sustainability

MDPI

Article

Influence of Packaging Design on Technical Emptiability of Dairy Products and Implications on Sustainability through Food Waste Reduction

Michelle Klein [1,*], Charlotte Werner [2], Manfred Tacker [2] and Silvia Apprich [1]

[1] Institute of Packaging and Resource Management, Department Applied Life Sciences, FH Campus Wien, University of Applied Sciences, 1100 Vienna, Austria
[2] Circular Analytics TK GmbH, 1010 Vienna, Austria
* Correspondence: michelle.klein@fh-campuswien.ac.at

Abstract: Food loss and waste have been identified as significant contributors to existing environmental challenges. Previous studies have extensively quantified losses and waste throughout the value chain. However, there is a lack of knowledge regarding the influence of packaging design on food residue quantities. This study analyses the technical emptiability of dairy product packaging, building upon previously described methods and proposing new methods for a standardized analysis. The results demonstrate significant variations in residue amounts depending on product type, fat content, viscosity, packaging type and design, as well as consumer handling. The findings indicate that residues of high-viscosity products, such as yoghurt drinks and buttermilk, can accumulate to a level exceeding 4% of the total filling weight in the packaging; meanwhile, the residues of low-viscosity products, such as milk, collectively represent less than 1% of the total filling weight. Consumer handling instructions on packaging significantly reduce residues, as shown by the instruction to shake before opening, which notably decreases the residues of high-viscosity products. Future legislation to minimize food waste and reduce the environmental impact of packaging will necessitate that the packaging industry produces easy-to-empty packaging. This will improve sorting, recycling, recyclate quality, and environmental impact, consequently enhancing the sustainability of dairy packaging.

Keywords: technical emptiability; dairy products; food loss; food waste; food residues; emptiability; sustainability; milk; dairy; beverage carton; packaging; food waste reduction

check for updates

Citation: Klein, M.; Werner, C.; Tacker, M.; Apprich, S. Influence of Packaging Design on Technical Emptiability of Dairy Products and Implications on Sustainability through Food Waste Reduction. *Sustainability* **2024**, *16*, 6335. https://doi.org/10.3390/su16156335

Academic Editors: Ioannis N. Daliakopoulos, Katia Lasaridi, Konstadinos Abeliotis and Thrassyvoulos Manios

Received: 20 June 2024
Revised: 18 July 2024
Accepted: 22 July 2024
Published: 24 July 2024

1. Introduction

Food loss and food waste are among the major present contributors to climate change. The consequences of wasted food include additional burdens on waste management systems, the exacerbation of food insecurity, societal impacts, accelerated biodiversity loss, and pollution and waste generation [1–5].

Within the Sustainable Development Goals, the United Nations set Goal 12.3, to halve food waste at the retail and consumer level by 2030 [6].

The term "food loss" is defined as "*all the crop and livestock human-edible commodity quantities that, directly or indirectly, completely exit the post-harvest/slaughter production/supply chain by being discarded, incinerated or otherwise, and do not re-enter in any other utilisation [. . .], up to, and excluding, the retail level.*" [1]. This definition encompasses losses that occur during storage, transport, and processing, as well as losses of imported quantities. The FAO defines losses as including the commodity as a whole with its non-edible parts [1]. Food waste, on the other hand, is defined as "*food [. . .] and associated inedible parts removed from the human food supply chain in the following sectors: manufacturing of food products [. . .]; food/grocery retail; food service; and households. "Removed from the human food supply chain" means one of the* *following end destinations: landfill, controlled combustion, sewer, litter/discards/refuse, co/anaerobic digestion, compost/aerobic digestion or land application.*" [1].

Significant quantities of food are wasted throughout the chain of production, distribution, and retail, and at the consumer end. It is estimated that 931 million tons of food waste were generated globally in 2019; of this, 61% is attributed to waste generation in private households, 26% is from food services, and 13% of food waste occurs at the retail stage of the food life cycle. The average per capita annual food waste is 74 kg. The generation of food waste in households exhibits a similar pattern across country income groups, as observed by the FAO [1]. Given that food waste at the consumer or household stage has a greater environmental impact than food waste at other points along the value chain, it is crucial to prioritize the reduction in waste at the consumer or household level [7]. It has been reported that 20 to 30% of total environmental emissions in households originate from food consumption, which highlights the impact of wasted rather than consumed food [8].

The issue of food waste in households has been extensively researched and is attributed to a number of factors. One contributing factor is the tendency to prepare and cook more food than can be consumed in a timely manner [9]. Another is the lack of planning, bulk buying, and the unwillingness to consume leftover food [10]. In addition to consumer behavior, packaging plays a significant role in the potential for food waste generation. This includes packaging with an excess of content that cannot be consumed within the product's shelf life, multipacks, or offers to purchase more for a reduced price. Another important aspect is the printed "best before" date on the packaging [11].

In the UK, 75 to 90% of the consumers believe that the greater environmental impact is not caused by the wasted food, but by the packaging waste [11]. This demonstrates that consumers are unaware of the environmental consequences of their consumption habits and the fact that food packaging systems account for only a small percentage of the total environmental footprint of food consumption [12].

Indeed, several studies have indicated that food waste has a greater environmental impact than food packaging [13–15]. Consequently, the reduction in food waste could enhance food security and alleviate pressure on the environment, biodiversity, waste management systems, and climate change, while also conferring economic advantages to agricultural production [1].

1.1. Dairy Industry in the DACH Region

In 2020, the Austrian, German, and Swiss dairy industry generated an annual revenue of approximately EUR 33 billion, making it the second largest sector of food production [16]. The total dairy consumption per capita in 2021 was between 70.1 kg in Austria [17] and 77.9 kg in Germany [16,18,19].

1.2. Packaging

Packaging fulfils a multitude of crucial functions, starting with product protection and consumer information; the containment function allows for distribution and convenient logistics [20–24].

Packaging design can have an influence on the amount of product which remains within the packaging when emptied by the consumer [21]. Consequently, packaging contributes to sustainability, as it can prevent food waste [22–24].

The sustainability of food packaging can be described in terms of two distinct types of effects. The direct environmental effects are caused by the production, use, and disposal of packaging [20,22,25]. In contrast, indirect effects are described as packaging-related food loss and waste. This includes food waste through poor emptying behavior and food degradation through insufficient barrier functions of packaging or damaged packaging [22,25].

In the DACH region, a variety of packaging options are employed for dairy products.

In Germany alone, 655,400 tons of yoghurt was produced in 2023, encompassing a range of varieties, including dessert yoghurt, drink yoghurt, skyr, cream cheese, and curd [26–31]. Yoghurts are typically sold in cups made of polypropylene (PP) or polystyrene

(PS), glass jars, bottles, and pouches, and canisters when purchased in bulk [18–21]. The lids of plastic cups are either made of aluminum, paper laminate, or plastic film [32–35].

The presence of residual products in packaging materials following disposal can negatively impact the recyclability of the packaging material [36–42].

Residues that remain on the surface can influence polymer detection during near-infrared radiation (NIR) sorting, thereby reducing the efficiency of the sorting process [43]. Given the importance of recyclability in the context of packaging circularity, it is crucial to avoid product residues [20,44].

In the context of existing and forthcoming legislation, such as the Circular Economy Package and the Packaging and Packaging Waste Regulation (PPWR) legislation, the topic of emptiability is of significant importance. Actions include ambitious increases in recycling rates, the utilization of recycled materials by the industry, and the reduction in food waste [44,45].

1.3. Emptiability

The analysis of technical emptiability represents a convenient method for determining the amount of unintentional wasted food. The influencing factors may be attributed to product properties, which include mechanisms of adhesion and other rheological properties [46].

In several studies, food residues from dairy products have been proven to be an economic, ethical, and ecological problem [47–49].

The absorption of milk onto surfaces is due to the fat and hydrocolloids, which act as stabilizers [46].

In a qualitative and quantitative study by Williams and Wikström et al. (2023), it was found that 3 out of 4 kg of disposed dairy products in beverage cartons were discarded due to poor emptying behavior of the packaging. The authors proposed that the high viscosity of the products and their adhesive behavior towards the packaging surface were contributing factors [7]. In further studies, where reasons for food waste were evaluated by questionnaire from consumers, 22 out of 38 yoghurts were claimed to be difficult to empty, while for milk only for 3 out of 19 samples were put into this category for reasons as to why the food was wasted [50].

Further aspects of technical emptiability analysis are the factor of packaging design, consumer behavior, and packaging handling.

