Waste Management 201 (2025) 114781

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Comprehensive characterization of beverage cartons in urban waste: A case study from Austria

Lea Gritsch *, Gisela Breslmayer, Jakob Lederer

Christian Doppler Laboratory for a Recycling-based Circular Economy, Institute of Chemical, Environmental and Bioscience Engineering, TU Wien, Austria

ARTICLE INFO

Keywords:
Beverage carton
Packaging waste
Separate waste collection
Waste characterization
Separate collection rate
Urban waste collection

ABSTRACT

Beverage cartons are an important packaging material for dairy and other food products. Despite this importance, there are few studies that provide an in-depth characterization of beverage cartons when they become waste. This study aims to fill important data gaps on this packaging waste by presenting the results of a comprehensive characterization of beverage cartons, using the case study of Vienna. Through manual sorting analysis and high-temperature washing, moisture and dirt content and beverage carton types were assessed and annual quantities and separate collection rates were calculated. The results show that over 6,000 tonnes of beverage carton waste are generated in Vienna each year, mainly from fresh milk and juice. Over 80% of these are disposed of in mixed MSW, resulting in a net separate collection rate of 19.6%. The specific separate collection rate varied significantly depending on the type of packaging, ranging from 5 to 36%. In particular, beverage cartons with a high plastic content (up to 38%) showed a lower separate collection rate, undermining recycling efforts of beverage cartons. Moisture and dirt levels reached up to 28% of the gross mass, but only moderate differences were found between beverage cartons from mixed MSW and separate collection. Targeted consumer education and improved recycling processes would be essential to increase the usability of beverage carton secondary raw materials for high-value applications.

1. Introduction

Packaging has become an integral part of today's society, playing a crucial role in global trade and modern consumer behaviour (Emblem, 2012; Robertson, 2012). However, as household sizes shrink, e-commerce and on-the-go consumption grows, the demand for packaging −especially single-use packaging- is growing and packaging waste generation has reached record levels (EC, 2022a; Geyer et al., 2017; Jang et al., 2020). This trend has led to a growing awareness of the need for sustainable packaging solutions. As governments and industries focus on improving circularity and recyclability, new regulations were initiated. For instance, at global level, the plastic treaty aims to improve the sustainability of plastics, including packaging (Bergmann et al., 2022; Landrigan et al., 2023). At national and state level, many countries such as for instance Australia, California, Canada, Japan, or South Africa, have adopted waste management laws in order to reduce negative impacts of packaging waste (Nhamo, 2007; Tencati et al., 2016). In the EU, the Circular Economy Action Plan, have set ambitious targets for packaging recycling (EC, 2015, 2018b, 2020; EPC, 2018). According to the EU's Packaging and Packaging Waste Regulation, and also set out in the European Plastics Strategy, all packaging must be recyclable or reusable by 2030 (EC, 2018a, 2022b), which presents significant challenges, especially for plastic packaging and composite packaging (4evergreen, 2024; Ragaert et al., 2017; Soares et al., 2022; ZSVR and UBA, 2023).

Among the various types of packaging materials contributing to the waste challenge, beverage cartons (BC) represent a significant and complex fraction that merits closer examination due to their widespread use and unique material composition. BC consist of cardboard laminated with layers of plastic and often aluminium to ensure impermeability and barrier properties, and are widely used as packaging for liquids (Emblem, 2012; FBCA, 2022; Lahme et al., 2020). Aluminum foil is used as an additional gas and light barrier for aseptically packaged products and is therefore found in unrefrigerated products such as UHT (ultra-high temperature) milk (Robertson, 2012). Beverage cartons are used all-over the world. In Canada, they are the most important packaging material for milk, next to HDPE jugs (Sun et al., 2021), while in Thailand, milk, juice, and coconut juice are the most important

Abbreviations: BC, Beverage carton; MSW, Municipal solid waste; LPW, Lightweight packaging waste.

* Corresponding author.
E-mail address: lea.gritsch@tuwien.ac.at (L. Gritsch).

https://doi.org/10.1016/j.wasman.2025.114781
Received 17 October 2024; Received in revised form 24 March 2025; Accepted 29 March 2025
Available online 7 April 2025
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beverages packed in beverage cartons (Jacob et al., 2022). In Europe, 75 % of the milk and 59 % of the juice are packaged in BC, and according to the Food and Beverage Carton Alliance, the market volume of BC in Europe is approximately 1 million tonnes (FBCA, 2024).

While BC outperform some alternatives, such as plastic and glass bottles, in life cycle assessments due to their renewable material content and renewable energy in the production processes (FBCA, 2020; Markwardt et al., 2017; Pasqualino et al., 2011), their apparently low recycling have been criticized. In Thailand, for instance, in the year 2013, a beverage carton recycling rate of 26.3 % was achieved (Agamuthu and Viswanathan, 2014), while in Canada, recycling rates vary between 35–67 %, depending on the province (Sun et al., 2021) In the EU, in 2021, roughly half of the BC placed on the market were collected for recycling (490,000 tonnes), but actual recycling rates are currently not published by the European industry alliance and are difficult to obtain from other sources (Robertson, 2021). The latest published recycling rate was 51 % for all EU member states in 2019 (Robertson, 2021). However, a new calculation method for the recycling method came into force in 2020, resulting in significantly lower recycling rates (EC, 2019a; Kremser et al., 2022; Robertson, 2021). According to independent sources, even in Germany, known for its sophisticated waste management system, the recycling rate of BC is only around 38–48 %, in other countries it is between 21 and 30 %, and in Austria only one in three BC is recycled (Fischer, 2024; Getränkekarton Austria, 2023; Lahme et al., 2020).

