# Doctoral Thesis

## The relationship between packaging and food waste and its consideration in sustainability assessments

Submitted in satisfaction for the degree of Doctor of Science of the Vienna University of Technology, Faculty of Technical Chemistry

# Dissertation

## Der Zusammenhang zwischen Verpackung und Lebensmittelverlusten und dessen Berücksichtigung in Nachhaltigkeitsbewertungen

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der Naturwissenschaften unter der Leitung von

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# Abstract

Almost a third of all food produced is lost or wasted each year. Due to the use of energy, fertilizers and pesticides, food production substantially pollutes air, climate, soil, and water. Even more tragic if food is then lost or wasted. Since the function of packaging is to transport food safely and to protect its contents, food losses can be reduced by optimized packaging. At the same time, packaging that has not been optimized may also have the opposite effect, be it by too large packages or a design that makes it difficult to empty. Packaging and its manufacturers are in any case subject to public criticism since with the rising amount of packaging its ecological impact increases as well. Particularly, if it is not recycled but incinerated or, at worst, if it ends up in nature. When designing packaging it is important to weigh the environmental impact between packaging and possible food waste. The present work is therefore dedicated to the overarching goal of creating a better understanding of the interaction between packaging and food waste, as well as the subsequent consideration of this relationship in sustainability assessments of packaging.

In a first step, existing literature was analyzed to identify hot spots of packaging-related food loss and waste along the food supply chain. It was investigated in which way packaging leads to food loss and waste and how such quantities can be operationalized.

After testing for emptiability was recognized as the most feasible option for this thesis, methods for operationalization were established. Based on a case study with dairy products, it was recognized that highly viscous products in inaccessible packaging (e.g. bottles) are particularly affected by poor emptiability. The accompanying life cycle analysis revealed that emptiability can lead to even greater environmental impacts than by the packaging material itself, as was the case for cream in a beverage carton.

In a third and final step, a comparative sustainability assessment was carried out using tomato ketchup as a case study. First, products were tested for their emptiability which showed that up to 29% ketchup can remain in polypropylene bottles, while emptiability of ketchup in glass packaging only led to 4% food loss. While glass packaging achieved poorer LCA results compared to polypropylene bottles, the entire food packaging system was able to perform better, a direct effect of its good emptiability. An economic analysis showed that although higher food losses lead to higher costs for consumers, it does produce a positive overall economic effect. Finally, multi-criteria decision analysis was used to identify the most sustainable alternative, which was again heavily influenced by emptiability.


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## Kurzfassung

Weltweit gehen jährlich rund ein Drittel aller Lebensmittel verloren. Da die Produktion von Lebensmitteln durch den Einsatz von Energie, Düngemitteln und Pestiziden zu deutlichen Belastungen von Luft, Klima, Böden und Gewässern führt, ist deren Verlust umso tragischer. Verpackungen haben die Funktion, Lebensmittel sicher transportierbar zu machen und ihren Inhalt zu schützen, wodurch Lebensmittelverluste reduziert werden können. Ebenso können nicht-optimierte Verpackungen zu Verlusten führen, sei es durch die Verwendung zu großer Packungen oder einem Design, welches eine nur mangelhafte Restentleerbarkeit ermöglicht. Verpackungen und deren Hersteller stehen jedenfalls in der öffentlichen Kritik, denn mit der zunehmenden Menge an Verpackungen wachsen auch deren ökologische Auswirkungen. Besonders in der Kritik stehen Verpackungen aus Kunststoff, vor allem wenn diese am Ende ihres Lebensweges nicht recycelt, sondern verbrannt oder im schlimmsten Fall in der Natur landen. Es gilt, ökologische Auswirkungen zwischen Verpackung und Lebensmittelverlusten abzuwägen. Die vorliegende Arbeit widmet sich deshalb dem übergeordneten Ziel, ein besseres Verständnis für das Zusammenspiel zwischen Verpackung und Lebensmittelabfällen zu schaffen, sowie dieses in Nachhaltigkeitsbewertungen von Verpackungen zu berücksichtigen.

In einem ersten Schritt wurde bestehende Literatur analysiert, um Hot Spots von verpackungsbedingten Lebensmittelverlusten entlang der Wertschöpfungskette zu identifizieren. Es wurde untersucht, in welcher Art und Weise Verpackungen zu Lebensmittelverlusten führen und wie solche Mengen operationalisiert werden können.