Method development and quantification of food residues for ultra-high-temperature (UHT) milk when emptying packaging was primarily conducted by Meurer et al. (2017) [51]. These methods were subsequently adapted by Wohner et al. (2019) [32] and applied to a diverse range of products and packaging systems, including cups for yoghurt, as well as bottles and beverage cartons containing different types of drinking milk and other milk products.

1.4. The Aim of This Study

This study builds upon and refines the previously published methods, applying them to a broader range of product types and packaging systems, as well as a greater number of samples.

The analysis was conducted within the context of a sustainability assessment for dairy product packaging in the DACH region. The technical emptiability of packaging was defined as an indirect effect on the environment. When assessing the carbon footprint and the sustainability of different packaging options, it is necessary to consider the environmental emissions from food waste.

The development of the aforementioned methods allows for the quantification of the amount of food remaining in diverse packaging systems for different dairy products. This enables the drawing of conclusions regarding consumer handling, product properties, and the influence of packaging factors, such as opening size and positioning, and the geometry of the packaging.

2. Materials and Methods

The selected regional focus is the dairy industry in Germany, Austria, and Switzerland. Product samples were either purchased at different supermarkets or handed in by retailers, producers, and packaging manufacturers from the respective area. In total, 124 articles were selected for testing and categorized according to certain aspects (Table 1).

Table 1. Dairy categories and criteria for tested products.

Category	Sub-Category	Number of Samples	Criteria
Drinking milk and mixed milk products	Whole milk/unskimmed milk/ESL milk	15	Fat content 2.5–3.9%
	Low-fat/skimmed milk	6	Fat content 0.2–1.8%
	UHT whole milk	8	Fat content 3.5–3.8%, unchilled storage
	UHT low-fat milk	5	Fat content 0.5–1.5%, unchilled storage
	ESL milk	10	Fat content 1.5–3.6%
	Buttermilk	5	Fat content 1%
	Cocoa/Choco drink/milk drink	11	Milk based drink containing chocolate or cocoa, fat content 1.1–3.6%
	Coffee drink	9	Milk based drink containing coffee, fat content 0.1–4.5%
	Whey drink	4	Fat content 0.5%
	Protein drink	4	Fat content 0.1–3.6%
Yoghurt and drinking yoghurt	Fruit/chocolate/coffee yoghurt	22	Fat content 3.2–4%
	Yoghurt drink (plain, fruit, drinking kefir)	9	Fat content 0.1–1.8%

In order to keep samples from beverage carton companies anonymous, samples were given generic letter–number combinations and short descriptions about their specific design features (Table 2).

Table 2. Beverage carton (BC) types and relevant design specifics. Filling volume 1000 mL if not otherwise specified.

Carton Type	Carton Size (H × W × D) in cm	Top Type	Geometry	Opening Size (Inner Diameter)	Lid/Straw Position
BC 1	1000 mL: 23 × 7 × 7; 500 mL BC slim: 19 × 6 × 6; 500 mL BC short: 14.5 × 6.7 × 6.7	Bottle-shaped top		3.5 cm	Centered on top of the carton
BC 2	20.2 (back)/18.8 (front) × 7.7 × 7	Diagonal flat top		3.1 cm	On the lower side of the flat top
BC 3	200 mL: 10.5 × 4.5 × 4.5 1500 mL: 25 × 9.2 × 6.5	Flat top		1.7 cm	In the corner of the flat top
BC 3 with straw	10.8 × 6.3 × 4	Flat top		Paper-based straw with 15.7 cm length	Straw positioned in the corner of the flat top
BC 4	500 g: 18 × 6 × 6	Gable top	Cut out longitudinal edge	1.7 cm	
BC 4 with straw	10.8 × 5.7 × 5.5	Gable top	Cut out longitudinal edge	Paper-based straw with 14 cm length	Straw positioned centered on one side of the gable top
BC 5	500 mL: 14.5 × 7 × 7 1000 mL: 23.2 × 7 × 7	Gable top		2.0 cm	

Table 2. *Cont.*

Carton Type	Carton Size (H × W × D) in cm	Top Type	Geometry	Opening Size (Inner Diameter)	Lid/Straw Position
BC 6	14.5 × 7 × 7	Gable top	Cut out longitudinal edge	2.0 cm	
BC 7	23.2 × 7 × 7	Gable top		2.0 cm	
BC 8 with straw	14.5 × 7.4 × 4.7	Flat top		Paper-based straw with 17.3 cm length	Straw positioned in the corner of the flat top
BC 9	20.3 × 7 × 7	Flat top		2.0 cm	In the corner of the flat top
BC 10	19 × 9.2 × 6	Flat top	Aluminum foil on the inside, aseptic carton	2.0 cm	In the corner of the flat top
BC 11	19 × 9.2 × 6	Flat top		2.0 cm	In the corner of the flat top
BC 12	20.8 × 7 × 7	Mix of Flat and Gable Top	Six corners on the lid side	2.0 cm	

Each product was obtained and tested in triplicate (n = 3).

The products in cups were stored in an upright position, while bottles and beverage cartons were stored either lying down or upright for at least 24 h prior to testing.

The storage temperature was set at 5 ± 2 °C, and the transfer time between storage and the start of the emptying process did not exceed 5 min. The tests were performed at room temperature (20 ± 2 °C). This was performed to simulate direct consumption.

The testing of the technical emptiability is based on methods published by Meurer et al. (2017) [51] and Wohner et al. (2019) [52]. Prior to emptying, each product was checked for consumption and emptying instructions on the labels. In cases where instructions recommended the product be shaken prior to opening, this step was included prior to the described emptying process. For the weighing the scale Sartorius Extend (model number ED8201-CW) scale (Sartorius Lab Instruments, Goettingen, Germany) was used.

The overall process design included the following steps:

1. Weighing of the unopened packaging, including product content.
2. If recommended on the label, products were shaken according to the instruction.
3. Emptying of the packaging as described as below for the following:
    - Dairy products in bottles and beverage cartons;
    - Dairy products in to-go cups with snap-on lids;
    - Dairy products in beverage cartons with drinking straws;
    - Dairy products in pouches;
    - Dairy products in cups.
4. Weighing of the emptied packaging (packaging including residues).
5. Washing and drying of the packaging at 23 °C for at least 24 h.
6. Weighing of the cleaned packaging (exclusive of any residual matter).

- Emptiability Method of Dairy Products in Bottles and Beverage Cartons

This method was selected for all products packaged in bottles and beverage cartons. Following the weighing of the packaging and, if recommended, the application of a shaking motion, the packaging was opened and emptied for one minute. For this step, the bottle or carton was held upside down in a manner that ensured the opening was parallel to the tabletop. The packaging was then placed on the table for five seconds, rotated five times, and then placed back on the table for 10 s. Subsequently, the packaging was inverted for a further one-minute period. The method then proceeded with the weighing of the emptied packaging and the aforementioned steps.

- Emptiability Method of Dairy Products in To-go cups with Snap-On Lids

The cups containing the to-go products were opened, and if included in the packaging, the specific drinking lid was placed on the cup for emptying. The subsequent emptying proceeded in accordance with the previously described procedure for bottles and beverage cartons.

- Emptiability Method of Dairy Products in Beverage Cartons with Drinking Straw

Some beverage packaging included a straw. The method was based on the same principle as described for bottles and cartons, with a slight adaptation. The packaging was emptied in an inverted position through the straw and the packaging was pressed during the two minutes of emptying.

- Emptiability Method of Dairy Products in Pouches

The consumption of yoghurt packed in pouches was facilitated by inverting the packaging and then squeezing between the thumb and index finger from the packaging bottom to the lid. This process was repeated three times.

- Emptiability Method of Dairy Products in Cups

Yoghurt products packaged in cups were emptied with a teaspoon if the mass of the content was less than one kilogram. The size of the teaspoon was 3×4.5 cm. For larger packaging, a tablespoon was used. First, the lid was cleaned by scratching with the spoon up to seven times, or until no product was left on the lid. The cups were inverted at an angle of 45° measured from the tabletop, after which the product was removed using the spoon. The time taken to empty the cup was recorded and found to be less than one minute for cups containing less than 400 g of product. For cups containing 400–500 g of product, the emptying time was set at two minutes, while for cups containing more than 500 g of product, the emptying time was set at three minutes.

3. Results

The samples are analyzed for their emptiability, comparing different packaging systems for the same product as well as comparing the emptiability of different products in the same packaging system.

Influencing factors, such as lid-size, lid-positioning, geometric design, and consumer handling instructions are identified and elaborated on.

3.1. Influence of Product Handling Information

In the case of buttermilk samples, different packaging systems could be found in Austrian supermarkets. In all but one case, the handling instruction to shake the packaging before opening was printed on the packaging. These instructions were followed in the emptying process. The results showed large differences in the retention rate depending on the packaging type and the consumer handling.