In the most widespread recycling process, hydropulping, only the fibre content can be recycled, but not the plastic and aluminum parts, which are currently mostly incinerated (Georgiopoulou et al., 2021; Gürlich et al., 2022; Kremser et al., 2022; Robertson, 2021). Innovative recycling technologies, such as PolyAl recycling, are emerging, but there are currently only a few plants, resulting in long transport distances (FBCA, 2024) and the challenge of making these plants economically viable (Robertson, 2021). Thus, the increasing proportion of non-fiber materials complicates efforts to achieve full recycling (Deutsche Umwelthilfe, 2014; FBCA, 2024; Georgiopoulou et al., 2021; Kremser et al., 2022; Martínez-Barrera et al., 2019). The high plastic content also has negative consequences for BC distributors, as demonstrated by a recent decision by the German Environment Agency to classify 1 L BC for milk as a single-use plastic article and thus subject to the requirements of the Single-Use Plastics Directive (EC, 2019b; UBA, 2024).

Another major obstacle is the need for improved collection and sorting systems. In Thailand, in the year 2013, for instance, separate collection was, according to Agamuthu and Viswanathan (2014), a voluntary commitment of the private sector, and collection was organized as single stream. Contrary to that, the commingled collection of BC with other packaging types, such as lightweight packaging waste (LPW) or paper-based materials, as practiced in most EU countries, necessitates subsequent sorting, resulting in significant losses (FBCA, 2024; Lahme et al., 2020; Robertson, 2021). However, EU legislation lacks a mandatory collection target for BC and they are often excluded from deposit refund schemes (BMK, 2023; FKN, 2021). In Austria, the national packaging ordinance requires a separate collection rate (SCR) of 50 % by 2022 (BML, 2014), which was exceeded at 63 % (Getränkekarton Austria, 2022), but the country still faces challenges in meeting the 80 % target by 2025, especially in urban areas (BML, 2014), which are known to have less successful separate collection than rural areas (Lederer et al., 2022; Schuch et al., 2023; Seyring et al., 2016). Achieving this target will therefore require improvements not only in separate collection, but also in the datasets used to calculate the SCR. It is also important to understand the influence of packaging material composition or moisture and dirt content on the SCR (Gritsch et al., 2024). This requires analyzing BC not only in one waste stream, but in mixed MSW and in separate collection, in order to fully capture specific data on packaging attributes.

Despite the prominence of BC in the packaging sector, significant data gaps remain regarding their collection, recovery and recycling. Some studies have analyzed BC in specific waste streams, in some of these cases BC are explicitely treated as a separate fraction in waste sorting analyses, e.g. as 'tetrapak' (Denafas et al., 2014), 'beverage carton' (Edjabou et al., 2015; Jacob et al., 2022; Spies et al., 2024), 'milk/juice carton and alike' (Edjabou et al., 2021), but often they are not identified as a separate fraction or it is unclear to which fraction they should be assigned (Boer et al., 2010; Faraca et al., 2019; Liikanen et al., 2016), and Robertson (2021) provides an overview of the recycling options for aseptic BC. However, there are hardly any analyses and characterization of the quality of BC, except for Thoden van Velzen et al. (2013; 2017), who provide detailed analyses and characterization of BC in different MSW streams in the Netherlands, but there is still a considerable need for research in this area in other countries.

This study addresses this gap by analyzing the qualities and quantities of BC in household waste in Vienna, Austria, through manual sorting, focusing on mixed MSW and LPW. Key research questions include: (1) What types of beverage cartons are found in different MSW streams? (2) What is the quality of beverage cartons in terms of composition, moisture and dirt? (3) What are the quantities of beverage cartons per year in the analyzed waste streams? (4) What is the separate collection rate of beverage cartons?

2. Methods and materials

2.1. Management of BC collection in Vienna

Management of BC collection in Vienna and collection amounts from 2006 to 2020 are described in detail by Gritsch and Lederer (2023). Until 2018 they were collected in a door-to-door mono-collection called "Ökobox". Following a successful pilot test in 2018, a commingled collection of BC, plastic bottles and metals ("yellow-blue LPW collection") was introduced in a mixed system of collection points and curbside collection. Collection points are organized with collection containers, while curbside collection is organized with either collection containers or collection bags, the latter in selected single-family house areas. Commingled collection led to an increase in the SCR of BC, which could be explained by the increased convenience for consumers, who only had to store one instead of three waste fractions, or possibly because BC was explicitely mentioned as a target fraction on the emblem of the collection containers, which is a highly visible information (Gritsch and Lederer, 2023).

2.2. Sampling and pre-sorting

The data for this study was collected during a large sampling campaign in Vienna in 2022, where all MSW flows in Vienna were sampled, including the target flows for BC (LPW container and LPW bag collection) and mixed MSW. The calculation of the sample sizes and the selection of the samples was carried out by MA 48, the municipal waste management department. The sampling and the sorting itself was carried out by an engineering office. The sampling campaign for mixed MSW is based on the 'Guideline for residual waste sorting analyses' published by the federal ministry (BMK, 2021), which was developed in consideration of national (ÖNORM S 2096, 2005) and European guidelines and recommendations (EC, 2004). To date, no guidelines have been established for LPW sampling. In this instance, the sampling was conducted on the basis of MA 48′s extensive experience in the field, with regular waste analyses having been conducted since 1997 (Egle et al., 2018).

Sorting was carried out according to a pre-defined sorting catalogue, which was based on the standard characterization defined in the Austrian technical guidelines (Beigl et al., 2017) and was supervised by the authors of this study. The pre-sorting of mixed MSW at the first stage included 16 main fractions, of which one was BC, and the LPW was sorted into 28 main fractions, of which one was BC. These respective BC fractions were retained for further in-detail characterization carried out by the authors of this study as described in section 2.4. For this study, only household waste was considered.

For mixed MSW, the sampling lasted for 15 days and each day, samples were collected from 20 randomly selected addresses throughout the city, which resulted in total in 300 sampled addresses and in 3,000 kg of sorted mixed MSW. In contrast, LPW was sampled from the collection vehicles using a wheel loader shovel. Of the 15 collection routes in the city of Vienna, 13 were sampled randomly to ensure that the routes were as representative as possible. Each collection vehicle along a route represented one sample, with 12 vehicles sampled for container collection and one vehicle sampled for bag collection.

