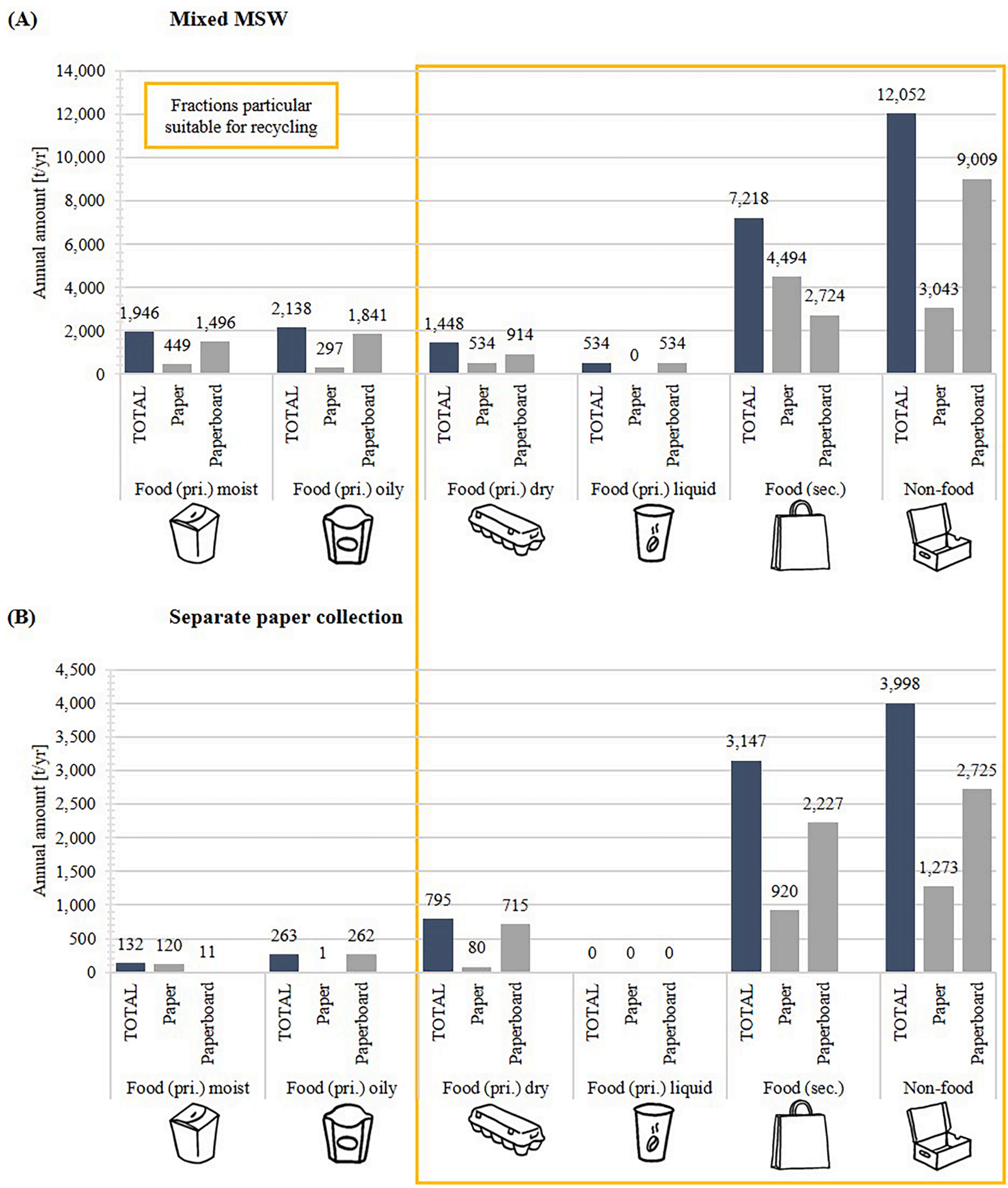


**Fig. 4.** Annual amounts of paper and paperboard packaging waste in mixed MSW (A) and separate paper collection (B), shown in t/yr on a wet matter basis, packaging suitable for recycling circled in yellow, icons showing examples of packaging for the respective fraction (sec., secondary; pri., primary).