Figure 1 illustrates the results of the five assessed samples. In the case of sample BC 1, one sample was accompanied by instructions to shake, while the other was devoid of clear instructions. In the absence of instructions, the residue amount found in the packaging after the standardized emptying process accounted for 4.49% of the filling amount. However, when shaken, the amount can be reduced to 1.01%. The other samples in an HDPE bottle and in an BC 5 and BC 6 beverage carton type had printed instructions to shake before consumption on the packaging. The lowest amount of food residues was measured in the HDPE bottle with 0.88% of the total content remaining in the packaging. The beverage cartons BC 5 and 6 showed high retention rates, with 3.88% and 4.06%, respectively. In this case, the positioning and size of the lid were found to be additional factors affecting emptiability. When comparing the different beverage cartons, which were shaken prior to the emptying process, it was observed that the carton with the large lid, which was positioned centrally on the top of the carton, retained only one quarter of the amount of the two cartons, BC 5 and BC 6, where the lid is smaller in size and is positioned on the side of the gable.

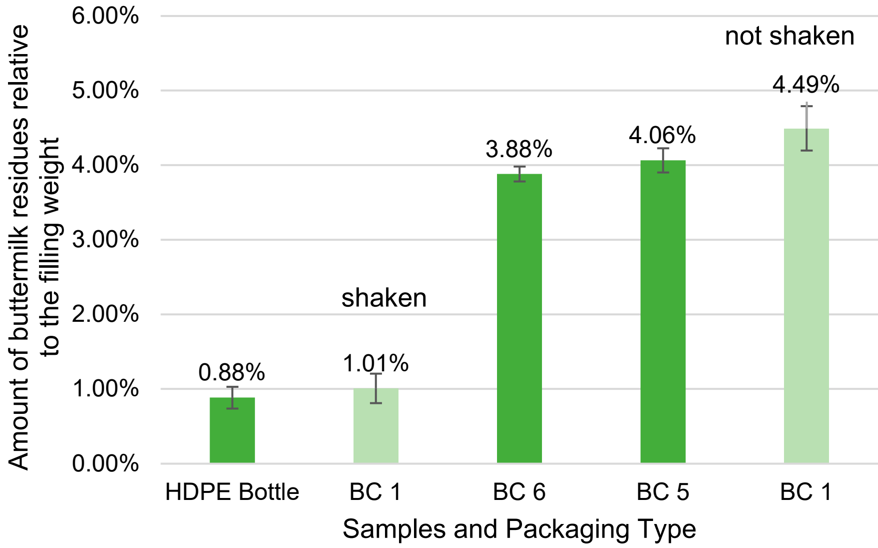

Figure 1. Buttermilk food residues in different packaging types after standardized emptying. For each sample, n = 3 applies. Light green color highlights BC 1, other packaging types are displayed in dark green.

3.2. *Coffee Drinks*

A variety of packaging types for coffee drinks were identified. A total of nine samples of coffee drinks were analyzed. The packaging types included cups made out from polypropylene (PP) with snap-on lids or aluminum lid, PET bottles as well as aluminum or fiber-based cans. The filling volume for two samples was 230 mL, all other packaging contained 250 mL.

The results presented in Figure 2 demonstrate the quantity of measured food residues in the various packaging types that were sampled. The lowest value was observed in a to-go cup with 0.52% of the total filling weight remaining in the packaging following the standardized emptying process. Other to-go cups demonstrated retention rates of 0.78%, 0.98%, and 1.46%. Another cup made of PP but featuring a foil instead of a hooded lid retained 1.19% of the filling weight. A notable discrepancy is evident between cans manufactured from aluminum and those crafted from fiber-based materials. While the aluminum packaging retained 0.66% of the total filling weight, the carton packaging retained a significantly higher quantity, at 1.54%, but with a high variance. No discernible differences were observed in the product properties or packaging geometry. The aluminum packaging had a filling volume of 250 mL, while the cartons can have a capacity of 230 mL.

Two PET bottles with identical geometric shapes and opening sizes were also subjected to testing. The results demonstrated that 0.71% and 0.79% of food residues remained after emptying.

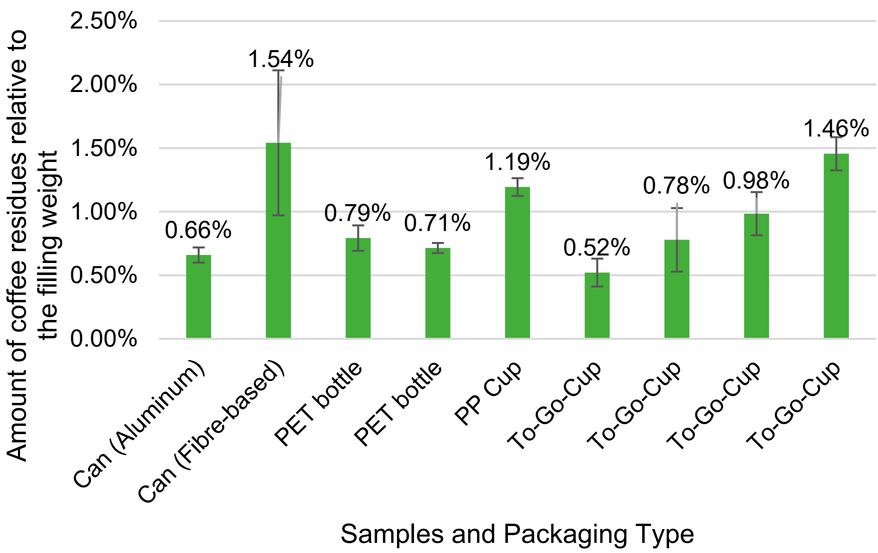

Figure 2. Food residues measured in different packaging types for coffee drinks. For each sample, n = 3 applies.

3.3. Cocoa, Chocolate Drinks, and Other Milk Drinks

Chocolate drinks are a popular beverage in the DACH region, available in a variety of packaging types and sizes. The filling volume of these drinks ranges from 220 to 750 mL. In this study, eleven samples were tested for emptiability (Figure 3).

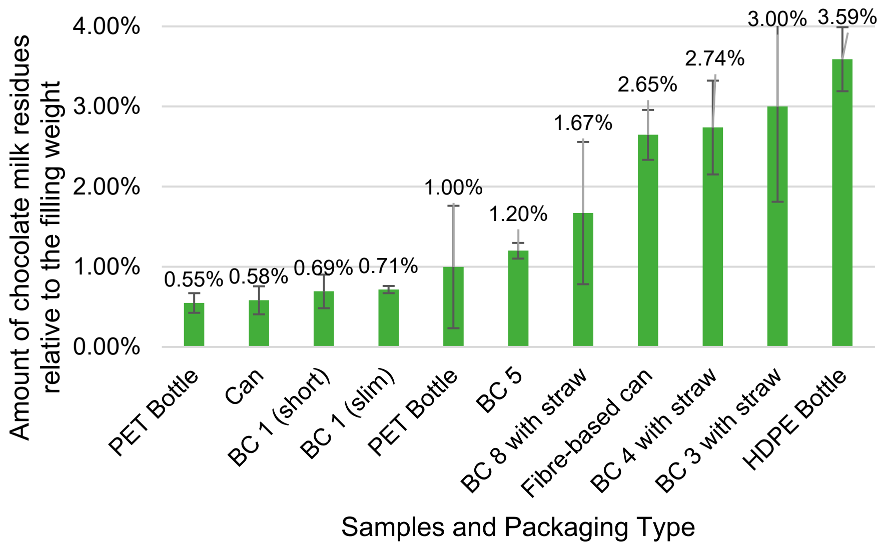

Figure 3. Food residues measured in different packaging types for chocolate drinks. For each sample, n = 3 applies.

Four different beverage cartons were sampled; of these, two packages were designed with a screw cap (BC 1 and BC 5) and the two others included a straw for drinking (BC 4 with straw and BC 3 with straw). The two samples in the BC 1 packaging retained the lowest amounts in the tested beverage cartons with 0.69% and 0.71% of the total filling volume. Although the two samples vary in geometry, the results are comparable, indicating that the width and height of the packaging are of low relevance. The main influencing factors for the emptiability are the opening size of BC 1 and its centric positioning. In comparison to the result of BC 1, BC 5 retained nearly double the amount of residue. The opening of BC 5 is smaller in diameter and is located on the side of the gable, which is disadvantageous in the emptying process, as the product becomes trapped in the folding of the gable. Beverage cartons designed for use with a straw exhibit higher residue rates, with 1.67% observed for BC 8, 2.74% for BC 4, and 3.00% for BC 3.