For BC from mixed MSW and LPW container collection a sample division was necessary to obtain a sample for further analyses. For this purpose, the respective BC fraction were thoroughly mixed on a plastic sheet with a shovel and then piled up. This was spread out with the shovel to form a flat circle with a single layer of BC, which was quartered. Two opposite quarters were discarded, the remaining two quarters were reunited, mixed, spread out in a circle and halved for further analyses. For BC from LPW bag collection no sample division was conducted. This resulted in a total of 295 pieces BC from mixed MSW, 547 pieces from LPW container and 248 pieces from LPW bag obtained for detailed characterization.

2.3. Material flows

Material flows have been calculated using material flow analysis (MFA), which is widely accepted as methodology for the study of waste management systems (Brouwer et al., 2018; Lombardi et al., 2021; Schmidt and Laner, 2021; Thomassen et al., 2022; Van Eygen et al., 2018). Magistratsabteilung MA 48, the municipal waste management department and also operator of Vienna, provided the data for modelling the material flows of BC for the years 2009, 2015 and 2022, which is necessary to further calculate separate collection rates (section 2.5). Thus, the material flow of BC $\dot{m}_{BC,ij}$ was calculated per waste stream i (mixed MSW, LPW container, LPW bag, Ökobox) and year j, by multiplying the collected mass of waste stream $\dot{m}_{ij}$ and the concentration of BC in the waste stream c_{ij} according to the following equation (1).

$$\dot{m}_{BC,ij}[t/a] = \dot{m}_{ij} \bullet c_{ij} \tag{1}$$

2.4. Detailed characterization of BC

The first partial sample was used to determine the moisture content (MC) in a drying oven and to determine the residues and dirt content (RDC) first. It was then reunited with the other partial sample and the packaging characteristics were determined for the whole sample by handsorting.

2.4.1. Moisture content MC and residues and dirt content RDC

MC was computed per waste stream i (mixed MSW and LPW container collection, LPW bag collection) according to equation (2). For this, the gross mass $m_{gross,i}$ was recorded when freshly sampled from the waste streams, then the BC were cut open with a hooked cutter blade and dried overnight at 80 °C in a drying oven (model: Heratherm™ OGS400) to obtain the dry mass $m_{dried,i}$.

$$MC_i[\%] = \frac{m_{gross,i} - m_{dried,i}}{m_{gross,i}} \bullet 100 \tag{2}$$

The BC were then washed in an industrial front-loading dishwasher using hot water at 65 °C for 180 s. The dishwasher (model: COMENDA LF 321 M) was equipped with a rotating sprinkler at the top and bottom and a removable plastic basket was used to load the BC.

Afterwards they were dried again in the drying oven at 80 °C overnight to obtain the net mass $m_{net,i}$ in order to calculate the RDC per waste stream i according to equation (3) and based on Thoden van Velzen et al. (2017).

$$RDC_i[\%] = \frac{m_{gross,i} - m_{net,i}}{m_{gross,i}} \bullet 100 \tag{3}$$

2.4.2. Packaging characteristics and composition

The BC of the other half were cut open with a hooked cutter blade and dried on a plastic sheet at room temperature and atmospheric pressure for several days until all residual product content was dried. The entire sample was then manually sorted according to the following packaging characteristics: compound type, cap type, filling volume, product category. The product categories were based on Thoden van Velzen et al. (2017). The following Table 1 provides an overview of the subcategories of the analyzed packaging characteristics, including a definition or how it was determined and product examples that were found in the sorted sample.

As a final step, caps, plastic tops or other removable plastic subcomponents were manually removed from the compound body and weighed separately to gain information on the material composition and the minimum plastic content of the BC.

2.5. Separate collection rate SCR

The SCR was computed for all BC and for specific BC fractions i as a quotient of the separately collected quantity $m_{inLPW,i}$ to the total quantity $m_{inLPW,i} + m_{inmixedMSW,i}$ according to equation (4). Whether the SCR was calculated using wet or dry BC mass is stated separately in the results.

$$SCR_i[\%] = \frac{m_{inLPW,i}}{m_{inLPW,i} + m_{inmixedMSW,i}} \bullet 100 \tag{4}$$

3. Results and discussion

3.1. Material flows

In Vienna, BC account for about 10 % of LPW and 1 % of mixed MSW, which is comparable to the shares of non-beverage plastic bottles (Gritsch et al., 2024; MA 48, 2023). The extrapolation to annual quantities shows, that the total amounts of BC have decreased from 6,551 t/yr in 2009 to 6,012 t/yr in 2022 (Fig. 1). As BC were collected by mono-collection called "*Ökobox*" until 2018 (Gritsch and Lederer, 2023), the amounts found in the LPW in 2009 and 2015 were very small, which changed after 2018.

In 2022, 4,900 t/yr of BC were calculated to be in mixed MSW and 1,112 t/yr in the LPW, with 1,081 t/yr in the LPW container and only 31 t/yr in the LPW bag collection. This is significantly less than container collection, but bag collection is only carried out in selected areas of Vienna with only 9 % of the population (Gritsch and Lederer, 2023).

In total, this accounts for 3.1 kg per capita per year in Vienna in 2022 (Statistik Austria, 2024a).

National data show a total market volume of 19,660 t/yr in Austria in 2023, which with a population of 9.105 million would account for 2.2 kg per capita per year (Statistik Austria, 2024b; WKO, 2024). The differences may be due to the different consumption habits of people in urban and rural areas, but need to be further investigated, for example in comparison with other Austrian federal states. However, the national consumption data of Austria fits well with national consumption data of Germany, which reports 180,000 t/yr for 2021, which with a population of 83.237 million would be 2.2 kg per capita per year (Cayé and Marasus, 2023; Destatis, 2024). The Netherlands, for example, placed about 60,000 t/yr of BC on the market in 2016, which corresponds to 3.5 kg per capita, based on a population of 16.979 million (EUROSTAT, 2024; Thoden van Velzen et al., 2017). The slightly higher values compared to Vienna may be explained by the fact that in northern countries such as

Table 1
Description of beverage carton packaging characteristics Compound type, Cap type, Filling volume and Product category with examples found in the sorted waste sample.