Nachdem eine Testierung auf Restentleerbarkeit als machbar erkannt wurde, wurden in einem zweiten Schritt Methoden entwickelt, um ein solches Verfahren zu standardisieren. Anhand einer Fallstudie mit Milchprodukten konnte erhoben werden, dass hochviskose Produkte in nicht-zugänglichen Verpackungen (z.B. Flaschen) besonders stark von schlechter Restentleerbarkeit betroffen sind. Die begleitend durchgeführte Lebenszyklusanalyse offenbarte, dass dies für Rahm im Getränkeverbundkarton zu größeren Umweltauswirkungen führen kann als mit der Produktion und Entsorgung der Verpackung verbunden sind.

In einem dritten und letzten Schritt wurde am Fallbeispiel Tomatenketchup eine vergleichende Nachhaltigkeitsbewertung durchgeführt. Hierzu wurde zuerst eine Restentleerbarkeitsuntersuchung angestellt die zeigte, dass in Polypropylenflaschen bis zu 29% Ketchup zurückbleiben kann, die Restentleerbarkeit des Ketchups in einer Flasche jedoch nur zu rund 4% Lebensmittelverlusten führte. Während die Glasverpackung schlechtere ökobilanzielle Ergebnisse erzielte, konnte das gesamte

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Lebensmittelverpackungssystem durch die gute Restentleerbarkeit jedoch in Summe besser abschneiden. Eine ökonomische Betrachtung mittels Lebenszykluskostenanalyse zeigte, dass höhere Lebensmittelverluste zwar auch zu höheren Kosten für Konsumentinnen und Konsumenten führt, jedoch einen positiven ökonomischen Gesamteffekt produziert. Abschließend wurde mittels einer multikriteriellen Entscheidungsanalyse die Auswahl der nachhaltigsten Alternative getroffen, welche erneut substanziell durch die Restentleerbarkeit der Produkte beeinflusst wurde.

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# Contents



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## Abbreviations

| | |
|---|---|
| AC | Acidification |
| CC | Climate change |
| CRITIC | Criteria Importance through Intercriteria Correlation (CRITIC) |
| EVOH | Ethylene vinyl alcohol |
| FEU | Freshwater eutrophication |
| FLW | Food loss and waste |
| FRD | Fossil resource depletion |
| HDPE | High-density polyethylene |
| LCA | Life cycle assessment |
| LCC | Life cycle costing |
| MCDA | Multi-criteria decision analysis |
| PEF | Product Environmental Footprint |
| PET | Polyethylene terephthalate |
| PFLW | Packaging-related food loss and waste |
| PM | Particulate matter |
| PP | Polypropylene |
| PREI | Packaging relative environmental impact |
| PS | Polystyrene |
| TEU | Terrestrial eutrophication |
| TOPSIS | Technique for Order Preference by Similarity to Ideal Solution |
| UHT | Ultra-high temperature |
| UV | Ultra-violet |
| VA | Value added |

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## Published articles and contributions

This cumulative thesis is comprised of the following three journal articles:

Paper I Wohner B, Pauer E, Heinrich V, Tacker M. Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues. Sustainability 2019; 11(1).[1]

I have provided the following contributions to this paper:

- Conceptualization
- Methodology
- Investigation
- Writing – Original draft
- Visualization

Paper II 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(12): e7578.[2]

I have provided the following contributions to this paper:

- Conceptualization
- Methodology
- Validation
- Formal analysis
- Investigation
- Writing – Original draft
- Visualization

Paper III Wohner B, Gabriel VH, Krenn B, Krauter V, Tacker M. Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup. Science of The Total Environment 2020; 738: 139846.[3]

I have provided the following contributions to this paper:

- Conceptualization
- Methodology
- Validation
- Formal analysis
- Investigation
- Writing – Original draft
- Visualization

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# 1 Introduction

## 1.1 Food loss and waste

The global food and agriculture supply chain is responsible for 13.7 billion tons of $CO_2$ equivalents or 26% of the worlds emissions each year[4]. 50% of the total habitable land and 70% of freshwater withdrawal are used for agriculture, as well as considerable quantities of pesticides and fertilizers which pollute air, water bodies and soil if not managed properly[5]. Considering the expected population growth of up to 10 billion people by 2050[6], carbon emissions and the pressure on land and water resources by the food and agriculture sector are expected to increase even more. If food is then lost or wasted instead of being consumed, this leads to a tragic waste of resources.

