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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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ABSTRACT

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.

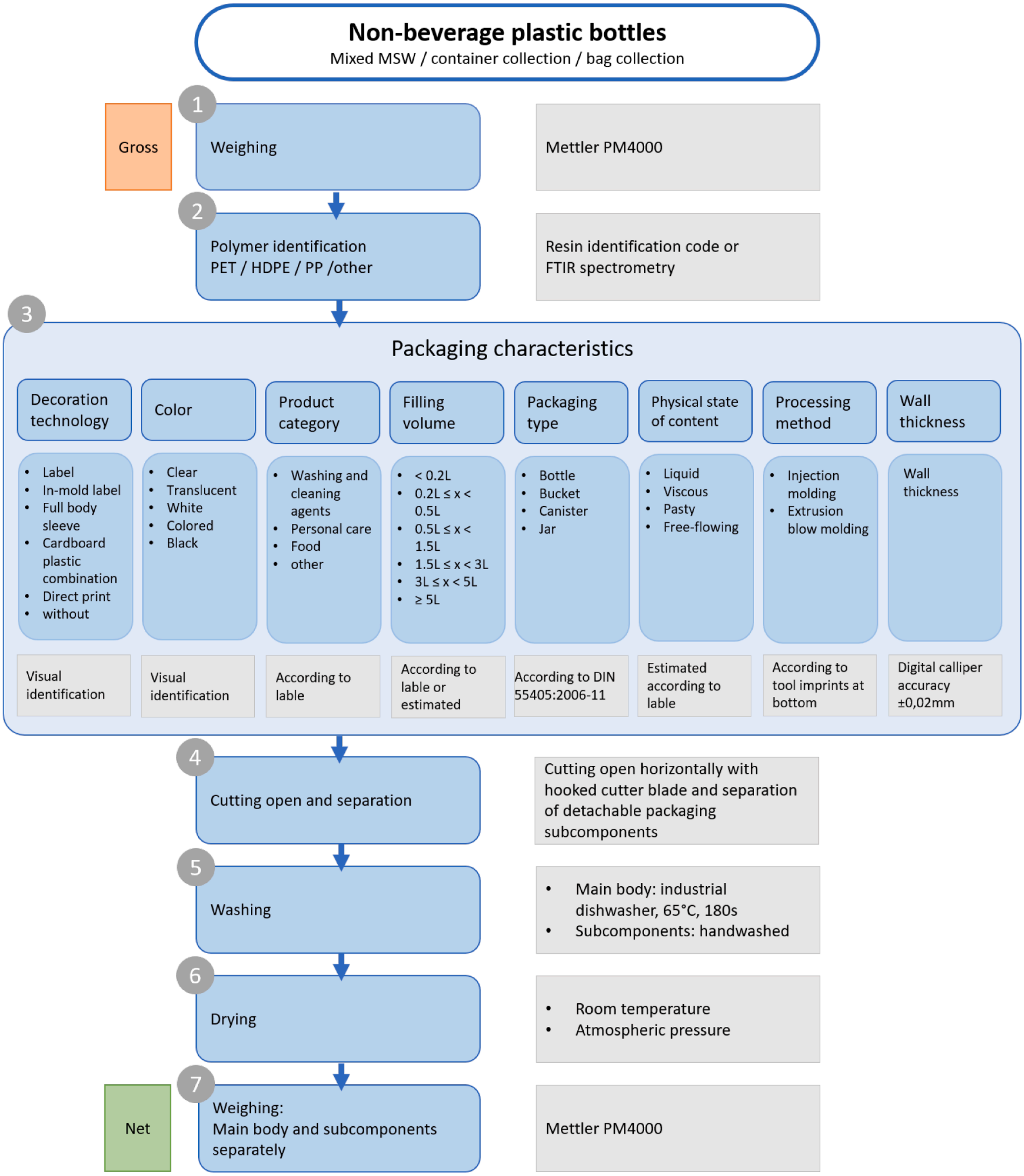

Fig. 1. Manual sorting procedure (1–7) and analysis methods (grey boxes) on non-beverage plastic bottles.