Analyzed packaging characteristics	Subcategories of analyzed packaging characteristics	Definition / Distinctive feature	Example
Compound type	Aluminum-carton-plastic	Packaging material made of carton, plastic laminate and aluminum foil as a light and gas barrier, used for aseptic products with a shelf life of weeks to months without cooling (Robertson, 2012).	Juices, long-life milk
	Carton-plastic	Packaging material made of carton and plastic laminate, usually used for refrigerated products with a shelf life of a few days (Robertson, 2012).	pasteurized milk (fresh milk), ESL milk, buttermilk, whey
Cap type	Tetra Top ® screw cap	Bottle-shaped top with big centered screw cap with a big base of plastic covering the entire top of the BC (Tetra Pak, 2025).	–
	Screw cap	All other screw caps	–
	No cap	No cap. Rather rare, has been more widespread in the past then now (Robertson, 2012), usually for BC with a straw.	–
Filling volume	≤ 0.25L	Determined according to declaration	–
	0.25 < x < 1L	Determined according to declaration	–
	≥ 1L	Determined according to declaration	–
Product category	Fresh milk	Determined by declaration and the storage advice 'store refrigerated before and after opening' on the packaging.	Pasteurized and/or microfiltrated milk, ESL milk
	Fermented dairy, desserts	Determined by declaration, ingredients and the storage advice 'store refrigerated before and after opening' on the packaging.	(Flavored) buttermilk, whey, yogurt, vanilla/chocolate milk
	UHT milk	Determined by declaration and the storage advice 'suitable for unrefrigerated storage if unopened, store refrigerated after opening' on the packaging.	long-life cow's milk
	UHT milk alternative	Determined by declaration, ingredients and the storage advice 'suitable for unrefrigerated storage if unopened, store refrigerated after opening' on the packaging.	UHT soy/oat/almond/rice/coconut milk
	Juice	Determined by declaration and the storage advice'store protected from heat and store refrigerated after opening'.	fruit juices, wine, icetea

Scandinavia, but also in the Netherlands, yoghurt is usually packaged in BC and not in cups as in Austria, which results in higher BC consumption (Thoden van Velzen et al., 2017). Similar values as in the Netherlands, namely 3.6 kg per capita, were found for Thailand in the year 2013 (Jacob et al., 2022), explained by the authors by the comparatively large food delivery and eating out rate in the country.

The data displayed in Fig. 1 are wet masses. However, it is well known that dirt and residues can make up a significant proportion of collected packaging and must be taken into account in mass-based calculations of performance indicators such as the SCR (Thoden van Velzen et al., 2019).

3.2. Types and qualities of BC

3.2.1. Moisture content MC and residues and dirt content RDC

BC from mixed MSW have the highest MC at 24.1 % in contrast to BC from LPW at 22.7 % and 22.1 %. As expected, the RDC values are higher than for MC. The RDC for BC from the mixed MSW is 28.4 %, that from the LPW is 23.0 % and 22.7 %, respectively (see Fig. 2).

Thoden van Velzen et al. (2013; 2017) found in their studies in the Netherlands RDC values in BC of 22–37 % and 27–43 % in separately collected waste and 26–52 % in BC recovered from mixed MSW. Moreover they found no clear relation between collection system and total average RDC level, which could be also the case in this study, because differences between mixed MSW and LPW are not considerable high.

The RDC values found in this study are at the lower end of the range reported by Thoden van Velzen et al. (2017). This could be due to the considerably high proportion of BC filled with yoghurt in the Netherlands, with a market share of around 27 %, which also shows the highest RDC levels in their study (Thoden van Velzen et al., 2017). That is likely due to rheological properties, which have previously been described as a major issue for food residues in packaging (Cragnell et al., 2014; Liu et al., 2018; Meurer et al., 2017), and is also supported by Wohner et al. (2019) and Klein et al. (2024), who found that high-viscosity products in BC had the highest amounts of residues. In addition to rheological issues, packaging design is also likely to have an impact on emptiability and residues, such as unfavorable geometries, cap types, foldings or the cutting rings in closures for aseptic BC (Klein et al., 2024; Meurer et al., 2017; SIG, 2019).

The clear difference between MC and RDC for BC from the mixed MSW compared to the only very small difference for LPW, could be an indication of the consumer behavior. Since there are obviously fewer dry residues in the BC from LPW than in the BC from the mixed MSW, they are possibly more likely to be rinsed out with water, at least this was qualitatively observed during manual sorting in this study. Williams et al. (2018) already mentioned, that packaging from separate collection show less residues, as consumers might rinse them in order to store them at home without smell. Moreover, it has already been described that packaging that is empty and clean is more likely to be disposed of separately, while packaging with residual contents is more likely to end up in mixed waste (Nemat et al., 2022; Thoden van Velzen et al., 2019; Wikström et al., 2016; Williams et al., 2018).

Particularly in the case of BC, residual contents, other organic impurities and increased moisture content have a major influence on the quality as secondary material. They provide a breeding ground for microorganisms, which in turn attack the paper fibres and leave a lasting odour in the secondary material, which has a detrimental effect on the quality (Miranda et al., 2011; Thoden van Velzen et al., 2017). Therefore, the use of secondary raw materials from hydropulped BC is regulated in the food packaging sector and is unattractive from the paper industry's point of view, because the European List of Standard Grades of Paper and Board for Recycling lists foodstuffs among the prohibited materials in the waste paper recycling process, probably due to hygiene issues arising from the residual content (BfR, 2019; EN 643, 2014).