Similar tendencies to coffee drinks in aluminum- and fiber-based cans can be observed for chocolate drinks. The aluminum can exhibited 0.58% food residue, while the fiber-based can exhibited a more than fourfold increase, at 2.65%. The PET bottle achieved the best result, with a value of 0.55%, which is similar in geometry to those tested for coffee drinks but contained 500 mL instead of 250 mL.

Another PET bottle with a more angular shape contained 1.00% of its content after emptying. The highest amount of food residue (3.59%) was measured in an HDPE bottle. As the shape of the bottle was similar to the PET bottle with the smallest residue amount, it can be reasoned that food properties and the surface structure of the bottle influence the emptying behavior.

Packaging options with a straw showed high variances in the results.

3.4. Protein Drinks

Four samples of protein drinks were tested for emptiability. Three of the samples were packaged in PET bottles, with a filling volume of 250 mL, 350 mL, or 500 mL, and one sample was packaged in a beverage carton. Despite the different filling volumes and bottle geometries, the residue rates for the bottles were found to be similar, with values between 0.54% and 0.72% (Figure 4). The beverage carton exhibited the lowest filling volume of 200 mL and the highest food retention rate of 2.81%. This is presumed to be attributable to the unfortunate design of the gable and an uncentred positioning of the opening, in addition to the small filling volume of 200 mL.

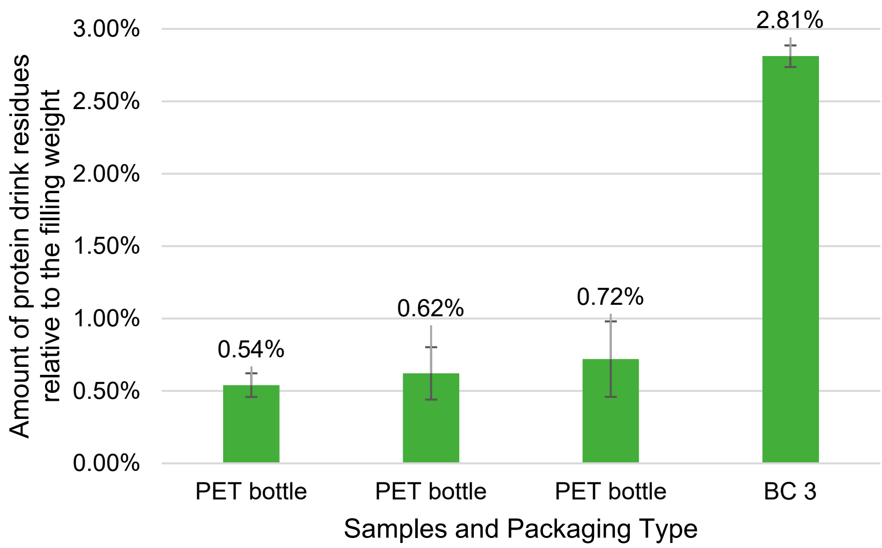

Figure 4. Food residues measured for protein drinks. Sampled were three PET bottles and one beverage carton. For each sample, n = 3 applies.

3.5. Whey Drinks

A similar tendency can be observed in the case of whey drinks, with the quantity of residue being lower due to the lower product viscosity. In this instance, the residues in the beverage cartons accounted for 0.50% to 1.04% of the total filling weight (Figure 5). The centrally located large opening of BC 1 appeared to be more conducive to emptying than the off-centered opening on the gable of BC 6 and BC 12.

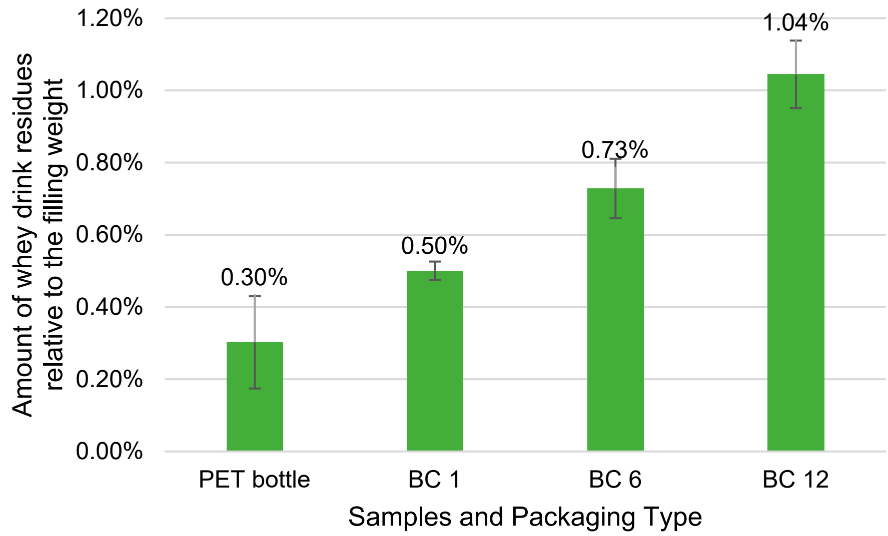

Figure 5. Food residues measured for whey drinks. One PET bottle and three beverage cartons were sampled. For each sample, n = 3 applies.

3.6. Yoghurt Drinks

In addition to bottles and beverage cartons, yoghurt drinks in the German-speaking region are sold in pouches. A total of nine packaging samples were evaluated. After emptying, the lowest amount of food residues was observed in bottles made of PET and HDPE, with a range from 1.28% to 2.62% (Figure 6). The two samples packaged in BC 1 retained 2.10% and 4.22% of the total content, respectively. No differences in food properties, emptying behavior, or packaging characteristics were observed. The highest retention rate was measured in BC 4, at 5.88%.

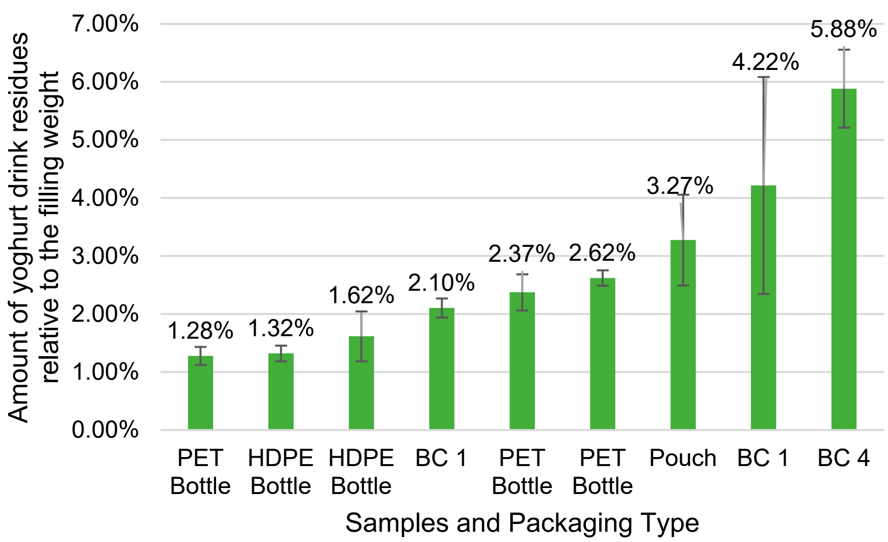

Figure 6. Food residues measured for yoghurt drinks. For each sample, n = 3 applies.

3.7. Comparison of Retained Dairy Residues in Beverage Cartons

BC 1 is distinguished by its geometrical symmetry, the considerable opening size, and the central positioning of the lid on the gable. Overall, this beverage carton has demonstrated the lowest level of residue compared to other tested beverage cartons.

The differences in the emptying behavior of the diverse product types can be observed in Figure 7. The highest amount of residue was observed for high-viscosity products, including buttermilk (4.49%) and yoghurt drinks (4.22% and 2.10%), which were not shaken prior to emptying. Milk samples with varying fat contents exhibited a low residue rate of between 0.28% and 0.32% (Figure 7).