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 nonexistent. 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

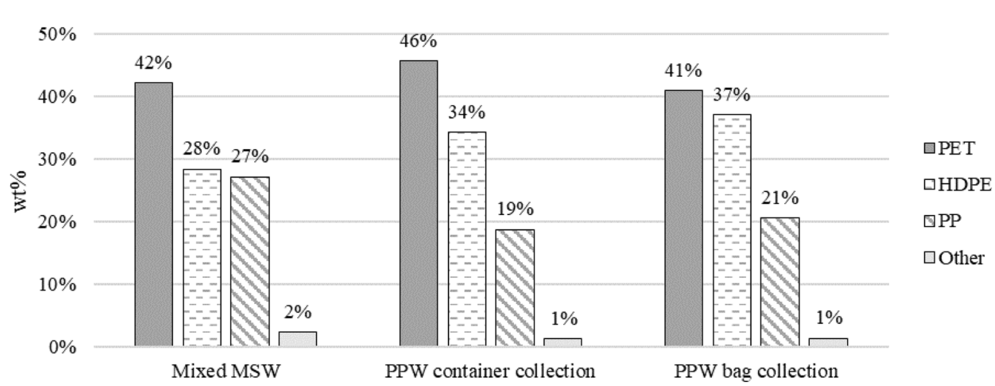

Fig. 2. Composition of non-beverage plastic bottles (incl. packaging subcomponents) regarding polymer in the waste streams of mixed MSW, PPW container collection and PPW bag collection, shown in wt% on a dry matter basis.