In the available literature, the terms 'food loss' and 'food waste' are often used synonymously, while some authors insist on a distinction[7]. Today, there is no common definition of the terms 'food loss' and 'food waste'[7]. According to the Food and Agriculture Organization of the United Nations (FAO), food loss is 'the result of decisions and actions by suppliers' and thus 'concerns all stages of the food supply chain up to, but excluding, the point where there is interaction with the final consumer and thus excludes retail, food service providers and consumers', while 'food waste' is the 'result of purchasing decisions by consumers, or decisions by retailers and food service providers that affect consumer behaviour'[8]. Hence, the distinction between 'food loss' and 'food waste' can be vital when setting political, social, or technological counter-measures.

In countries with higher amounts of food loss, mainly low-income countries, measures such as improving the infrastructure for storage and cooling of food as well as introducing optimized packaging may be of more importance than in countries with higher income, where such infrastructure already exists and higher quantities are wasted at the consumer level[9,10]. The FAO estimates that, globally, 13.8% of all the food produced in 2016 was lost, while there exists no recent global estimate for the amount that was wasted. Leastwise, the FAO estimated that in 2009, a combined quantity of food loss and waste (FLW) amounted to 1.3 billion tons or 30%[10]. As a result, this led to the emission of 3.3 gigatons of $CO_2$ equivalents. To put this into context, food waste would rank third after USA and China if it was compared to countries[11].

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## 1.2 Packaging functions

Packaging is one of the contributors to the total environmental impact of a food-packaging system[12]. It is a product to be used for the containment of goods[13], such as facilitating the transportation of liquids[14]. Packaging can be grouped into (i) primary packaging, which comes into direct contact with the product, (ii) secondary packaging, which contains one or more primary packaging units and (iii) distribution, transport or tertiary packaging, which contains one or more packages (packaging and its contents)[13]. Besides containment, packaging fulfils several additional functions, such as (i) protection, (ii) communication and (iii) convenience (or the facilitation of handling)[14,15].

### 1.2.1 Protection

Packaging must protect its contents along the supply chain, from the point of filling up until the consumption. It must not only protect its contents from their surroundings, but in some cases the surrounding from the contents as well (e.g. hazardous goods). The protective function can be grouped into

- Mechanical properties: Prevention against influences on the contents such as shocks or vibration, as well as preventing theft or tampering
- Barrier properties: Prevention against spoilage by absorption or transmission of UV light, oxygen or water vapor, as well as migration of undesired substances from the packaging material or the surroundings into its contents
- Thermal properties: Protecting the consumer from getting injured by hot contents or keeping the contents at a desired temperature
- Sealing properties: Providing a tightly sealed packaging in order to prevent leakage or contamination from its surroundings[15]

### 1.2.2 Communication

Packaging is responsible for communicating with consumers and further actors along the supply chain. The communication feature consists mainly on information and instructions of (i) the product, (ii) the packaging and (iii) the package:

- the product: weight, volume, ingredients, or shelf life
- the packaging: handling, opening and (re)closing, using, and handling

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- the package: sales price, origin and destination, and the name of the manufacturer

Information can be conveyed in the form of imprinted text, barcodes or QR codes on the packaging[15].

### 1.2.3 Convenience

Packaging can and should be used for facilitating the handling of the packaging and its contents. Such facilitation can be attained by incorporating design features to support easy opening and (re)closing or emptying of contents. Furthermore, by considering the apportionment into its design, i.e. using smaller package sizes[14], the user is more likely to consume all of the contents, thus reducing the amount of FLW[15].

## 1.3 Environmental impact of packaging and packaging waste

In the European Union (EU), the amount of packaging waste reached a record high of 77 million tons in 2017, which represents an increase of 9.3% in 10 years[16]. Packaging and packaging waste consists mainly of the materials paper and cardboard, plastic, glass, wood and metal[16], in the EU as well as in Austria (Table 1).

Table 1: Generated packaging waste in 2017 by material in the European Union (EU)[16] and Austria[17]

| Packaging material | Generated waste in 2017 in the EU (metric tons) | Share of material (%) | Generated waste in 2017 in Austria (metric tons) | Share of material (%) |
|---|---|---|---|---|
| **Paper and cardboard** | 31.429.879 | 40.6 | 575.620 | 41.8 |
| **Plastic** | 14.548.499 | 18.8 | 302.306 | 22.0 |
| **Glass** | 14.060.109 | 18.2 | 278.337 | 20.2 |
| **Wood** | 13.255.270 | 17.1 | 112.960 | 8.2 |
| **Metal** | 3.976.924 | 5.1 | 63.188 | 4.6 |
| **Other** | - | - | 44.594 | 3.2 |
| **Total** | 77.486.579 | 100 | 1.377.005 | 100 |

In 2017, the European Union reported a recycling rate of 67% and a recovery rate (recycling, composting and incineration with energy recovery) of 82%[16],

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compared to Austria with rates of 66% and 95% respectively[16]. There is, however, no official data on packaging waste not managed properly (i.e. 'littered'). Still, the World Bank estimates that one third of all waste produced globally is going to an open dump[18].