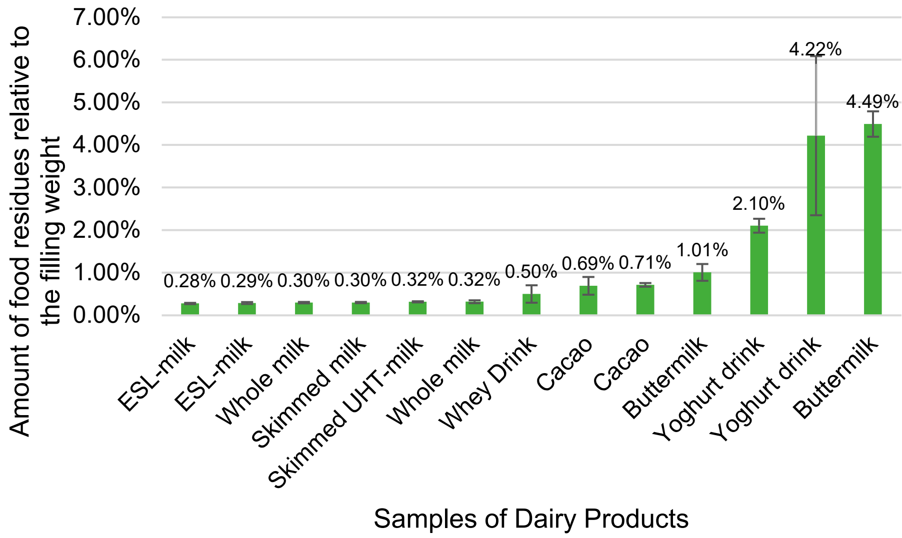

Figure 7. Quantified food residues of diverse dairy products in beverage carton type 1. For each sample, n = 3 applies.

In contrast to BC 1, BC 5 is characterized by an asymmetric positioning of the lid on the side of the gable and the smaller opening size. This results in a greater degree of product entrapment and retention within the packaging following standardized emptying. Diverse types of milk exhibit low residue rates, with values ranging from 0.27% to 0.53%, while for cacao, 1.20% of residues were measured. The high viscosity of buttermilk results in 4.06% of the product remaining in the packaging after standardized emptying (Figure 8).

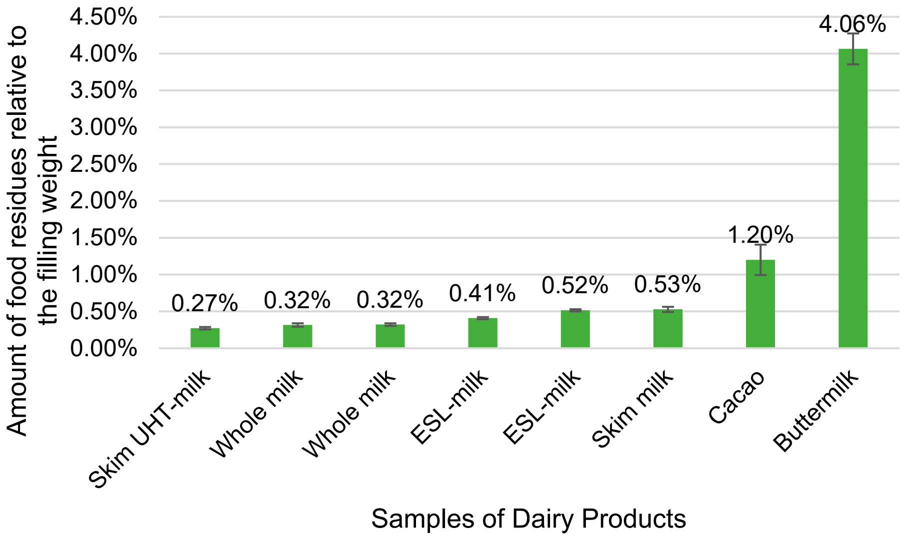

Figure 8. Quantified food residues of diverse dairy products in beverage carton type 5. For each sample, n = 3 applies.

3.8. Retained Dairy Residues in PET Bottles

All assessed PET bottles are characterized by their symmetric round shape and centric lid positioning. Yoghurt drinks showed more than double the amount of food retained in the bottle, compared to other dairy products. The lowest values were measured for ESL milk (0.17%) and whey drinks (0.30%). The whey drink and cacao showed high variability with values such as ±0.28% and ±0.76%, respectively (Figure 9).

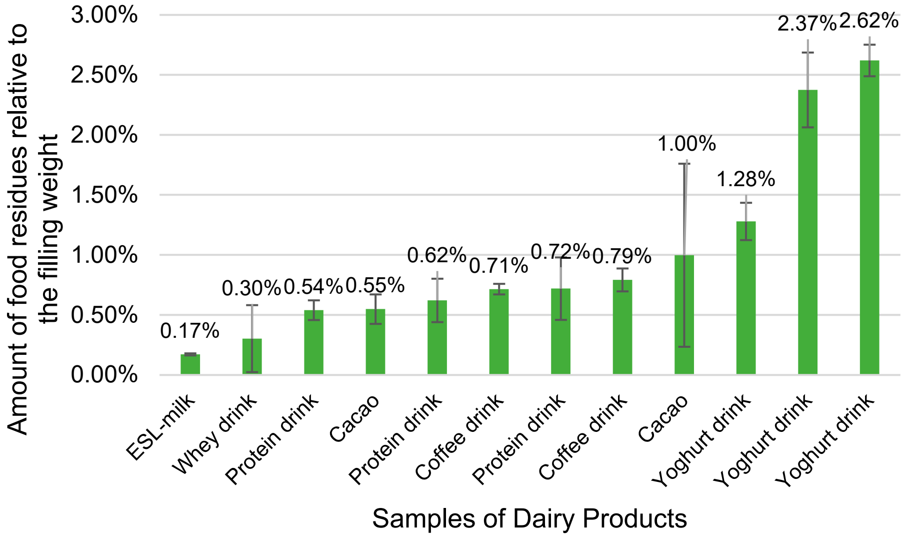

Figure 9. Quantified food residues of diverse dairy products in PET bottles. For each sample, n = 3 applies.

3.9. Food Residues in Fruit Yoghurt Packaging

The category of fruit yoghurt is characterized by a high degree of heterogeneity in terms of filling weight, with a range of values observed, from 50 g to 1000 g. Except for one sample, cups retained on average 1.70% of their content. One cup with a filling weight of 100 g retained 32% of its content, due to the cup's shape, which inhibited emptying with the teaspoon. The mold exhibits a slight conical inlet towards the base. Additionally, a 7 mm high, inwardly drawn edge is present on the base of the cup (Figure 10).

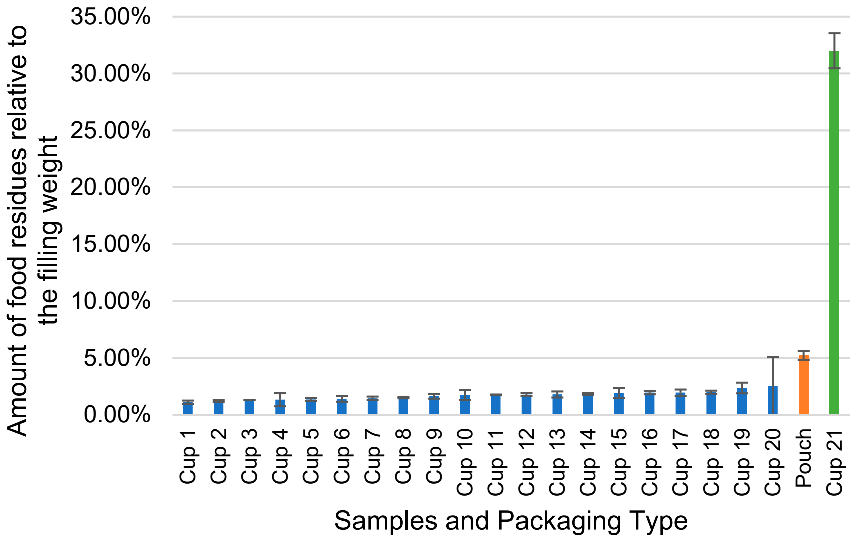

Figure 10. Quantified food residues of yoghurt in cups and a pouch. For each sample n = 3 applies. Cups with good emptiability behavior are highlighted in blue bars, the pouch is marked in orange and the cup with unfavorable design has been highlighted in green.

4. Discussion

The measurement of food residues retained by different packaging plays a significant role in the assessment of the sustainability of packaging options.

The project involved the further or novel development of packaging-system-specific methods for determining the technical emptiability of dairy products. These methods were based on existing methods published by Meurer et al. (2017) and Wohner et al. (2019) [32,51]. A total of 124 products from 15 different product categories were analyzed.

Of these, 76 samples were liquid milk products. The samples were packaged in differently designed packaging options, allowing for a comparison of retained food residues in different packaging. Sixteen different beverage cartons were assessed, of which three samples contained a paper straw for drinking.