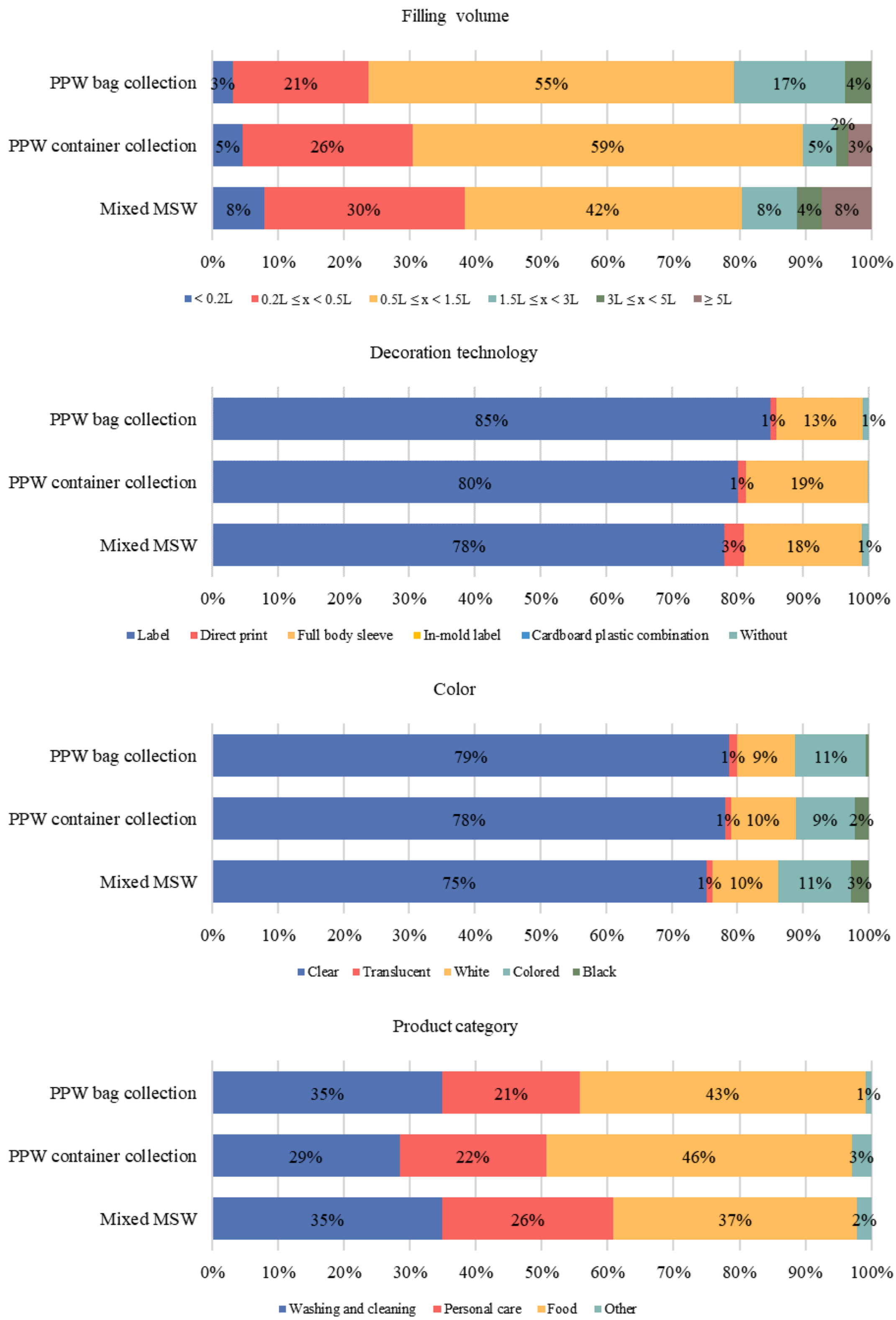

Fig. 3. Composition of non-beverage PET plastic bottles with regard to packaging characteristics 'filling volume', 'decoration technology', 'color' and 'product category' shown per waste stream in wt% on a dry matter basis.

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

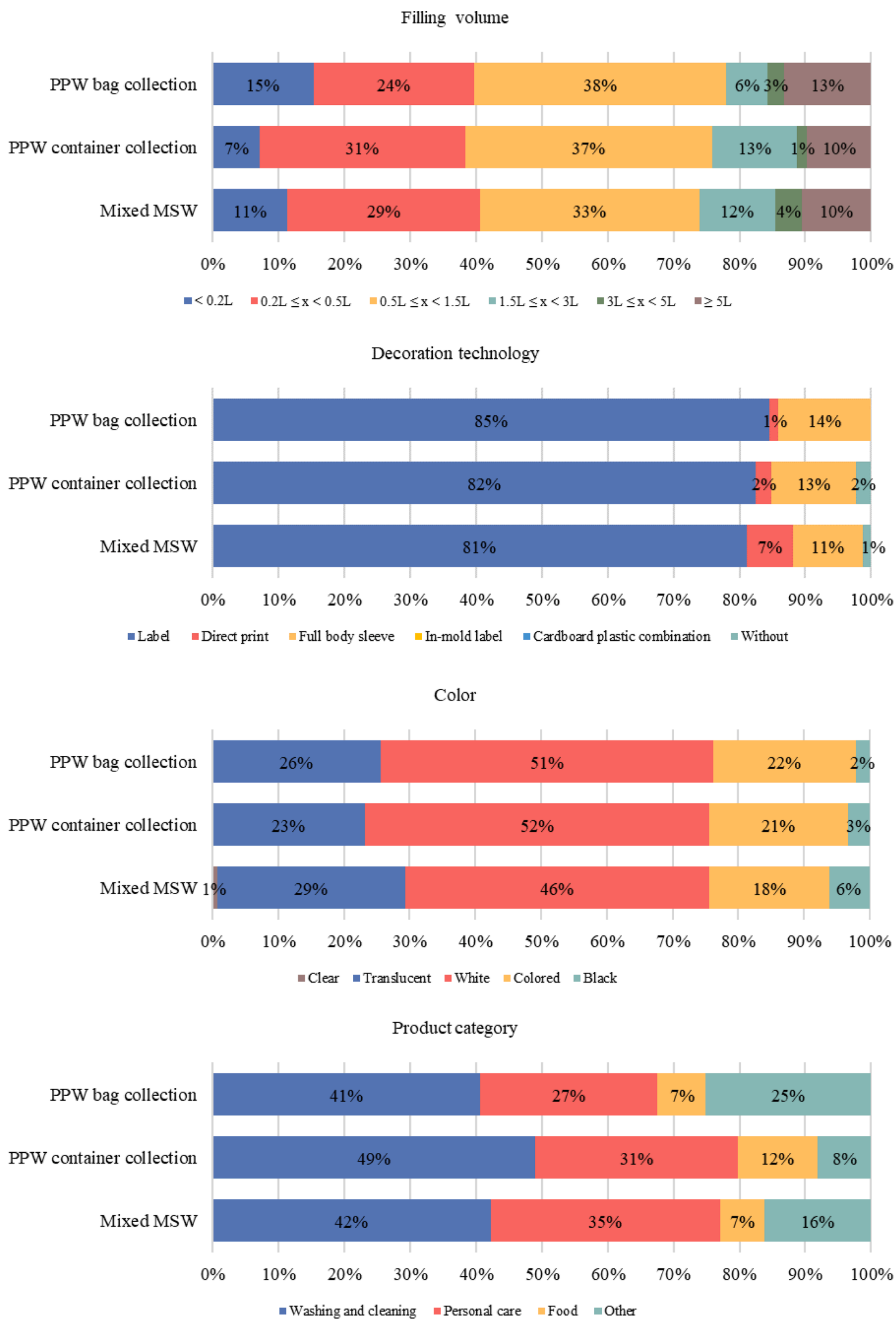

Fig. 4. Composition of non-beverage HDPE plastic bottles with regard to packaging characteristics 'filling volume', 'decoration technology', 'color' and 'product category' shown per waste stream in wt% on a dry matter basis.