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

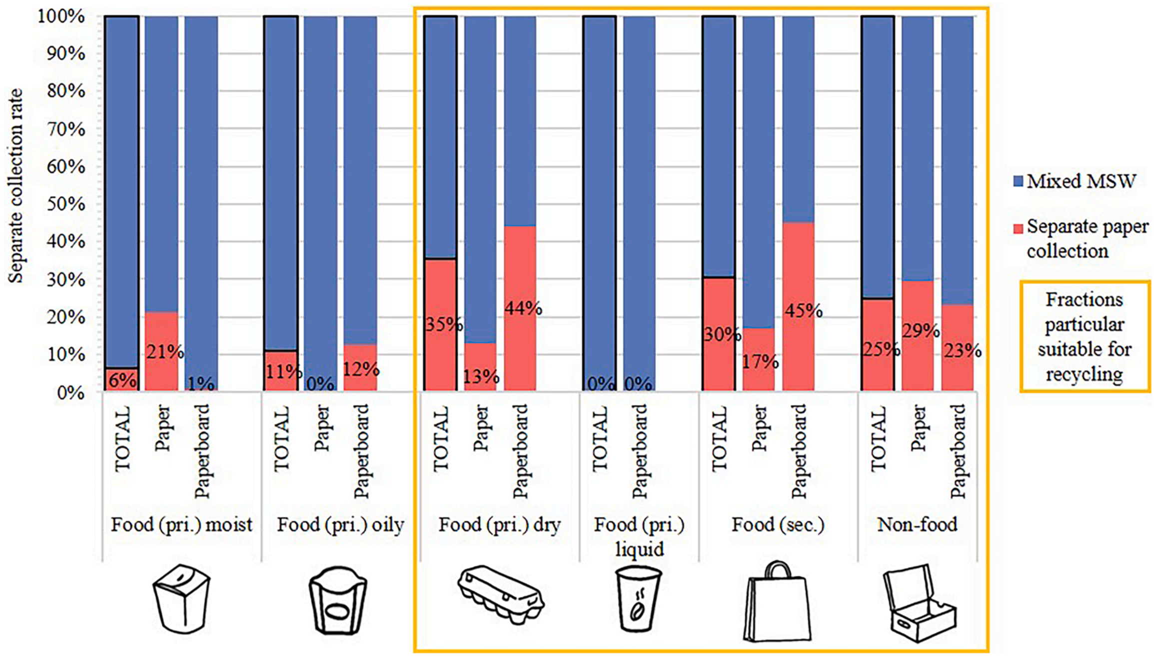


**Fig. 5.** Separate collection rates (SCR) as percentage of packaging waste in separate paper collection (red bars) in relation to packaging waste in mixed MSW (blue bars), packaging suitable for recycling circled in yellow, icons showing examples of packaging for the respective fraction (sec., secondary;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

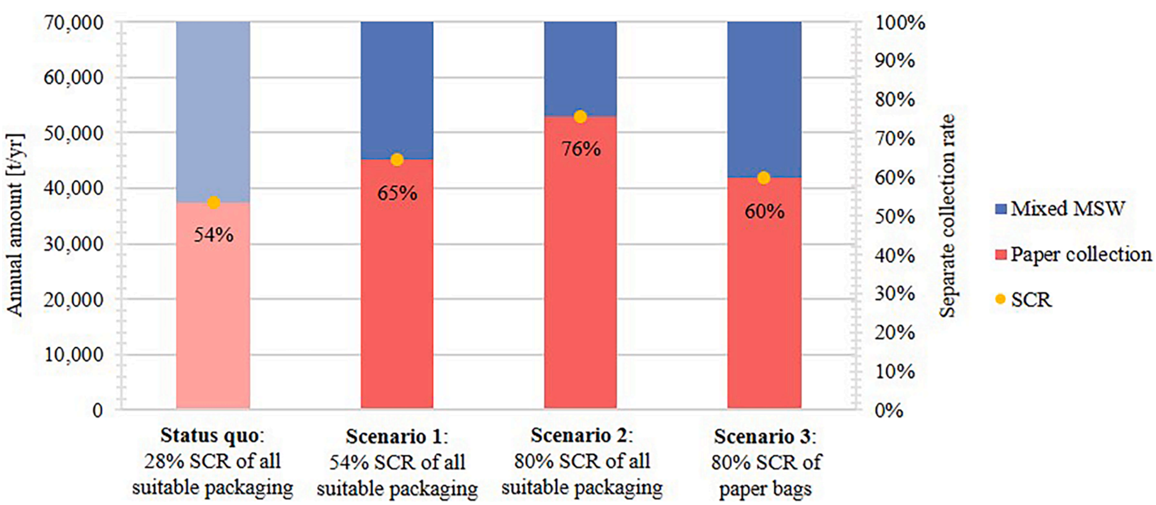


**Fig. 6.** Status quo of paper, paperboard and corrugated board packaging in mixed MSW and in paper collection and three different scenarios (1–3) for improved separate collection of paper and paperboard packaging. Annual amounts in mixed MSW (blue bars) and separate paper collection (red bars) in t/yr 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.

## References

4evergreen, 2023. Guidance on the improved collection and sorting of fibre-based packaging for recycling. https://4evergreenforum.eu/wp-content/uploads/4evergreen-WS-3-2023-7.12.pdf (accessed 26 November 2024).

4evergreen, 2024. Circularity by design guideline for fibre-based packaging. Version 3. https://4evergreenforum.eu/wp-content/uploads/4evergreen-Circularity-by-Design3.pdf (accessed 31 October 2024).