While the amount of packaging waste has increased, so has the criticism by the public, particularly on packaging made from plastic. In the eyes of consumers, using plastic is considered a 'knock-out criterion' when assessing the sustainability of packaging[19], while it is often identified as the one with the most favorable results in comparative life cycle assessments (LCA)[20]. It has to be noted, however, that LCA is not able to quantify the environmental impact caused by littering of certain objects, such as damage to human health by the consumption of seafood which ate plastic debris beforehand[21]. It is estimated that 4.8 to 12.7 million metric tons of plastic, and thus of plastic packaging as well, entering the oceans every year[22], which would lead to the fact that by 2050, there could be more plastic than fish in the sea (by mass)[23].

When talking about the environmental impact of packaging, it is imperative to understand the relative importance, i.e. its contribution to the impact of the total food-packaging system ('packaging relative environmental impact', PREI[24]). In most applications, plastic packaging, or packaging in general, has a considerably smaller environmental impact than is associated with the production of its contents[25]. To put this into perspective, packaging is responsible for only 5% of greenhouse gas emissions related to the global food supply chain[4], which translates to a contribution of 1.3% to the total greenhouse gas emissions globally. However, the relative environmental importance of packaging can vary greatly, depending on the type of food-packaging system. While the PREIs of plastic films and trays for products as cheese[26] or beef[27] can be as low as 1%, for beverages, values for aluminum cans, disposable glass or PET bottles can range from 34%[28] to 78%[29].

As a result, for products with low PREIs, even small quantities of packaging-related FLW (PFLW) could lead to greater environmental impacts than that associated with the production and disposal of the packaging material. Consequently, assessing and, in the best case, quantifying the amount of FLW related to packaging design should be of high priority in life cycle or sustainability assessments of packaging.

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# 2 Aims and structure of the thesis

As described in the introduction section, PFLW can contribute substantially to the total environmental impact of a food-packaging system. Therefore, the overall goal of this thesis is to quantify and include PFLW in sustainability assessments of packaging.

To address this goal, the following approach is taken:

Firstly, the available literature is reviewed to gain an extensive understanding of the relationship between packaging and FLW. Drivers and hotspots of FLW at different food supply chain stages are researched and already established methods for the quantification of PFLW are identified. This is addressed by the first paper (see section 'Full text: Paper I', p. 41ff)

Then, if no such methods are available, the gained knowledge is used to propose an operationalization for the quantification of PFLW. Consequently, the amount of food left in its associated packaging is measured, which is subsequently referred to as 'emptiability testing'. Taking dairy products as a use case, their PFLW is quantified by means of gravimetric analysis as well as the simulation of spooning out the contents. After quantifying PFLW, its environmental impacts are compared to those of the packaging itself to evaluate its relative importance. This is addressed by the second paper (see section 'Full text: Paper II', p. 57ff).

Next, the proposed method is refined and extended to a further use case of tomato ketchup products. Finally, PFLW of the investigated products is quantified, the LCA and LCC (life cycle costing) of the packaging, its contents and PFLW is calculated and lastly the most sustainable product identified by means of a multi-criteria decision analysis (MCDA). This is addressed by the third paper (see section 'Full text: Paper III', p. 80ff).

From the proposed approach, the following research questions can be derived:

i. What are the main drivers and issues of PFLW?
ii. How can PFLW be quantified?
iii. Are environmental impacts of PFLW relevant in comparative LCA studies of packaging?
iv. What are the economic implications of PFLW?

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v. Does the consideration of PFLW influence the ranking of packaging in sustainability assessments?

Paper I addresses research questions (i) and (ii), Paper II questions (ii) and (iii) and Paper III questions, (ii), (iii), (iv), and (v).

Concerning the structure of this thesis, first the methods used in the papers are described in section 3 (p. 7ff.), then the summary of the papers including their results are presented in section 4 (p. 12ff.). Section 5 of this thesis (p. 29ff.) lists the conclusions and scientific contribution. Finally, the full text of all papers is attached to the end of the thesis (p 41ff.).