The considerable range of residue amounts indicates that, in addition to food properties, packaging-related aspects such as packaging type and packaging design exert a considerable influence. Overall, low-viscosity products demonstrated superior emptying behavior compared to products with a high viscosity. This is exemplified by the results of butter milk, which is a high-viscosity product, and ESL milk, which is a low-viscosity product. These results are in accordance with the findings of Schmidt (2011) and Schinkel et al. (2023) [53,54].

Furthermore, the results for different packaging types and designs for the same product indicate that bottles are a favorable packaging system choice in terms of emptiability. When beverage cartons are selected as a packaging option, cartons with a bottle-shaped top exhibit a lower amount of residue than those with a gable or flat-shaped top. An overview of the results for each product and packaging type is provided in Table 3.

Table 3. Results of measured food residues for liquid milk products in diverse packaging options. Values are depicted in percentage of total product filling weight. In cases of more than one sample per product type and packaging option, an average value was calculated. The value marked with an asterisk is an average taken from two samples with different product handling.

Product Type	Yoghurt Drinks	Buttermilk	ESL Milk	UTH Skimmed Milk	UTH Milk	Coffee Drinks	Chocolate Drinks	Skimmed Milk	Protein Drinks	Whey Drinks	Whole Milk
n	9	5	10	5	8	9	11	6	4	4	5
Average	2.74	2.87	0.41	0.54	0.72	0.96	1.67	0.53	1.17	0.64	0.29
BC 1	3.16	2.75 *	0.28	0.32			0.70	0.30		0.50	0.31
BC 2			0.89					0.84			
BC 3					0.78				2.81		
BC 3 with straw							3.00				
BC 4	5.88										
BC 4 with straw							2.74				
BC 5		4.06	0.46	0.27			1.20	0.53			0.32
BC 6		3.88								0.73	
BC 7			0.39					0.20			
BC 8 with straw							1.67				
BC 9				0.74	0.85						
BC 10				0.69	0.89						
BC 11					0.67						
BC 12								1.1		1.04	
To-Go Cup with lid						0.94					
To-Go Cup with foil						1.19					
PET bottle	2.09		0.17			0.75	0.77		0.63	0.30	
Glass bottle								0.18			
HDPE bottle	1.47	0.88			0.37		3.59				
Aluminum can						0.66	0.58				
Fiber-based can						1.54	2.65				
Pouch	3.27										

4.1. Data Comparison to the Existing Literature

While packaging and food loss are two topics which are widely researched individually, packaging-related food loss is largely unexplored, with the exception of a few available studies [52].

The residue amounts in packaging for the product category UHT milk do not correlate with the existing data published by Meurer et al. (2017), which is due to differences in emptying methods [51]. UHT milk in an HDPE bottle retained 0.37% ± 0.03%, while Meurer et al. (2017) reported a retained volume of 0.80 ± 0.03 mL, which equates to 0.08% of the filling volume and the approximate product weight [51]. The product samples T38 and M6 are of an identical shape and dimension to packaging type 2, as described in the study by Meurer et al. (2017), in which residues of 0.6% of the filling volume were measured [51]. In this study the measured food waste for the same packaging type was quantified in two samples with values of 0.76% and 0.93%, respectively. These values also demonstrate no correlation to existing results. The dimensions of samples M13, T30, and T31 are identical to those of packaging type 5, as assessed by Meurer et al. (2017); yet again, no correlation could be quantified in the results. This can be attributed to the different type of closing mechanism which may result in a different pouring behavior and retention rate [51].

When comparing the results to the data published by Wohner et al. (2019), it is important to note that the applied methodology has been developed further and that the new approach considers a higher differentiation in packaging design [32].

The results obtained for buttermilk with 4.18% and 4.13% remaining in the beverage carton packaging with a bottle top design were similar to those reported by Wohner et al. (2019). This finding is consistent with the results for buttermilk in BC type 1 without instructions to shake, which showed a food retention rate of 4.49% [32]. In the case of buttermilk in beverage cartons with a gable top, 3.41% of the original contents were retained, while in this study, similar packaging designs (BC 5 and BC 6) retained 4.06% and 3.88% of the filling, respectively.

For whole milk in a gable-top beverage carton Wohner et al. (2019) measured 0.34%, while in this study, both samples in a BC 5 packaging type retained 0.32%, which is a comparable value and shows little influence of detailing in the methodological processes of emptying [32].

The results for low-fat milk in a gable-top beverage carton exhibit similar tendencies. Wohner et al. (2019) measured 0.51% of residues, while this study yielded samples with results of 0.20 and 0.53% [32]. In contrast, in both studies, the results for the same product type in a flat-top beverage carton vary drastically between the two studies. While Wohner et al. (2019) published results of 0.52% food residues, this study measured 1.10% of the retained product [32].

The results for liquid yoghurt, chocolate milk, and café latte published by Wohner et al. (2019) could not be replicated in the study, indicating that differences in the emptying process and potential differences in temperature during analysis influence the results. Another factor to consider is that the packaging design of the assessed samples differed between the two studies. Details in packaging design and product properties from Wohner et al. (2019) cannot be reconstructed [32].

4.2. Implications of Food Waste on Global Warming Potential

Life Cycle Assessment (LCA) serves as a tool for determining the environmental impact of a product by quantifying energy and material use, as well as waste and emissions generation, and has become an important decision-making tool in packaging design [20].

So far, many comparative LCAs have been published, but many overlook the interaction of product and product packaging, leaving indirect environmental impact by food waste out of the equation [20].

The proposed approach by Pauer et al. (2019), that emptiability serves as a quantification for packaging-related food losses and waste, was taken up in this study [20].

For their methodological framework, only assumptions could be taken; those data are now available.

Other studies have already published LCA data for different packaging options and foods and drinks [55–57].

The carbon footprint of 1 kg of ESL milk in a beverage carton was estimated to be 1.4 kg CO_2 equivalent. The emission of skimmed milk was slightly lower if sold in a beverage carton, with an estimated value of 1.2 kg CO_2 equivalent. Furthermore, it was determined that UHT milk emits 1.3 kg CO_2 equivalent when unskimmed, while skimmed UHT milk emits 1.1 kg CO_2 equivalent [55]. A beverage carton was quantified by Fehringer (2019) to emit between 83 g and 100 g CO_2 equivalent in the assessment category of climate change [57]. Now, assuming a 1.4 kg CO_2 equivalent, a value of 100 g CO_2 equivalent being attributed to the packaging and 1.3 kg CO_2 equivalent being attributed to ESL milk, the environmental emissions of the discarded food compared to the environmental impact can be assessed.

Taking an average residue value for ESL milk in beverage cartons of 0.44% and the aforementioned carbon footprint of 1 kg ESL milk of 1.3 kg CO_2 equivalent, the environmental emissions of the food waste sum up to 5.72 g of CO_2 equivalents.

A study conducted by Ghinea and Leahu (2020) determined the global warming potential for 1 kg yoghurt, which was quantified with 2.92 kg CO_2 equivalent [58]. For the sample of yoghurt in a cup with a 100 g filling volume and a retention rate of 32%, this would mean environmental impacts of 93.44 g CO_2 equivalent.

4.3. Importance of Technical Emptiability in the Context to the PPWR

The majority of viscous products are utilized within the food industry. Consequently, the primary impetus for scientific research into this topic originates from this sector [53].

In the Impact Assessment Report accompanying the current draft of the Packaging and Packaging Waste Regulation, several barriers to packaging recycling are identified. One of these non-recyclable packaging types is highly contaminated with food in cases where the packaging is difficult to empty and is therefore considered an obstacle to packaging circularity [59].

The latter standard, CR 13688:2000, argues that residues do not inhibit material recycling, but claims that it does not reflect the current state of knowledge [59].

The PPWR recognizes the negative impact of product residues on collection, sorting, and recycling as well as the potential for material contamination as a key intervention for waste prevention. This intervention focuses on the definition of Design for Recycling [59].

In hindsight, to inform future legislation on the circularity and recyclability of packaging, note that high viscosity products in poorly designed packaging systems can be seen as a major problem, as poor emptiability can lead do low recyclate quality [53]. To date, no clear thresholds have been communicated as no standardized methodology has been published to measure the emptiability of different packaging systems and products.

4.4. Limitations

It is of paramount importance to emphasize that the methodology employed should reflect and promote sustainable consumption practices amongst consumers. Consequently, wasteful consumer handling may result in elevated residue levels remaining within the packaging. As evidenced by the elevated variance values, additional, as-yet-unidentified influencing factors warrant investigation. Variables such as temperature during storage and emptying, as well as product and packaging properties, could potentially influence the results. The objective of this exploratory study was to conduct a comprehensive analysis of diverse products and packaging types to identify optimal packaging solutions for specific products.