APA - Austria Presse Agentur, 2019. Digitalisierung sorgt für weniger Altpapier und mehr Kartonmüll. https://www.derstandard.at/story/2000112672122/digitalisierung-sorgt-fuer-weniger-altpapier-und-mehr-karton-muell (accessed 21 December 2023).
Austrian Standards International. ÖNORM S 2097:2005, Sortieranalyse von Abfällen. Wien: Austrian Standards International, 2005.
Bajpai, P., 2014a. Collection Systems and Sorting of Recovered Paper. In: Bajpai, P. (Ed.), Recycling and Deinking of Recovered Paper. Elsevier Science, Burlington, pp. 37–53.
Bajpai, P., 2014b. Introduction. Bajpai, P. Recycling and Deinking of Recovered Paper. Elsevier Science, Burlington, pp. 1–19.
Beigl, P., Happenhofer, A., Allesch, A., 2019. Leitfaden Für Die Planung, Durchführung und Auswertung von Altpapiersortieranalysen (Guidelines for planning, Implementation and Evaluation of Waste Paper Sorting Analyses), p. 49.
Benoit, S., Schaefers, T., Heider, R., 2016. Understanding on-the-go consumption: identifying and quantifying its determinants. Journal of Retailing and Consumer Services 31, 32–42. https://doi.org/10.1016/j.jretconser.2016.03.003.
BfR - Bundesinstitut für Risikobewertung, 2019. XXXVI. Papiere, Kartons und Pappen für den Lebensmittelkontakt: stand vom 01.06.2019, 17 pp.
BMK - Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, 2021. Innovation und Technologie, Leitfaden für die Durchführung von Restmüll-Sortieranalysen (Guidelines for Residual Waste Sorting Analyses), p. 31.