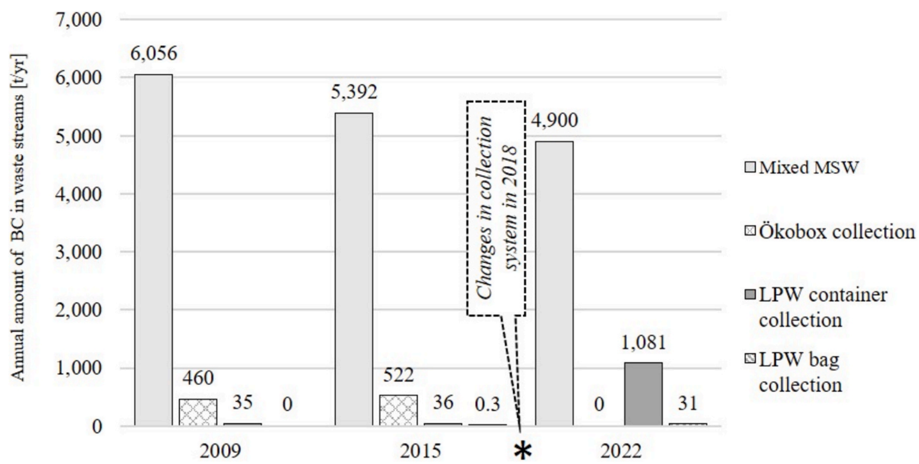

Fig. 1. Annually collected amounts of beverage cartons (BC) in Vienna in the mixed MSW, Ökobox collection, LPW container collection and LPW bag collection for the years 2009, 2015 and 2022, in t/yr on a wet mass basis.

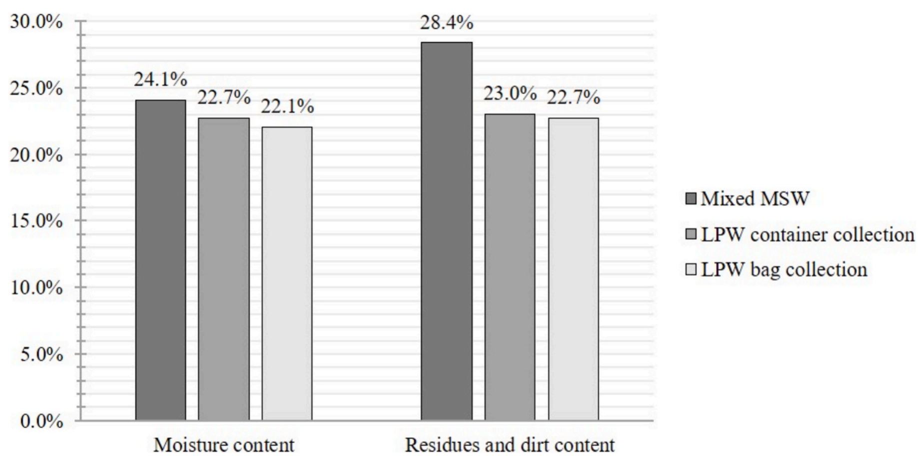

Fig. 2. Moisture content and residues and dirt content of BC in mixed MSW, LPW container and LPW bag collection, in w%.

3.2.2. Packaging characteristics and composition

The BC in the mixed MSW as well as in the LPW container collection are composed of approximately equal parts of aluminum-carton-plastic and carton-plastic compound type, as (Fig. 3). In the LPW bag collection, more carton plastic compounds were found at 65 %. In all three waste streams BC with a filling volume $\geq$ 1L are predominant with 85 % in mixed MSW, 91 % in LPW container and 79 % in LPW bag collection, totalling 3,767 t/yr. Consequently, BC with a filling volume of less than 1 L account for 9–21 % or 599 t/yr. Fresh milk has the largest share of all product categories in all three waste streams (40–55 %), totaling 1,797 t/yr, followed by juice (21–23 %) with 1,004 t/yr and UHT milk (9–20 %) with 839 t/yr. UHT milk alternatives represent the smallest amount at 293 t/yr, but they account for a significant 13 % of the LPW container collection. They are becoming increasingly popular among consumers and are recording steadily growing sales (Mertdinç et al., 2023).

Regarding the cap type, only a very small proportion of the BC were made without a cap (2 % in mixed MSW, 1 % in LPW container and 0.1 % in LPW bag collection). Thus, the highest total quantity of BC were made with a screw cap (3,474 t/yr) or a Tetra Top® screw cap (800 t/yr). Compared to BC with simple screw caps, BC with Tetra Top® have a significantly higher plastic content, as the entire top of these BC is made of plastic. Tetra Top®-BC with $\geq$ 1L consist of at least 8 g of plastic in a total mass of 31 g, which represents about 25 % (Fig. 4). Those with $0.25 < x < 1$ L have at least 33 % plastic content and those with $\leq$ 0.25L at least 38 %. In comparison, BC with a simple screw cap have plastic contents of at least 8 %, 12 % and 17 %, respectively. The actual plastic content of the whole BC is higher as the plastic laminations have not been taken into account. Thoden van Velzen et al. (2017) found cardboard shares between 67–79 %, plastic rigid shares of up to 14 % and plastic lamination shares between 12–23 %. This high proportion of plastic in BC is often subject of discussion, because it lowers the efficiency of the recycling process if only paper is recycled (Deutsche Umwelthilfe e.V., 2014; Gürlich et al., 2022). However, despite the higher plastic content the Tetra Top® cap can improve the emptiability of the BC (Klein et al., 2024), which in turn improves the overall life cycle impact.