5. Conclusions

In this study, existing emptiability methods were newly or further developed and applied to a wider range of product categories and packaging systems. The objective was to propose a standardized method for future comparability of emptiability results. In light of future international regulations, such as the PPWR, the emptiability of packaging for highly viscous products is of crucial importance in order to ensure the recyclability of the packaging material and to minimize the carbon footprint and other social, economic, ethical, and environmental implications of wasted food. Future research should concentrate on the development of further methods for technical emptiability. This will enable insights to be gained into residue amounts for a wider range of products in the food and non-food sectors, and for other packaging systems than those analyzed here. The results of this research must be validated by quantitative and qualitative analysis of consumer handling, as well as by the evaluation of the status quo of the residue amounts found in sorting and recycling facilities. This implies that the issue must be addressed from both a waste generation perspective and an end-of-life scenario. Consequently, it is essential to determine the impact of residues on recyclability.

The presented results constitute a call to action for the food and packaging industries to optimize packaging design in order to reduce food waste. Furthermore, they encourage customers and other stakeholders to support action to avoid packaging options which lead to high amounts of food waste.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16156335/s1, Table S1: Research Data Emptiability Dairy.

Author Contributions: Conceptualization, M.K.; methodology, M.K.; validation, M.K., S.A. and M.T.; formal analysis, M.K.; investigation, M.K.; resources, M.K. and C.W.; data curation, M.K.; writing—original draft preparation, M.K.; writing—review and editing, M.K., S.A. and M.T.; visualization, M.K.; supervision, S.A. and M.T.; project administration, M.K. and C.W.; funding acquisition, S.A. and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was created within a research project of the Austrian Competence Centre for Feed and Food Quality, Safety and Innovation (FFoQSI). The COMET-K1 competence center FFoQSI is funded by the Austrian federal ministries BMK, BMDW and the Austrian provinces Lower Austria, Upper Austria, and Vienna within the scope of COMET—Competence Centers for Excellent Technologies. The program COMET is handled by the Austrian Research Promotion Agency FFG.

Data Availability Statement: The data presented in this study are available in the Supplementary Materials.

Acknowledgments: The authors would like to express their gratitude to all project participants who provided product samples. Special thanks are directed to all students and interns who were involved in data collection, as well as to the team members of the Institute of Packaging and Resource Management at FH Campus Wien and Circular Analytics. In particular, the authors would like to thank Mary Grace Wallis for her invaluable contribution in reviewing and providing comments on the manuscript.

Conflicts of Interest: Authors Charlotte Werner and Manfred Tacker were employed by the company Circular Analytics TK GmbH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. United Nations Environment Programme. *Food Waste Index: Report 2021*; United Nations Environment Programme: Nairobi, Kenya, 2021.
2. Block, L.G.; Keller, P.A.; Vallen, B.; Williamson, S.; Birau, M.M.; Grinstein, A.; Haws, K.L.; LaBarge, M.C.; Lamberton, C.; Moore, E.S.; et al. The Squander Sequence: Understanding Food Waste at Each Stage of the Consumer Decision-Making Process. *J. Public Policy Mark.* **2016**, *35*, 292–304. [CrossRef]
3. Hebrok, M.; Boks, C. Household food waste: Drivers and potential intervention points for design—An extensive review. *J. Clean. Prod.* **2017**, *151*, 380–392. [CrossRef]

4. Schanes, K.; Dobernig, K.; Gözet, B. Food waste matters—A systematic review of household food waste practices and their policy implications. *J. Clean. Prod.* **2018**, *182*, 978–991. [CrossRef]
5. Abeliotis, K.; Lasaridi, K.; Costarelli, V.; Chroni, C. The implications of food waste generation on climate change: The case of Greece. *Sustain. Prod. Consum.* **2015**, *3*, 8–14. [CrossRef]
6. United Nations—Department of Economic and Social Affairs. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations—Department of Economic and Social Affairs: New York, NY, USA, 2015.
7. Williams, H.; Wikström, F.; Otterbring, T.; Löfgren, M.; Gustafsson, A. Reasons for household food waste with special attention to packaging. *J. Clean. Prod.* **2012**, *24*, 141–148. [CrossRef]
8. Tukker, A.; Huppes, G.; Guinée, J.; Heijungs, R. *Environmental Impact of Products (EIPRO) Analysis of the Life Cycle Environmental Impacts Related to the Final Consumption of the EU-25*; European Commission Joint Research Centre: Brussels, Belgium, 2006.
9. Quested, T.; Johnson, H. *Household Food and Drink Waste in the UK: Final Report*; Wastes & Resources Action Programme (WRAP): Banbury, UK, 2009; ISBN 1-84405-430-6.
10. WRAP. *Food Storage and Packaging: An Investigation of Consumer Attitudes and Behaviour in Respect of Food Storage and Packaging*; WRAP: Banbury, UK, 2007.
11. WRAP. *Food Behaviour Consumer Research: Quantitative Phase*; WRAP: Banbury, UK, 2007.
12. Hanssen, O.J. Environmental impacts of product systems in a life cycle perspective. *J. Clean. Prod.* **1998**, *6*, 299–311. [CrossRef]
13. Denkstatt. Vermeidung von Lebensmittelabfällen durch Verpackung: Kurzdarstellung der Ergebnisse einer Studie der denkstatt GmbH in Kooperation mit der ARA AG und weiteren Partnern aus den Bereichen Einzelhandel, Verpackungsproduktion und Forschung. Available online: https://www.scheyer.at/media/285/download/Abfallvermeidung%20durch%20Lebensmittelverpackung_Kurzdarstellung_V1.2.pdf?v=1&inline=1 (accessed on 27 May 2024).
14. Grant, T.; Barichello, V.; Fitzpatrick, L. Accounting the Impacts of Waste Product in Package Design. *Procedia CIRP* **2015**, *29*, 568–572. [CrossRef]
15. Büsser, S.; Jungbluth, N. The role of flexible packaging in the life cycle of coffee and butter. *Int. J. Life Cycle Assess.* **2009**, *14*, 80–91. [CrossRef]
16. Bundesanstalt für Landwirtschaft und Ernährung. *Presseinformation: Milchmarkt 2021: Pro-Kopf-Verbrauch von Milch Sinkt Auf 47,8 Kilogramm*; Bundesanstalt für Landwirtschaft und Ernährung: Nordrhein-Westfalen, Germany, 2022.
17. AgrarMarkt Austria. Versorgungsbilanz für Milch & Milchprodukte 2021. Available online: https://www.ama.at/marktinformationen/milch-und-milchprodukte/aktuelle-informationen/2022/versorgungsbilanz-fuer-milch-milchprodukte-2021 (accessed on 27 May 2024).
18. Bundesamt für Landwirtschaft. Milch und Milchprodukte. Available online: https://www.blw.admin.ch/blw/de/home/nachhaltige-produktion/tierische-produktion/milch-und-milchprodukte.html (accessed on 27 May 2024).
19. Bundesministerium Land- und Forstwirtschaft, Regionen und Wasserwirtschaft. Milchwirtschaft in Österreich. Available online: https://info.bml.gv.at/themen/landwirtschaft/landwirtschaft-in-oesterreich/tierische-produktion/milch/milchwirtschaft.html (accessed on 27 May 2024).
20. Pauer, E.; Wohner, B.; Heinrich, V.; Tacker, M. Assessing the Environmental Sustainability of Food Packaging: An Extended Life Cycle Assessment including Packaging-Related Food Losses and Waste and Circularity Assessment. *Sustainability* **2019**, *11*, 925. [CrossRef]
21. Williams, H.; Wikström, F. Environmental impact of packaging and food losses in a life cycle perspective: A comparative analysis of five food items. *J. Clean. Prod.* **2011**, *19*, 43–48. [CrossRef]
22. Flanigan, L.; Frischknecht, R.; Montalbo, R. *An Analysis of Life Cycle Assessment in Packaging for Food & Beverage Applications*; United Nations Environment Programme: Nairobi, Kenya, 2013.
23. Verghese, K.; Lewis, H.; Lockrey, S.; Williams, H. Packaging's Role in Minimizing Food Loss and Waste Across the Supply Chain. *Packag. Technol. Sci.* **2015**, *28*, 603–620. [CrossRef]
24. Verghese, K.; Lewis, H.; Lockrey, S.; Williams, H. *Final Report: The Role of Packaging in Minimising Food Waste in the Supply Chain of the Future*; RMIT University Report: Melbourne, Australia, 2013.
25. Pongrácz, E. The Environmental Impacts of Packaging. In *Environmentally Conscious Materials and Chemicals Processing*; Kutz, M., Ed.; Wiley: Hoboken, NJ, USA, 2007; pp. 237–278. ISBN 9780471739043.
26. Verriet, J.; Leroy, F. Yogurt's flexible image during its rise in popularity in post-war Belgium. *Appetite* **2017**, *108*, 132–140. [CrossRef]
27. Wierzejska, R.; Siuba-Strzelińska, M.; Jarosz, M. Evaluation of dairy products available on the Polish market in the context of nutrient profiles. Clear arguments for reformulation of foodstuffs. *Rocz. Panstw. Zakl. Hig.* **2017**, *68*, 43–50. [PubMed]
28. Chandan, R.C.; Kilara, A. *Manufacturing Yogurt and Fermented Milks*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2013; ISBN 9781119967088.
29. Statista. Produktion von Joghurt (ohne Zusätze) in Deutschland in den Jahren 2000 bis 2023. Available online: https://de.statista.com/statistik/daten/studie/239697/umfrage/herstellung-von-joghurterzeugnissen-in-deutschland/ (accessed on 27 May 2024).
30. Behare, P.; Kumar, H.; Mandal, S. Yogurt: Yogurt Based Products. In *Encyclopedia of Food and Health*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 625–631, ISBN 9780123849533.