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# 3 Methods

## 3.1 Life cycle assessment

Life cycle assessment is a 'method to address potential environmental aspects throughout a product's life cycle, from the acquisition of raw materials to its end-of-life treatment' ('cradle-to-grave')[30]. The first known LCA, then still referred to as 'Resource and Environmental Profile Analysis' (REPA), was conducted in 1969[31] for the Coca-Cola Company. The company commissioned this study to have a solid base for their decision on whether they should self-manufacture beverage cans, use refillable or disposable glass bottles or if they should introduce plastic bottles. While the study was never published, the company indicated to have used it to support packaging-related decisions. Since then, several REPA studies[31] were conducted until 1990 the term 'life cycle assessment' was first used by the Society of Environmental Toxicology and Chemistry (SETAC)[32]. Finally, the first international ISO standard on the principles and framework on LCA was released in 1997 and revised in 2006[30].

According to ISO 14040[30] (and 14044[33]), LCA consists of a (i) goal and scope definition, (ii) the creation of a life cycle inventory, (iii) the calculation of the impact assessment and (iv) an interpretation phase. LCA is an iterative technique, meaning that an unexpected change in one scope could lead to the modification of another.

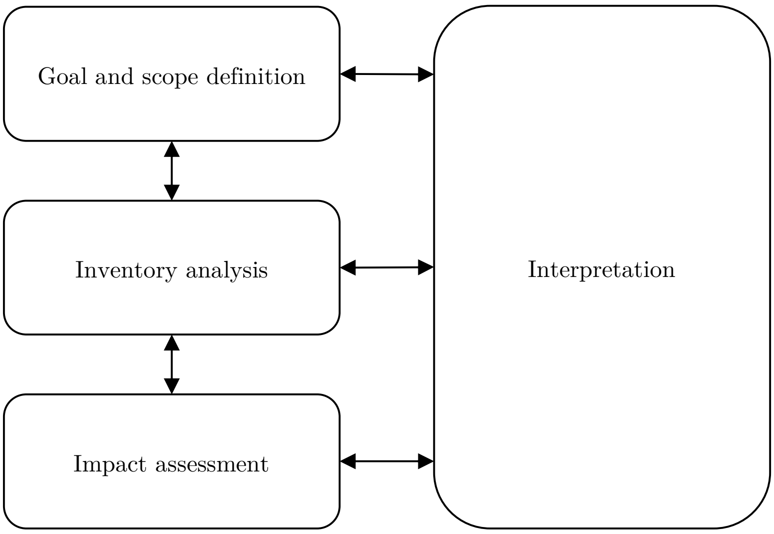


Figure 1: Four phases of a life cycle assessment (own representation, based on ISO 14040[30])

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In the first phase, the *goal* is formulated, including the reasons for carrying out the study, its intended application and the targeted audience, as well as the *scope*, consisting of, inter alia, the system boundaries, the functional unit, the selection of impact categories (e.g. climate change, eutrophication of fresh water, acidification, and more), and allocation procedures. The primary purpose of a functional unit is to 'provide a reference to which the inputs and outputs are related'[30]. For instance, if the goal of an LCA study is to understand the potential environmental impacts of different vehicles for public transport, the functional unit could be that of 'a person transported over 1 km'. In the case of beverage packaging, an appropriate functional unit could be either the 'facilitation of the distribution of 1 liter beverage' or 'the facilitation of the consumption of 1 liter beverage'. For instance, if a packaging leads to FLW of 50%, twice as much food has to be produced for the consumption of 1 kg compared to a loss rate of 0%[34]. Consequently, results of the LCA can vary greatly depending on the choice of functional unit.

In the second phase, all 'relevant inputs and outputs of a product system' are quantified by data collection, validation and, if required, an allocation of different flows, to finally generate a *life cycle inventory*[30].

In the third phase, the *impact assessment* is calculated by 'evaluating the significance of potential environmental impacts' after assigning the respective characterization of each flow for every selected impact category[30].

In the fourth and final phase, the findings from the life cycle inventory and impact assessment are *interpreted*, potentially including conclusions and recommendations for decision-makers[30]. Such conclusions should be drawn after the consideration of identified limitations of the study and thus the evaluation of the robustness of results due to a lack of data quality or sensitivity of certain assumptions[33].