BMK - Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2023a. Bundes-Abfallwirtschaftsplan 2023 (Federal Waste Management Plan 2023), p. 170.
BMK - Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2023b. Die Bestandsaufnahme der Abfallwirtschaft in Österreich. Statusbericht 2023 für das referenzjahr 2021 (status report 2023 for the reference year 2021), p. 264.
BMLFUW - Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2014. Verordnung des Bundesministers für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft über die Vermeidung und Verwertung von Verpackungsabfällen und bestimmten Warenresten (Austrian Packaging Ordinance).
den Boer, E., Jedrczak, A., Kowalski, Z., Kulczycka, J., Szpadt, R., 2010. A review of municipal solid waste composition and quantities in Poland. Waste Manag. 30, 369–377. https://doi.org/10.1016/j.wasman.2009.09.018.
Brouwer, M., Picuno, C., van Thoden Velzen, E.U., Kuchta, K., de Meester, S., Ragaert, K., 2019. The impact of collection portfolio expansion on key performance indicators of the Dutch recycling system for Post-Consumer Plastic Packaging Waste, a comparison between 2014 and 2017. Waste Manag. 100, 112–121. https://doi.org/10.1016/j.wasman.2019.09.012.
Brunner, P.H., Rechberger, H., 2016. Handbook of Material Flow analysis: For environmental, resource, and Waste Engineers. CRC Press, Taylor & Francis Group, Boca Raton, London, New York, p. 435.
Burger, A., Cayé, N., Schüler, K., 2022. Aufkommen und Verwertung von Verpackungsabfällen in Deutschland im Jahr 2020 - Abschlussbericht, p. 267. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2022-09-29_texte_109-2022_aufkommen-verwertung-verpackungsabfaelle-2020-d.pdf (accessed 21 February 2023).
Burggräf, P., Steinberg, F., Sauer, C.R., Nettesheim, P., Wigger, M., Becher, A., Greiff, K., Raulf, K., Spies, A., Köhler, H., Huesmann, R., Atapin, A., Kaufeld, S., Krolle, A., Faul, A., Winter, J., Küppers, B., Ludes, A., 2023. Boosting the circular manufacturing of the sustainable paper industry – a first approach to recycle paper from unexploited sources such as lightweight packaging, residual and commercial waste. Procedia CIRP 120, 505–510. https://doi.org/10.1016/j.procir.2023.09.027.
Cayé, N., Marasus, K.S., 2023. Aufkommen und Verwertung von Verpackungsabfällen in Deutschland im Jahr 2021, p. 301. https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/162_2023_texte_aufkommen_verpackungsabfaelle.pdf (accessed 6 May 2024).
Cimpan, C., Maul, A., Jansen, M., Pretz, T., Wenzel, H., 2015. Central sorting and recovery of MSW recyclable materials: a review of technological state-of-the-art, cases, practice and implications for materials recycling. J. Environ. Manage. 156, 181–199. https://doi.org/10.1016/j.jenvman.2015.03.025.
Cristóbal García, J., Pierri, E., Antonopoulos, I., 2022. Separate collection of municipal waste - Citizen' involvement and behavioural aspects - Extended discussion paper from AA-CEAP1 Subgroup 3: Consumer behaviour. Joint Res. Cen. Tech. Rep. https://doi.org/10.2760/665482.
Denafas, G., Ruzgas, T., Martuzevičius, D., Shmarin, S., Hoffmann, M., Mykhaylenko, V., Ogorodnik, S., Romanov, M., Neguliaeva, E., Chusov, A., Turkadze, T., Bochoidze, I., Ludwig, C., 2014. Seasonal variation of municipal solid waste generation and composition in four East European cities. Resources, Conservat. Recycl. 89, 22–30. https://doi.org/10.1016/j.resconrec.2014.06.001.
Destatis - Statistisches Bundesamt Deutschland, 2024. Bevölkerungsstand Statistiken (Population statistics). https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/_inhalt.html#233972 (accessed 9 July 2024).