3.3. Separate collection rate

The calculated gross SCR for 2022 is 18.5 % (Fig. 5). Compared to the SCR calculated for 2009 (7.6 %) and 2015 (9.4 %), this represents a doubling, which can be attributed to the commingled collection of BC with other LPW instead of mono collection, as already shown by Gritsch and Lederer (2023). According to national data, 13,803 t of BC were collected in Austria in 2023 out of a total market volume of 19,660 t, which would correspond to a SCR of 70 % (WKO, 2024), which is much higher than in Vienna. However, these two values are not directly comparable. On the one hand, the exact calculation basis for the national data remains uncertain, in particular whether net or gross collected amounts were used. Gross values, which include dirt, residues, and contaminants, cannot be directly compared with the volume of BC placed on the market, as this would artificially increase the SCR. In

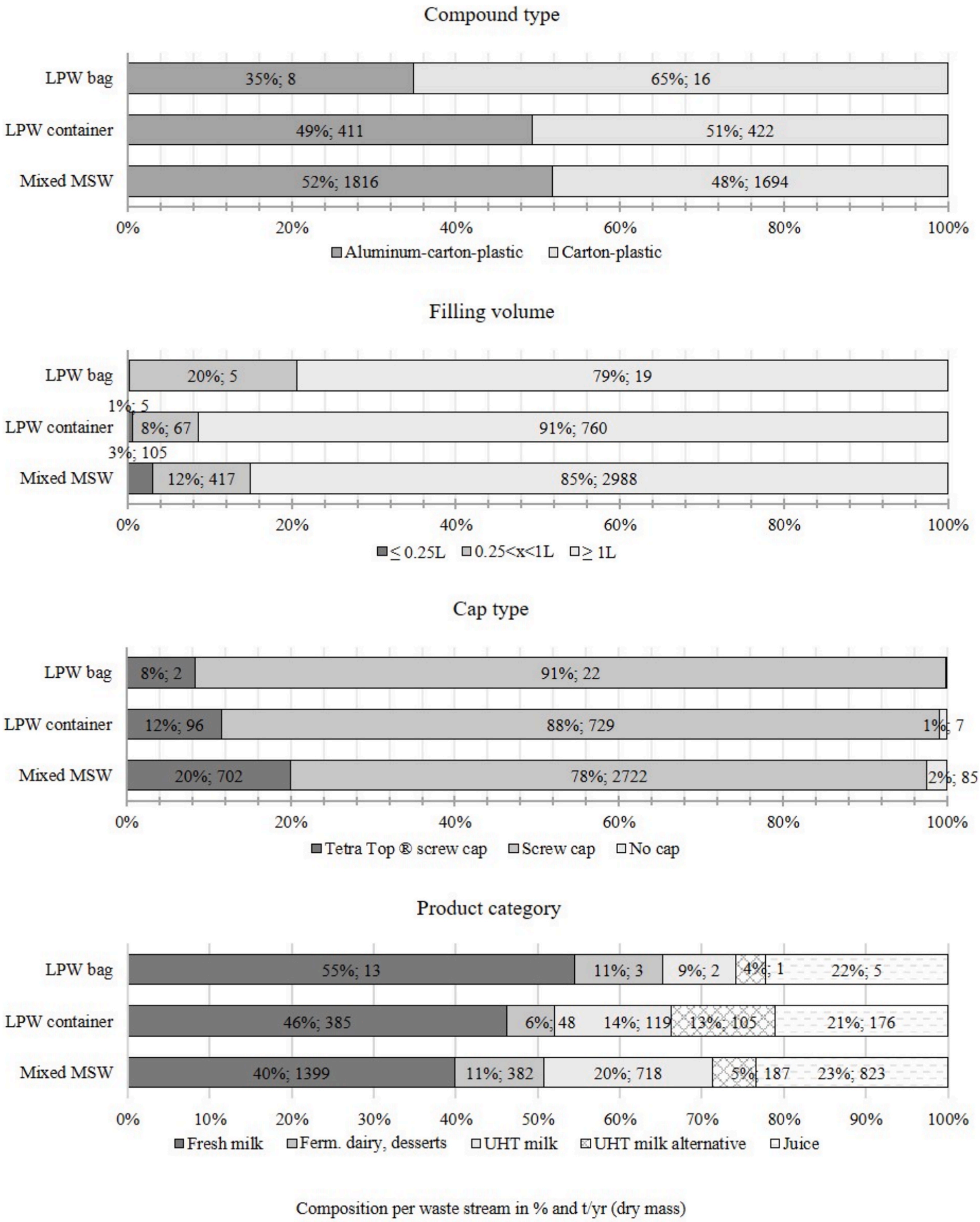

Fig. 3. Composition of BC with regard to packaging characteristics 'compound type', 'filling volume', 'cap type' and 'product category', shown per waste stream (LPW bag, LPW container, mixed MSW) in % and t/yr (dry mass) for the year 2022.

contrast, the calculated SCR for Vienna is not based on the market volume of BC in Vienna, but on the quantities in household waste, specifically in mixed MSW and LPW, as indicated by the indices in Equation (4), which allows a valid like-for-like comparison. In contrast to the calculated gross SCR, the weight-averaged net SCR of BC (excluding moisture, dirt and residues) is 19.6 %, which can be explained by the higher RDC of BC from mixed MSW and therefore an overestimation of their mass. This can be seen even more clearly in other packaging such as plastic bottles (Gritsch et al., 2024). Thoden van Velzen et al. (2013) found SCR of BC between 3–57 % in different Dutch municipalities, and a similar weight-averaged SCR of 20 %.