While ISO 14040 and 14044 give guidance on how to conduct LCA studies in general, it still leaves practitioners a great deal of leeway. These standards never actually aimed for a true standardization, particularly by stating that ‚there is no single method for conducting LCA'[30,35]. However, reproducibility and comparability of LCA results is only possible using standardized methods. As a result, the European Commission developed the Product Environmental Footprint (PEF) guidance[36,37], a framework containing more detailed requirements and recommendations for conducting LCA or PEF studies. Consequently, Product Environmental Footprint Category Rules (PEFCR) for several types of products were developed based on the PEF guidance during a

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pilot phase between 2013 and 2018. In 2020, the European Commission proposed that future green claims should only be based on results produced by PEF-compliant studies[38], indicating that PEF could indeed become a mandatory and highly relevant framework for LCA in the future. As a result, life cycle assessments in this thesis were based on the methodology laid out in the PEF guidance.

In particular, the following information from the PEF guidance is used for the LCA calculations in Papers II and III:

- Defining the system boundaries
- Default transport mode and distances
- Default recycled content of packaging materials
- Default type and quantity of secondary packaging (for Paper II)
- Allocation procedures and factors for the input and output of secondary materials (‘Circular Footprint Formula’)
- Selection of impact categories, their indicators, and methods
- Identification of the most relevant impact categories

## 3.2 Life cycle costing

Historically, (*conventional*) life cycle costing (LCC) is seen as a method that ‘generally includes costs associated with a product that are borne directly by a given actor’ and which is ‘usually presented from the perspective of the producer or consumer alone’[39]. As a result, by contrast to LCA, no end-of-life and thus only part of a products’ life cycle is considered[39].

By contrast, *environmental LCC* is often carried out alongside an LCA by using the same study parameters such as system boundaries and the functional unit, thus enabling the consideration of the full life cycle and taking a system’s perspective rather than the perspective of the producer or consumer alone. Since double-counting between environmental LCC and LCA should be avoided, costs of externalities such as greenhouse gas emissions are generally omitted from LCC[39].

In this thesis, LCC was performed together with LCA. Further, the goal of the LCC was to consider its results from a sustainability and thus a system’s perspective. Therefore, environmental LCC, or more precisely the concept of ‘value added’ (VA), was selected for assessing the economic effects of PFLW.

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The general assumption of VA is that the sales price of a product is typically higher than its production process, resulting in a margin or 'value added'. VA is calculated as the difference between revenues and costs and given in a monetary unit such as Euro (€)[40]. Finally, the total life cycle cost is the 'sum of all value added over the life cycle'[41], including the same flows of the LCA but excluding costs associated with environmental externalities.

## 3.3 Multi-criteria decision analysis

As reported in section 3.1, not only climate change but several other impact categories can be selected and calculated in LCA, leading to a multitude of different results. In a comparative study, this could lead to a situation where product A yields better results in some, but product B in other impact categories, complicating the identification of the 'better' product. In LCA, this can be addressed by the steps (i) normalization ('calculation of the magnitude of category indicator results relative to reference information'[30]), (ii) weighting ('converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices'[33]) and, finally, (iii) the calculation of a single score by summing up all normalized and weighted values as documented in the PEF guidance[36]. However, while such an aggregated value may be easier to communicate to or to use by a decision-maker, it is associated with a higher uncertainty compared to individual impact category results[42]. The identification of the 'best' product is becomes even more complicated when further metrics other than LCA results are taken into consideration, such as LCC results. A method increasingly used to aid such multi-dimensional sustainability assessments is 'multi-criteria decision analysis' (MCDA)[43].

Within MCDA, there is a rich pool of methods to choose from, each with different restrictions or requirements[44]. For this thesis, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)[45] was selected by using the MCDA tool[46] considering the requirements on the method listed in Paper III. Using TOPSIS, the best possible alternative is identified as the one having the shortest geometric distance to the positive ideal solution and the longest distance from the negative ideal solution. The general process of performing TOPSIS can be summarized as follows:

1. Creation of an evaluation matrix of m alternatives and n criteria
2. Normalization of the matrix
3. Weighting of the normalized matrix

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4. Determination of the positive ideal and negative ideal solution
5. Calculation of the Euclidian distances
6. Calculation of the relative closeness value to the ideal solution
7. Ranking of the alternatives[45]

The process of weighting criteria can influence the outcome of a MCDA substantially. Weights can be determined either (i) a priori, meaning that they are set before or (ii) a posteriori, where they are set after data is collected. A priori weights are generally determined subjectively by surveys or interviews, while a posteriori weights are calculated objectively, based on the collected data[47]. In Paper III, a posteriori weights were used, calculated using the methods (i) Criteria Importance through Intercriteria Correlation (CRITIC)[48] and (ii) entropy[49]. While both methods are based on the concept of reducing redundancy by the calculation of standard deviations, CRITIC not only incorporates contrast but also conflict intensity between the selected criteria. The reader is referred to the full text of Paper III (p.80ff) for a detailed description of the calculation procedures concerning CRITIC, entropy and TOPSIS.