EC - European Commission, 2004. Methodology for the Analysis of Solid Waste (SWA-Tool). https://www.wien.gv.at/meu/fdb/pdf/swa-tool-759-ma48.pdf (accessed 6 November 2024).
EC - European Commission, 2018. Directive (EU) 2018/852 of the European Parliament and of the Council of 30 May 2018 amending Directive 94/62/EC on packaging and packaging waste.
EC - European Commission, 2022a. Factsheet - Circular Economy: Packaging and Packaging Waste Regulation, p. 2. https://ec.europa.eu/commission/presscorner/detail/en/fs_22_7160 (accessed 27 July 2023).
EC - European Commission, 2022b. Fragen und Antworten zur Verordnung über Verpackungen und Verpackungsabfälle. https://ec.europa.eu/commission/presscorner/detail/de/qanda_22_7157.
EC - European Commission, 2022c. Proposal for a regulation of the European Parliament and of the Council on packaging and packaging waste, amending regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC: COM (2022) 677 final.
Edjabou, M.E., Jensen, M.B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C., Astrup, T.F., 2015. Municipal solid waste composition: sampling methodology, statistical analyses, and case study evaluation. Waste Manag. 36, 12–23. https://doi.org/10.1016/j.wasman.2014.11.009.
Edjabou, M.E., Takou, V., Boldrin, A., Petersen, C., Astrup, T.F., 2021. The influence of recycling schemes on the composition and generation of municipal solid waste. J. Clean. Prod. 295, 126439. https://doi.org/10.1016/j.jclepro.2021.126439.
Emblem, A., 2012. Packaging and society. In: Emblem, A. (Ed.), Packaging technology: Fundamentals, Materials and Processes, 1st ed. Woodhead Publ, Oxford, pp. 3–9.
Esguerra, J.L., Carlsson, A., Johansson, J., Anderberg, S., 2024. Characterization, recyclability, and significance of plastic packaging in mixed municipal solid waste for achieving recycling targets in a Swedish city. J. Clean. Prod., 143014 https://doi.org/10.1016/j.jclepro.2024.143014.
EUROSTAT, 2022. Packaging waste by waste management operations - Paper and cardboard packaging waste generated. https://ec.europa.eu/eurostat/databrowser/view/ENV_WASPAC_custom_4346361/default/table?lang=de (accessed 1 January 2023).
EUROSTAT, 2023. Packaging waste statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics&oldid=580504.
EUROSTAT, 2024. Recycling rate of packaging waste by type of packaging (paper and cardboard packaging). https://ec.europa.eu/eurostat/databrowser/view/cei_wm020_custom_10169243/default/table (accessed 1 March 2024).
Faraca, G., Edjabou, V.M., Boldrin, A., Astrup, T., 2019. Combustible waste collected at Danish recycling centres: characterisation, recycling potentials and contribution to environmental savings. Waste Manag. 89, 354–365. https://doi.org/10.1016/j.wasman.2019.04.007.
Feil, A., Thoden van Velzen, E., Jansen, M., Vitz, P., Go, N., Pretz, T., 2016. Technical assessment of processing plants as exemplified by the sorting of beverage cartons from lightweight packaging wastes. Waste Manag. 48, 95–105. https://doi.org/10.1016/j.wasman.2015.10.023.
Fischer, A., 2024. Kampf um die Faser: Herausforderungen und Perspektiven im Papierrecycling. https://www.fachpack.de/de-de/fachpack-360/2024-2/video/solpack-irgendwas-mit-fasern-axel-fischer (accessed 26 November 2024).
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 Manag. 185, 10–24. https://doi.org/10.1016/j.wasman.2024.05.035.
Gritsch, L., Lederer, J., 2023. A historical-technical analysis of packaging waste flows in Vienna. Resources, Conservat. Recycl. 194, 106975. https://doi.org/10.1016/j.resconrec.2023.106975.