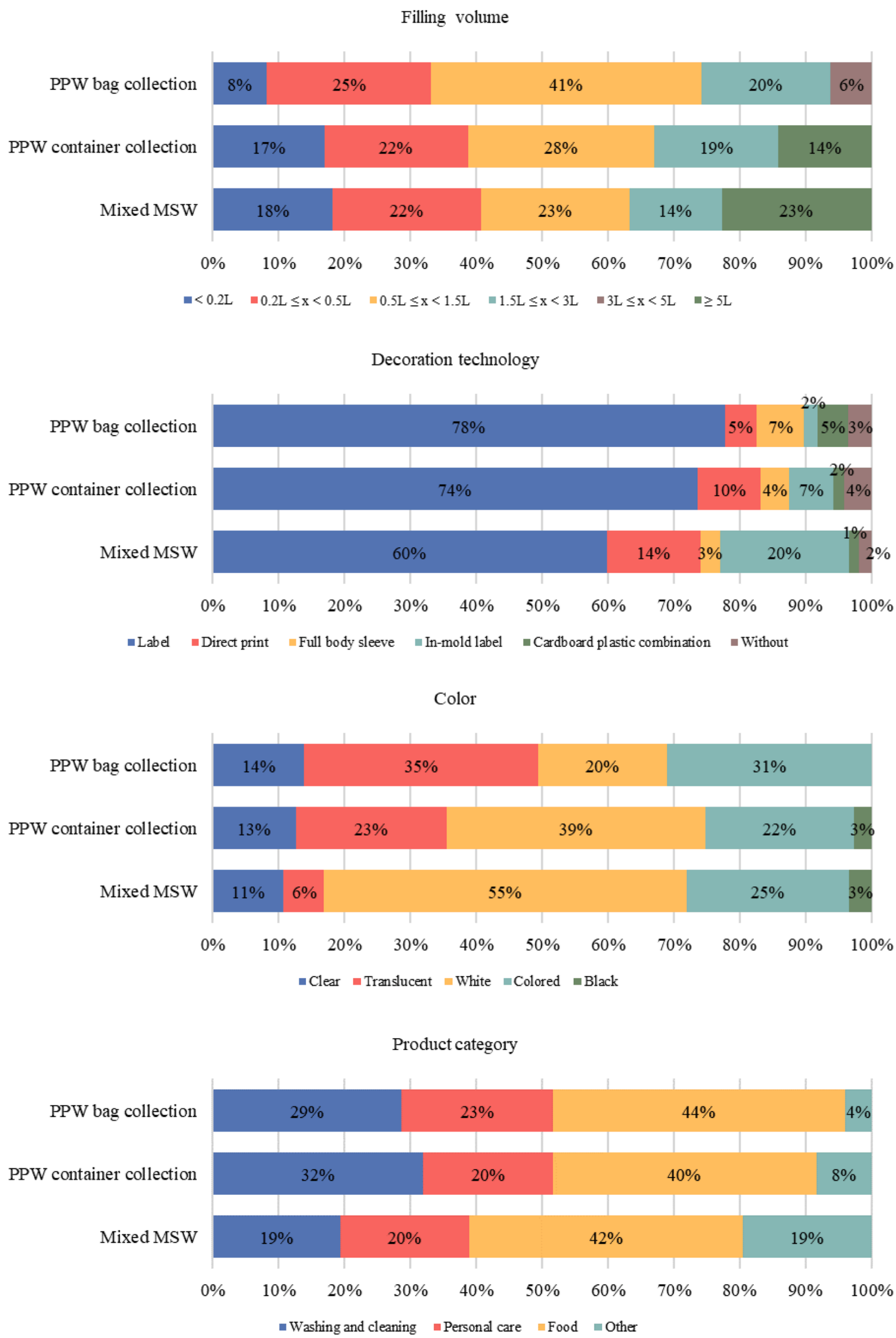

Fig. 5. Composition of non-beverage PP plastic bottles with regard to packaging characteristics 'filling volume', 'decoration technology', 'color' and 'product category' shown per waste stream in wt% on a dry matter basis.