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# 4 Summary of published articles

## 4.1 Packaging-related food losses and waste. An overview of drivers and issues

### 4.1.1 Background, aim and methods

Against the motivation of gaining a deeper understanding of the drivers and associated environmental issues of packaging-related FLW, a systematic review was performed. First, literature was searched in the online database ScienceDirect[50] by using the keywords 'food waste' AND 'packaging', as well with the additional keyword 'LCA'. Moreover, the bibliography of the selected literature was screened for further relevant scientific literature and reports of renowned organizations (such as the FAO), to be also included in the review. Finally, 88 publications were analyzed.

### 4.1.2 Results and discussion

Main causes of PFLW reported in the literature were distilled and summarized in Table 2.

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Table 2: Overview of causes reported in literature for packaging-related food loss and waste along the food supply chain (based on Table 1, Paper I).

| Stage | | Type of packaging related food loss and waste |
|---|---|---|
| **Food in the supply chain** | Primary production | Not applicable |
| | Post-harvest handling and storage | Damage of products due to contaminants, sharp edges or splinters of field containers, over-packing of field crates |
| | Processing and packaging | Problems in the filling process<br>Packaging failures while sealing<br>Packaging changes due to marketing reasons |
| | Distribution and retail | Packaging does not provide enough mechanical protection (inappropriate packaging material, poor stackability, no packaging at all)<br>Damage to barcodes on packaging |
| **Food in households** | | Difficult to open packaging<br>Difficult to empty packaging<br>Inappropriate packaging size |

No PFLW could be identified for the primary production stage since no packaging is used or required during the agricultural production. Together with the introduction of packaging, the first possibility of PFLW arises. After harvesting, food can be damaged by field containers with sharp edges[51] or contaminations[52]. At the processing and packaging stage, products can be damaged or lost by damaged packaging[53,54]. Additionally, product can be lost in automatic filling processes by unoptimized operations resulting in overfilling[55], or bad handling in manual filling processes[51]. Due to changes in marketing and the resulting modification of packaging designs, products could be disposed of if they are already packed but not intended to be marketed anymore[56].

During distribution of food, PFLW can occur due to damaged packaging, or by damage to the product by using inappropriate packaging or no packaging at all[57], or by packaging that is stacked poorly[58]. Unoptimized stock management and an exceedance of best before dates[59] leads to further avoidable losses. Moreover, the retail sector may discard food if the barcode on packages is not readable after getting damaged[57]. Finally, if one or more of several food items of a packaging is spoiled, the supermarket may dispose of the whole package due to an unwillingness of removing still edible food from the packaging[60,61].

At the consumption stage, causes of PFLW are manifold as well and can reach up to 20 or 25% of the total FLW of a household[62]. For instance, if packaging

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cannot be opened easily, consumers may spill products in the opening process[15,63,64]. After emptying, some food can remain inside the packaging which may be, at least partly, due to an unoptimized packaging design, such as a presence of a fold or corrugations inside the packaging, as well as the shape of the packaging itself[62,65].

Moreover, the size of a package can be one of the main reasons of PFLW at the consumption stage. If smaller packages are available, it proves to be easier to the consumer to buy the desired amount of food[15,66–68]. While too large packages are often linked to over-preparing and thus the generation of FLW, a direct causality is hard to prove and thus should be treated with caution[69].

As stated in the introduction section, food production and thus PFLW can be of greater significance than the production and waste management of packaging. Thus, it should be of high priority to include PFLW in LCA studies of packaging. Still, most of the available literature omits this aspect[70]. By including PFLW, the identification of the packaging with the better LCA results could change (Figure 2).