Gürlich, U., Kladnik, V., Pavlovic, K., 2022. Circular Packaging Design Guideline: Empfehlungen für recyclinggerechte Verpackungen, p. 108. Version 05, September 2022. https://digital.obvsg.at/obvfcwacc/download/pdf/8086818?originalFilename=true (accessed 13 February 2023).
Kim, Y., Kang, J., Chun, H., 2022. Is online shopping packaging waste a threat to the environment? Econ Lett 214, 110398. https://doi.org/10.1016/j.econlet.2022.110398.
Kladnik, V., Dworak, S., Schwarzböck, T., 2024. Composition of public waste - a case study from Austria. Waste Manag 178, 210–220. https://doi.org/10.1016/j.wasman.2024.02.031.
Krebs, T., 2019. Schlussbericht Zu IGF-Vorhaben Nr. 19118 N: Neue Methode zur Erfassung der Altpapierqualität hinsichtlich der Kriterien der Neufassung der DIN EN 643 zur Charakterisierung der Altpapiersorten, p. 117.
Lederer, J., Bartl, A., Blasenbauer, D., Breslmayer, G., Gritsch, L., Hofer, S., Lipp, A.-M., Mühl, J., 2022. A review of recent trends to increase the share of post-consumer packaging waste to recycling in Europe. Detritus 3–17. https://doi.org/10.31025/2611-4135/2022.15198.
Lederer, J., Schuch, D., 2024. The contribution of waste and bottom ash treatment to the circular economy of metal packaging: a case study from Austria. Resour., Conserv. Recycl. 203, 107461. https://doi.org/10.1016/j.resconrec.2024.107461.
Liikanen, M., Sahimaa, O., Hupponen, M., Havukainen, J., Sorvari, J., Horttanainen, M., 2016. Updating and testing of a Finnish method for mixed municipal solid waste composition studies. Waste Manag 52, 25–33. https://doi.org/10.1016/j.wasman.2016.03.022.
MA 48 - Magistratsabteilung MA 48 City of Vienna, 2022. Data on waste management in Vienna. Personal communication.
Miranda, R., Monte, M., Blanco, A., 2011. Impact of increased collection rates and the use of commingled collection systems on the quality of recovered paper. Part 1: increased collection rates. Waste Manag 31, 2208–2216. https://doi.org/10.1016/j.wasman.2011.06.006.
Miranda, R., Monte, M.C., Blanco, A., 2013. Analysis of the quality of the recovered paper from commingled collection systems. Resour., Conservat. Recycl. 72, 60–66. https://doi.org/10.1016/j.resconrec.2012.12.007.
Nemat, B., Razzaghi, M., Bolton, K., Rousta, K., 2020. The Potential of Food Packaging Attributes to Influence Consumers' Decisions to Sort Waste. Sustainability 12, 2234. https://doi.org/10.3390/su12062234.
Nemat, B., Razzaghi, M., Bolton, K., Rousta, K., 2022. Design affordance of plastic food packaging for consumer sorting behavior. Resour., Conservat. Recycl. 177, 105949. https://doi.org/10.1016/j.resconrec.2021.105949.

Nguyen, A.T., Parker, L., Brennan, L., Lockrey, S., 2020. A consumer definition of eco-friendly packaging. J. Clean. Prod. 252, 119792. https://doi.org/10.1016/j.jclepro.2019.119792.
ORF, 2024. Altpapier durch mehr Karton weniger wert.https://vorarlberg.orf.at/stories/3281596/#:~:text=J%C3%A4hrlich%20werden%20in%20Vorarlberg%2030.000,Qualit%C3%A4t%20des%20gesammelten%20Materials%20ab (accessed 18 November 2024).
Otto, S., Strenger, M., Maier-Nöth, A., Schmid, M., 2021. Food packaging and sustainability – Consumer perception vs. correlated scientific facts: a review. J. Clean. Prod. 298, 126733. https://doi.org/10.1016/j.jclepro.2021.126733.