31. Corrieu, G.; Béal, C. Yogurt: The Product and its Manufacture. In *Encyclopedia of Food and Health*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 617–624, ISBN 9780123849533.
32. Wohner, B.; Schwarzinger, N.; Gürlich, U.; Heinrich, V.; Tacker, M. Technical emptiability of dairy product packaging and its environmental implications in Austria. *PeerJ* **2019**, *7*, e7578. [CrossRef]
33. Aryana, K.J.; Olson, D.W. A 100-Year Review: Yogurt and other cultured dairy products. *J. Dairy Sci.* **2017**, *100*, 9987–10013. [CrossRef]
34. Franz, R.; Welle, F. Recycling of Post-Consumer Packaging Materials into New Food Packaging Applications—Critical Review of the European Approach and Future Perspectives. *Sustainability* **2022**, *14*, 824. [CrossRef]
35. Guazzotti, V.; Hendrich, V.; Gruner, A.; Fiedler, D.; Störmer, A.; Welle, F. Migration of Styrene in Yogurt and Dairy Products Packaged in Polystyrene: Results from Market Samples. *Foods* **2022**, *11*, 2120. [CrossRef]
36. Cyclos-HTP. *Verification and Examination of Recyclability: Requirements and Assessment Catalogue of the Institute Cyclos-HTP for EU-Wide Certification (CHI-Standard)*; Cyclos-HTP: Aachen, Germany, 2021.
37. Hopewell, J.; Dvorak, R.; Kosior, E. Plastics recycling: Challenges and opportunities. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **2009**, *364*, 2115–2126. [CrossRef]
38. Gall, M.; Freudenthaler, P.J.; Fischer, J.; Lang, R.W. Characterization of Composition and Structure–Property Relationships of Commercial Post-Consumer Polyethylene and Polypropylene Recyclates. *Polymers* **2021**, *13*, 1574. [CrossRef] [PubMed]
39. Strangl, M.; Lok, B.; Breunig, P.; Ortner, E.; Buettner, A. The challenge of deodorizing post-consumer polypropylene packaging: Screening of the effect of washing, color-sorting and heat exposure. *Resour. Conserv. Recycl.* **2021**, *164*, 105143. [CrossRef]
40. Strangl, M.; Ortner, E.; Buettner, A. Evaluation of the efficiency of odor removal from recycled HDPE using a modified recycling process. *Resour. Conserv. Recycl.* **2019**, *146*, 89–97. [CrossRef]
41. Strangl, M.; Ortner, E.; Fell, T.; Ginzinger, T.; Buettner, A. Odor characterization along the recycling process of post-consumer plastic film fractions. *J. Clean. Prod.* **2020**, *260*, 121104. [CrossRef]
42. Strangl, M.; Schlummer, M.; Maeurer, A.; Buettner, A. Comparison of the odorant composition of post-consumer high-density polyethylene waste with corresponding recycled and virgin pellets by combined instrumental and sensory analysis. *J. Clean. Prod.* **2018**, *181*, 599–607. [CrossRef]
43. Feil, A.; Pretz, T. Mechanical recycling of packaging waste. In *Plastic Waste and Recycling*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 283–319. ISBN 9780128178805.
44. European Commission. *Proposal for a Regulation of the European Parliament and of the Council on Packaging and Packaging Waste, Amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and Repealing Directive 94/62/EC*; European Commission: Brussels, Belgium, 2022.
45. European Commission (Ed.) *Closing the Loop—An EU Action Plan for the Circular Economy*; European Commission: Brussels, Belgium, 2015.
46. Cragnell, C.; Hansson, K.; Andersson, T.; Jönsson, B.; Skepö, M. Underlying mechanisms behind adhesion of fermented milk to packaging surfaces. *J. Food Eng.* **2014**, *130*, 52–59. [CrossRef]
47. Saikhwan, P.; Geddert, T.; Augustin, W.; Scholl, S.; Paterson, W.R.; Wilson, D.I. Effect of surface treatment on cleaning of a model food soil. *Surf. Coat. Technol.* **2006**, *201*, 943–951. [CrossRef]
48. Santos, O.; Nylander, T.; Rosmaninho, R.; Rizzo, G.; Yiantsios, S.; Andritsos, N.; Karabelas, A.; Müller-Steinhagen, H.; Melo, L.; Boulangé-Petermann, L.; et al. Modified stainless steel surfaces targeted to reduce fouling—Surface characterization. *J. Food Eng.* **2004**, *64*, 63–79. [CrossRef]
49. Michalski, M.C.; Desobry, S.; Babak, V.; Hardy, J. Adhesion of food emulsions to packaging and equipment surfaces. *Colloids Surf. A Physicochem. Eng. Asp.* **1999**, *149*, 107–121. [CrossRef]
50. Williams, H.; Lindström, A.; Trischler, J.; Wikström, F.; Rowe, Z. Avoiding food becoming waste in households—The role of packaging in consumers' practices across different food categories. *J. Clean. Prod.* **2020**, *265*, 121775. [CrossRef]
51. Meurer, I.R.; Lange, C.C.; Hungaro, H.M.; Bell, M.J.V.; Anjos, V.d.C.d.; Silva, C.A.d.S.; Pinto, M.A.d.O. Quantification of whole ultra high temperature UHT milk waste as a function of packages type and design. *J. Clean. Prod.* **2017**, *153*, 483–490. [CrossRef]
52. Wohner, B.; Pauer, E.; Heinrich, V.; Tacker, M. Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues. *Sustainability* **2019**, *11*, 264. [CrossRef]
53. Schmidt, M.C. Untersuchung und Verbesserung des Entleerungsverhaltens von Füllgut-Verpackungssystemen. Ph.D. Thesis, Universität Stuttgart, Stuttgart, Germany, 2011.
54. Schinkel, K.; Küppers, B.; Reichenbach, S.; Rohrmeier, T.; Müller, K.; Fell, T.; Sängerlaub, S. Amount of Fill Product Residues in Plastic Packagings for Recycling. *Waste* **2023**, *1*, 901–918. [CrossRef]
55. Reinhardt, G.; Gärtner, S.; Wagner, T. *Ökologische Fußabdrücke von Lebensmitteln und Gerichten in Deutschland*; IFEU—Institut für Energie-und Umweltforschung: Heidelberg, Germany, 2020.
56. Kauertz, B.; Busch, M.; Bader, J. *Ökobilanzielle Betrachtung von Getränkeverbundkartons in Deutschland: In den Getränkesegmenten Säfte und Nektare sowie H-Milch und Frischmilch*; IFEU—Institut für Energie-und Umweltforschung: Heidelberg, Germany, 2020.
57. Fehringer, R. *ALPLA LCA Packaging Report—Ökobilanz für Gebinde aus PET und Anderen Materialien*; C7-CONSULT: Lindau, Germany, 2019.

58. Ghinea, C.; Leahu, A. Life cycle assessment of fermented milk: Yogurt production. *Ovidius Univ. Ann. Chem.* **2020**, *31*, 49–54. [CrossRef]
59. European Commission. Impact Assessment Report, Accompanying the document Proposal for a Regulation of the European Parliament and the Council on Packaging and Packaging Waste, Amending Regulation (EU) 2019/1020, and Repealing Directive 94/62/EC. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022SC0384 (accessed on 27 May 2024).