The SCR calculated for specific packaging or product characteristics showed no big difference in compound type (18.7–21.5 %), however, increasing values for increasing filling volume, with 4.8 % for BC ≤

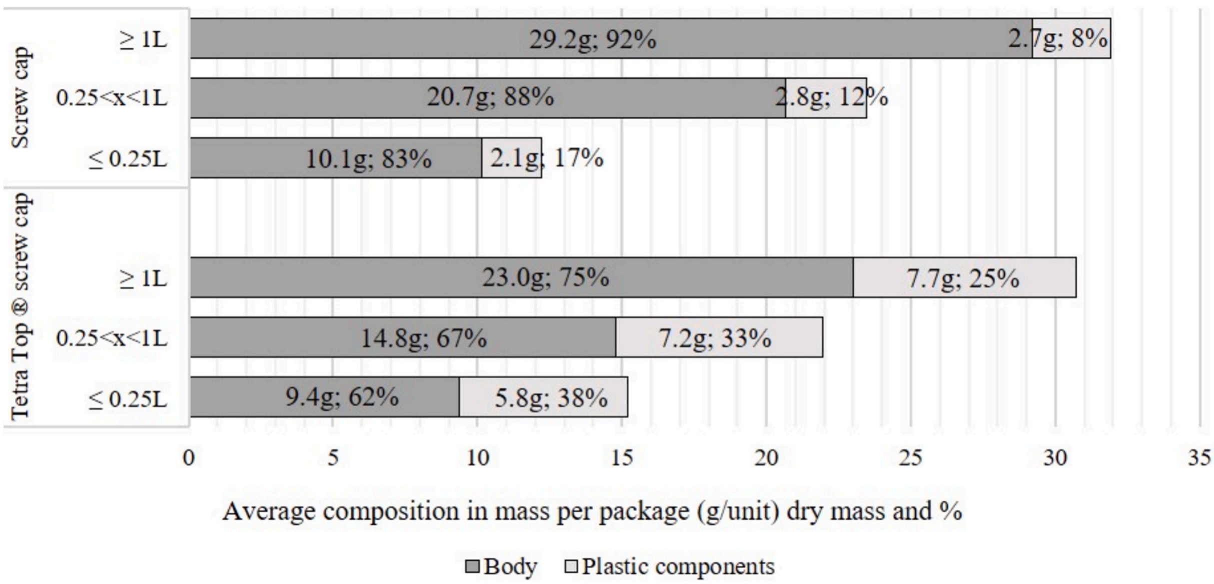

Fig. 4. Average composition of BC with screw cap and Tetra Top® screw cap, regarding the rigid plastic components and the main body, subdivided in the different sizes ≥ 1L, 0.25 < x < 1L, ≤0.25L, shown in mass per package (g/unit) in dry mass and %.

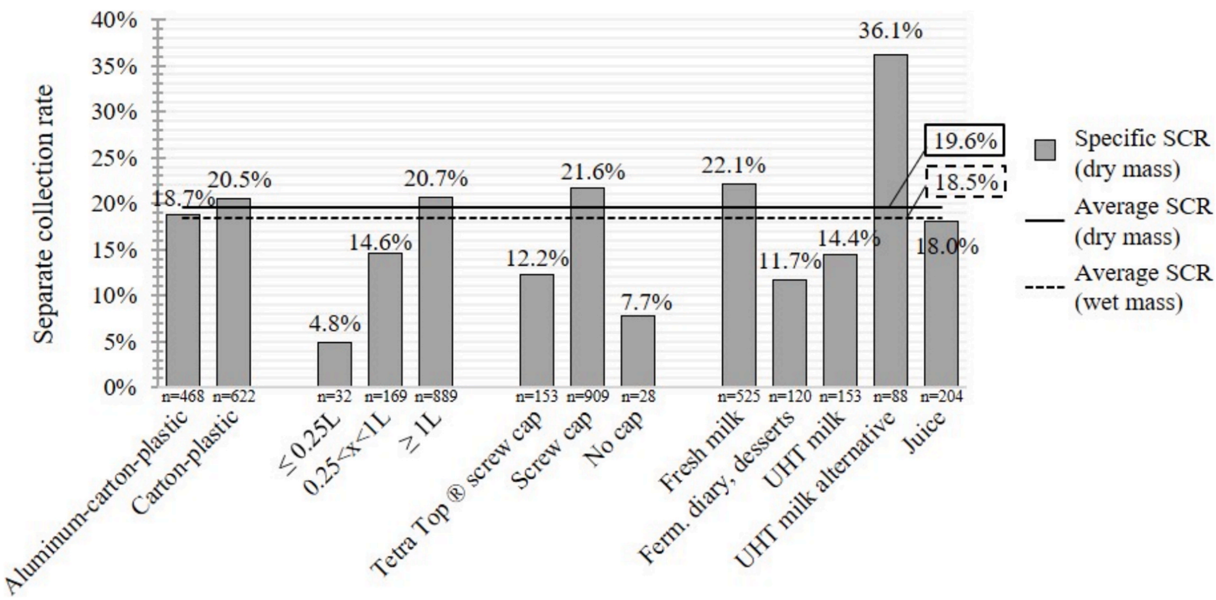

Fig. 5. Specific separate collection rates (SCR) for specific product characteristics of BC (grey bars) in w% on a dry matter basis and weight-averaged SCR for all BC in w% on a dry matter basis (black line) and wet matter basis (dashed line), sample size per fraction is given as n.

0.25L, 14.6 % for 0.25 < x < 1L and above-average 20.7 % for ≥ 1L. This is also in line with other studies, which show that small packaging is more likely to be disposed of in mixed MSW (Gritsch et al., 2024; Gritsch and Lederer, 2023; Nemat et al., 2022; Thoden van Velzen et al., 2019). BC with Tetra Top® and without cap showed SCR at a below-average rate with 12.2 % and 7.7 % respectively and only BC with other screw caps reached values above the average SCR at 21.6 %. In terms of product category, BC for UHT milk alternatives showed by far the highest SCR at 36.1 %. Probably because people who buy vegan products are more environmentally conscious (Dhont and Ioannidou, 2024; Habib et al., 2024) and therefore take waste separation more seriously (Briguglio, 2016; Rousta et al., 2015). Fermented dairy and desserts had the lowest SCR at 11.7 %.