Peters, R.J., Groeneveld, I., Sanchez, P.L., Gebbink, W., Gersen, A., Nijs, M.de, van Leeuwen, S.P., 2019. Review of analytical approaches for the identification of non-intentionally added substances in paper and board food contact materials. Trends Food Sci. Technol. 85, 44–54. https://doi.org/10.1016/j.tifs.2018.12.010.
Pivnenko, K., Eriksson, E., Astrup, T.F., 2015. Waste paper for recycling: overview and identification of potentially critical substances. Waste Manag. 45, 134–142. https://doi.org/10.1016/j.wasman.2015.02.028.
Pivnenko, K., Laner, D., Astrup, T.F., 2016a. Material cycles and chemicals: dynamic material flow analysis of contaminants in paper recycling. Environ. Sci. Technol. 50, 12302–12311. https://doi.org/10.1021/acs.est.6b01791.
Pivnenko, K., Laner, D., Astrup, T.F., 2018. Dynamics of bisphenol A (BPA) and bisphenol S (BPS) in the European paper cycle: need for concern? Resources. Conservation and Recycling 133, 278–287. https://doi.org/10.1016/j.resconrec.2018.01.021.
Pivnenko, K., Olsson, M.E., Götze, R., Eriksson, E., Astrup, T.F., 2016b. Quantification of chemical contaminants in the paper and board fractions of municipal solid waste. Waste Manag 51, 43–54. https://doi.org/10.1016/j.wasman.2016.03.008.
Ratchford, B., Soysal, G., Zentner, A., Gauri, D.K., 2022. Online and offline retailing: what we know and directions for future research. Journal of Retailing 98, 152–177. https://doi.org/10.1016/j.jretai.2022.02.007.
Robertson, G., 2021. Recycling of aseptic beverage cartons: a review. Recycling 6, 20. https://doi.org/10.3390/recycling6010020.
Robertson, G.L., 2012. Food Packaging: Principles and Practice, 3rd Edition, 3rd ed. CRC Press, Hoboken, p. 719.
Rousta, K., Bolton, K., Lundin, M., Dahlén, L., 2015. Quantitative assessment of distance to collection point and improved sorting information on source separation of household waste. Waste Manag 40, 22–30. https://doi.org/10.1016/j.wasman.2015.03.005.
Runte, S., Putz, H.-J., Schabel, S., 2016. Entwicklung von Anforderungen an die Rezyklierbarkeit von Papierprodukten. In: Thomé-Kozmiensky, K.J. (Ed.), Recycling Und Rohstoffe. TK Verlag, Neuruppin, pp. 557–572.
Santomasi, G., Aquilino, R., Brouwer, M., Gisi, S.de, Smeding, I., Todaro, F., Notarnicola, M., van Thoden Velzen, E.U., 2024. Strategies to enhance the circularity of non-bottle PET packaging waste based on a detailed material characterisation. Waste Manag 186, 293–306. https://doi.org/10.1016/j.wasman.2024.06.016.
Schmidt, S., Laner, D., 2021. The multidimensional effects of single-use and packaging plastic strategies on German household waste management. Waste Manag. 131, 187–200. https://doi.org/10.1016/j.wasman.2021.06.003.
Schuch, D., Lederer, J., Fellner, J., Scharff, C., 2023. Separate collection rates for plastic packaging in Austria - A regional analysis taking collection systems and urbanization into account. Waste Manag 155, 211–219. https://doi.org/10.1016/j.wasman.2022.09.023.
Seyring, N., Dollhofer, M., Weißenbacher, J., Bakas, I., McKinnon, D., 2016. Assessment of collection schemes for packaging and other recyclable waste in European Union-28 Member States and capital cities. Waste Manag. Res. 34, 947–956. https://doi.org/10.1177/0734242x16650516.