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.

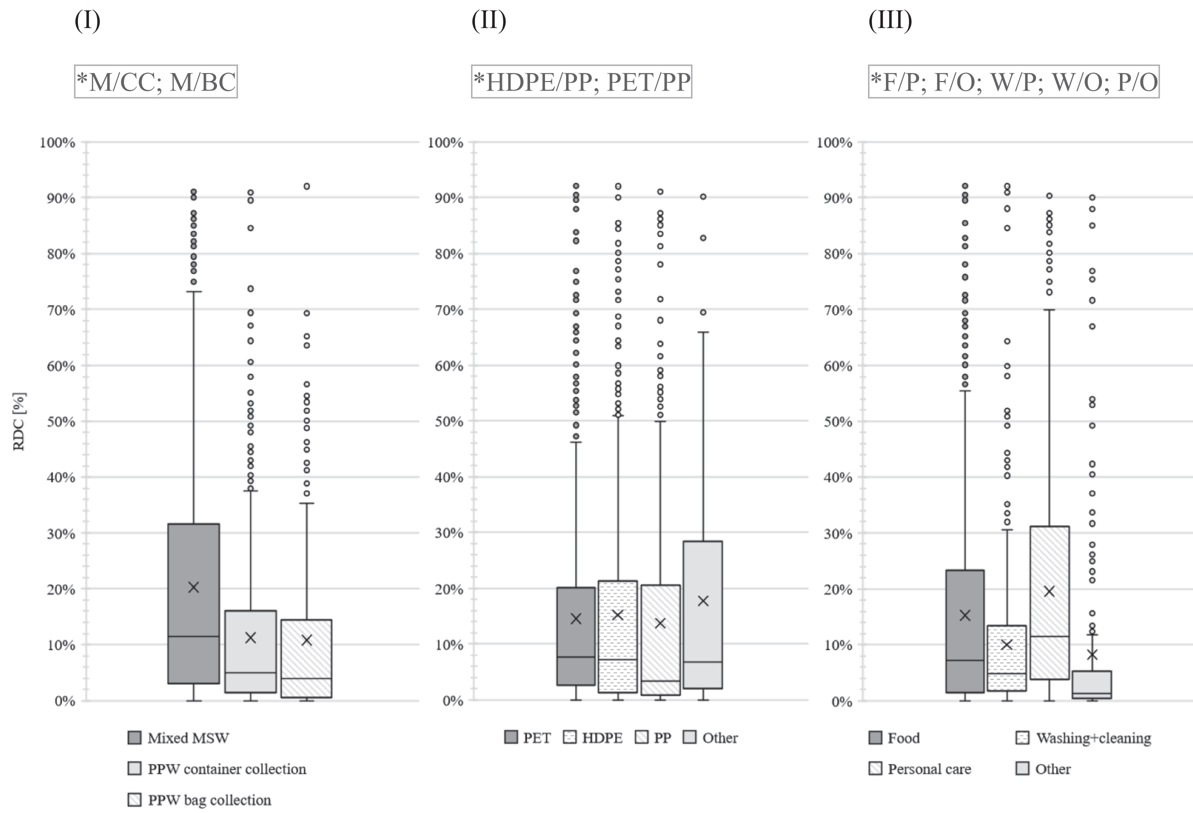

Fig. 6. RDC of non-beverage plastic bottles per waste stream (I), polymer (II) and product category (III) shown as boxplots; groups with significant difference in RDC according to post-hoc analysis are marked with* (M, Mixed MSW; CC, PPW container collection; BC, PPW bag collection; F, Food; P, Personal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