However, the analysis of the specific SCR should not suggest that the low SCR of BC in Vienna is solely attributable to packaging characteristics. As mentioned in the introduction, the urban context certainly plays an important role, as low SCRs have also been observed for other packaging waste fractions in Vienna (Gritsch et al., 2024; Gritsch and Lederer, 2023). It is plausible that a generally low participation rate in separate waste collection in urban areas contributes to the low SCR. In comparison, other large federal states in Austria achieve SCR of 53–70 % for all LPW (Hietler and Pladerer, 2019; TBH, 2019).

3.4. Limitations

One limitation of this study is that the observed differences in specific separate collection rates may be influenced by confounding factors. For example, the lower separate collection rate of fermented dairy/desserts compared to other products such as milk or juice could be due to differences in packaging size, as smaller packaging is more likely to be disposed of in residual waste, as described above, or due to the higher viscosity of these products, which probably leads to more residual content and could also influence disposal practices of consumers. These factors could distort the differences in SCR found and should be investigated in future research. Another limitation in terms of the specific SCR is that the present analysis is based on a mixed sample, no mean values of the specific SCR can be calculated, and therefore it is not possible to use statistical tests to confirm that the SCR differences are statistically significant.

In addition, the present study focused primarily on the analysis of residue levels in different waste streams, without investigating the influence of other relevant factors. A potential area for future research could be to investigate the relationship between residue levels and specific cap/top types, as well as the packaged product, as highlighted in the work of Klein et al. (2024). Exploring this relationship would provide valuable insights for refining design recommendations, particular those aimed at improving emptiability and reducing product waste.

Moreover, this study was conducted as a case study focused on Vienna, so the findings are geographically limited. Also, due to the time-consuming, labor-intensive, and costly nature of waste sampling and manual sorting, the analysis was focused on mixed MSW and LPW only, however, there are probably other waste streams that include BC, such as urban waste or commercial waste, but their relevance is considered to be low. In addition, the sampling period was limited to 15 days in 2022, so long-term characteristics were not captured and may not reflect potential seasonal variations. Further studies are needed to make comprehensive statements about the quality and quantity of BC in other urban areas, nationally and in the long term.

Finally, this study finds indications of consumer behavior with regard to waste sorting, but as this study looked at separate waste collection from a technical perspective, no definite conclusions can be drawn about this, and sociological research is recommended to explore the underlying incentives for consumers to collect packaging waste and the influence of packaging design in this process.

4. Conclusion

A few decades ago, the main argument in favor of beverage cartons (BC) was their low carbon footprint. However, the pursuit of circularity and recyclability has become a more recent challenge that manufacturers must address. This study provides the first comprehensive data on BC quantities and characteristics in an urban area outside the Netherlands, namely Vienna. Through manual sorting analysis and hot water washing, key parameters such as moisture content, residues and dirt content (RDC), BC types, and packaging characteristics were determined. Additionally, annual quantities and separate collection rates (SCR) were calculated, providing valuable information for improving BC collection and recycling systems.

The results of this study show that BC represent a substantial waste stream in Vienna at 6,012 tons per year, with a prevalence of BC with a filling volume of 1 L or more. Fresh milk and juice are the most commonly packaged products in these cartons. A major challenge identified is the high residues and dirt content (RDC) of BC, reaching up to 28 %, with only moderate differences observed between BC found in mixed MSW and those found in separate LPW. Residues in BC could be attributed to the high viscosity of the products, unfavorable packaging design leading to poor emptying or insufficient rinsing by consumers before disposal. As these factors were not specifically investigated in this study, they require further research. In addition, the separate collection rate (SCR) for BC is notably low, measured at 18.5 % gross and 19.6 % net, indicating a significant loss of recyclable material and highlighting the importance of considering factors such as moisture, residues and dirt when calculating mass-related performance indicators. The SCR also varies significantly depending on the packaging characteristics, ranging from a low of 5 % for BC $\leq$ 0.25L to a high of 36 % for milk alternatives. Furthermore, BC with a high plastic content (up to 38 %) had a considerably lower SCR, demonstrating that high plastic content not only hinders recycling but also has a negative impact on collection rates.

The characterization of packaging waste at the level of detail and including product residues presented in this study is essential to provide insight into waste management systems and their success. Based on the results of this study, several key recommendations can be made. To improve collection and recycling, efforts should focus on increasing consumer participation in separate collection, especially in urban areas, and improving consumer education on proper BC disposal and rinsing practices, together with the implementation of rigorous hygienization measures in the recycling process to reduce contamination.

From a policy perspective, consideration should be given to introducing a deposit system for BC to incentivize higher separate collection rates. Alternatively, exploring common collection and recycling routes for BC together with other paper-based composite packaging could streamline recycling processes and improve efficiency. In addition, legally binding design guidelines for manufacturers to reduce the plastic content in BC should be developed and implemented, as BC manufacturers could face more obligations in the future if they are classified as plastic packaging. This could be supported by incentives such as the modulation of BC licence fees. The guidelines should also include requirements for emptiability, to minimize product waste.

Looking to the future, it is essential to develop economically attractive recycling methods for the aluminum and plastic fractions of BC to move beyond fiber recovery alone. Consideration should also be given to the successful use of secondary raw materials in BC, as this is 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, 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.

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.

Acknowledgements

The financial support by the Austrian Federal Ministry for Economy, Energy and Tourism the National Foundation for Research, Technology and Development and the Christian Doppler Research Association is gratefully acknowledged. Furthermore, we greatly acknowledge the financial and non-financial support of our company partners, which are, in alphabetical order: Abfallbehandlung Ahrental GmbH, Altstoff Recycling Austria AG, Brantner Österreich GmbH, Holding Graz Kommunale Dienstleistungen GmbH, Lenzing Aktiengesellschaft, Linz Service GmbH, Mayr-Melnhof Karton AG, OMV Downstream GmbH, Wien Energie GmbH, and Wopfinger Transportbeton Ges.m.b.H. In addition, we thank *Magistratsabteilung MA 48*, the public Waste Management provider of Vienna. The authors also acknowledge TU Wien University Library for financial support through its Open Access Funding Program.

Data availability

Data will be made available on request.

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