Spies, A.M., Kroell, N., Ludes, A., Küppers, B., Raulf, K., Greiff, K., 2024. Assessing the resource potential of paper and board in lightweight packaging waste sorting plants through manual analysis and sensor-based material flow monitoring. Waste Manag. 189, 196–210. https://doi.org/10.1016/j.wasman.2024.07.034.
Stadt Wien, 2024a. Altpapier und Kartonagen - Mülltrennung. https://www.wien.gv.at/umwelt/ma48/beratung/muelltrennung/altpapier.html#:~:text=Sammlung,auf%20den%20Mistpl%C3%A4tzen%20und%20M%C3%A4rkten. (accessed 6 March 2024).
Stadt Wien, 2024b. Plastik-Verpackungen in die Gelbe Tonne (Plastic packaging in the yellow bin). https://www.wien.gv.at/umwelt/ma48/beratung/muelltrennung/plastikflaschen/sammlung-plastik-verpackungen.html#:~:text=Seit%202023%20k%C3%B6nnen%20alle%20Kunststoff,f%C3%BCr%20Plastikflaschen%2C%20Metalldosen%20sowie%20Getr%C3%A4nkekartons. (accessed 9 April 2024).
Statistik Austria, 2024. Bevölkerungsstand Statistiken - Offizielle Statistik der Stadt Wien (Population statistics - Official statistics of the City of Vienna). https://www.wien.gv.at/statistik/bevoelkerung/bevoelkerungsstand/(accessed 6 December 2023).
Stravens, M., 2023. Disposable Paper-based Packaging For Food. The false Solution to the Packaging Waste Crisis. Profundo, Amsterdam, p. 86. https://eeb.org/wp-content/uploads/2023/09/Paper-based-packaging-report-1.pdf. accessed 25 January 2024).
Sung, N., Kim, J., 2020. Does the internet kill newspapers? The case of South Korea Telecomm Policy 44, 101955. https://doi.org/10.1016/j.telpol.2020.101955.
Tanguay-Rioux, F., Héroux, M., Legros, R., 2021. Physical properties of recyclable materials and implications for resource recovery. Waste Manag. 136, 195–203. https://doi.org/10.1016/j.wasman.2021.10.007.
Thoden van Velzen, E., Huremović, D., Keijsers, E., op den Kamp, R., Brouwer, M.T., 2017. Recycling of beverage cartons in the Netherlands 2016:Technical report. Wageningen.
Thoden van Velzen, E.U., Brouwer, M.T., Feil, A., 2019. Collection behaviour of lightweight packaging waste by individual households and implications for the analysis of collection schemes. Waste Manag 89, 284–293. https://doi.org/10.1016/j.wasman.2019.04.021.
Welton Bibby & Barton Ltd, 2005. Paper bags. In: Kirwan, M.J. (Ed.), Paper and Paperboard Packaging Technology, pp. 161–174.
ZSVR - Stiftung Zentrale Stelle Verpackungsregister, UBA - Umweltbundesamt Deutschland, 2023. Recycling im Wandel: Gemeinsam für Qualität und Quoten!: Jahrespressekonferenz 4. Dezember 2023. https://www.umweltbundesamt.de/sites/default/files/medien/11901/dokumente/praesentation_pk_recycling_im_wandel_gemeinsam_fuer_qualitaet_und_quoten.pdf.

## Further reading

BMK - Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2024. Die Bestandsaufnahme der Abfallwirtschaft in Österreich. Statusbericht 2024 für das Referenzjahr 2022 (Status Report 2024 for the Reference Year 2022), p. 274.
Deutsches Institut für Normung, 2017. DIN 6730:2017, Papier, Pappe und Faserstoffe - Begriffe. Berlin.
European Committee for Standardization, 2014. EN 643:2014. Paper and board - European list of standard grades of paper and board for recycling. Brussels.