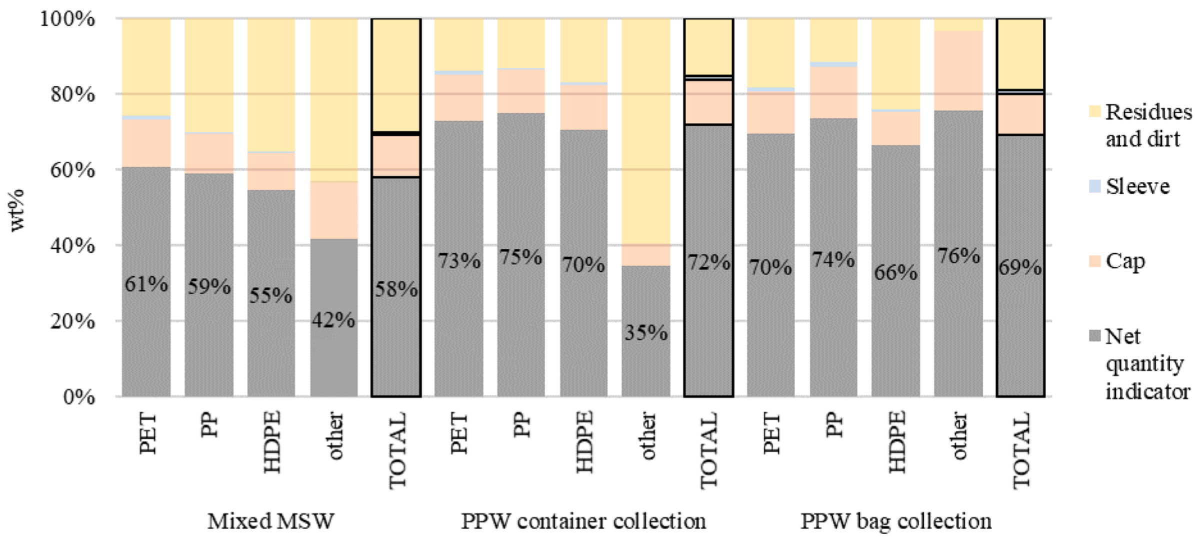

Fig. 7. Net quantity indicator per waste stream and polymer of non-beverage plastic bottles in wt%.

%). 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

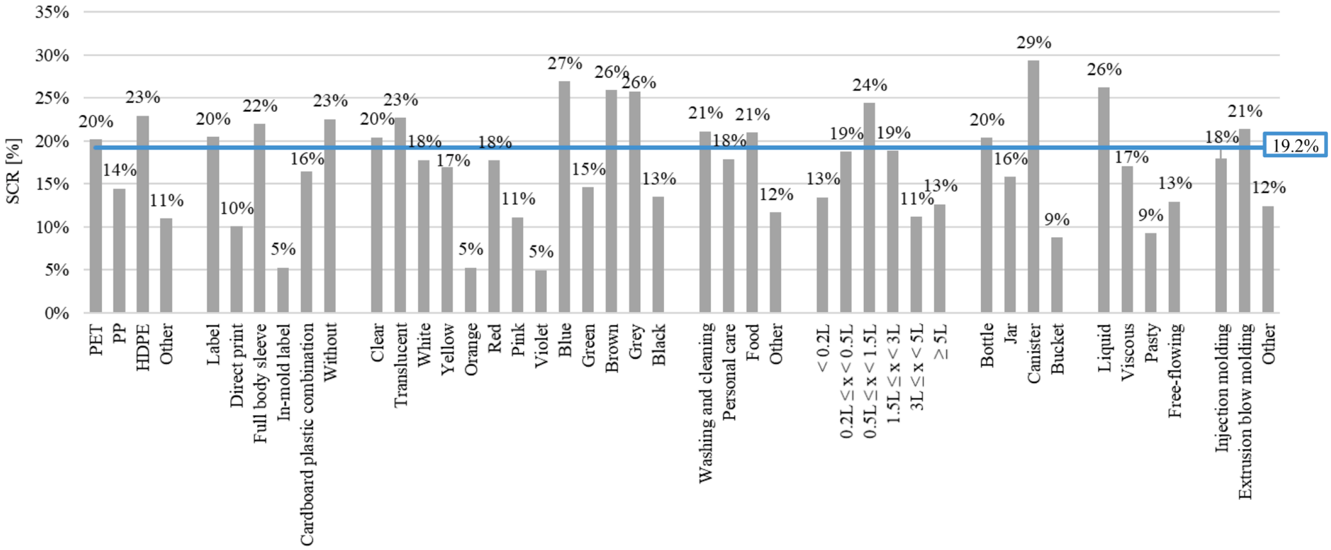

Fig. 8. Packaging characteristic-specific separate collection rates of non-beverage plastic bottles from MSW and average separate collection rate (blue line), calculated on a dry matter basis of the non-beverage plastic bottles incl. packaging subcomponents.

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 ≤ x < 0.5 L and 0.5 ≤ 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 ≤ 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.05.035.

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