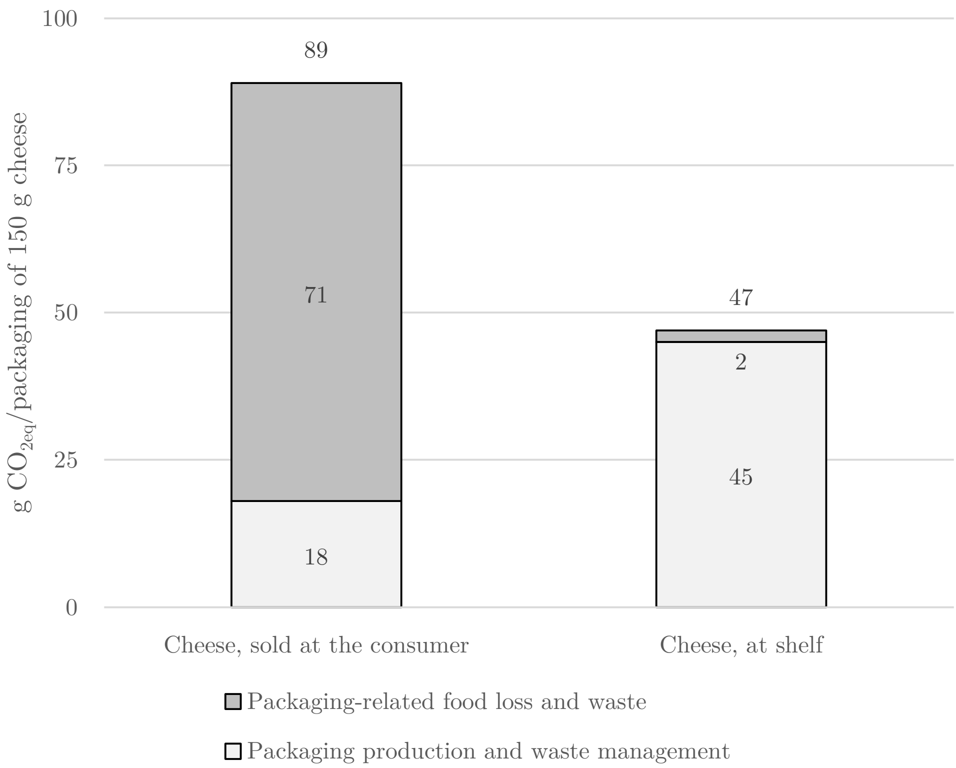


Figure 2: Carbon footprint of two packaging options for cheese, adapted from Figure 2 in Paper I and denkstatt (2014)[71]

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While the available literature on considering PFLW in LCA is scarce, several approaches for this process could be identified in publications, namely:

- Conducting a survey of a household's FLW including items of causes addressed at packaging design[62]
- Calculating break-even rates for environmental impacts between an increase of packaging and PFLW[72,73]
- Performing scenario analysis for probable amounts of PFLW based on expert opinion[74]
- Considering the barrier properties (e.g. water and oxygen barrier) of packaging when defining the functional unit in an LCA[75]
- Simulating the emptying behavior of a package ('emptiability') and quantifying the resulting food remaining inside[65]

It was concluded that PFLW is still an under-researched topic and that only a few, but fortunately an increasing number of authors include PFLW in LCA today.

## 4.2 Technical emptiability of dairy product packaging and its environmental implications in Austria

### 4.2.1 Background, aim and methods

Testing packages on their emptiability was identified as the most feasible approach for quantifying PFLW, concluding from Paper I. While some scientific literature on emptiability already exists[34,62,65], only Meurer et al. (2017) report their testing procedure in detail, where the authors performed gravimetric analysis on different types of packaging for ultra-high temperature (UHT) milk.

For Paper II, milk and dairy products were chosen as a case study since they are associated with high environmental impacts[76] and are consumed in large quantities in Austria[77]. In total, 36 products were purchased and tested, which were grouped as follows:

- Milk, buttermilk, and chocolate milk
- Café latte
- Cream and low-fat cream alternative
- Liquid yogurt

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- Yogurt, sour milk, fresh, and curd cheese

These products were packed in the following types of packaging:

- Beverage cartons
- Plastic (polyethylene terephthalate, PET) and glass bottles
- Plastic cups and tubs (polypropylene, PP and polystyrene, PS)
- Plastic pouches (multi-layer of high-density polyethylene, HDPE, PP, and ethylene vinyl alcohol, EVOH)

Since Meurer et al. (2017) only detail the testing procedure for UHT milk, adopting this methodology or rather developing new procedures for other types of products was necessary. For milk (whole milk, low-fat milk, lactose-free skimmed milk), buttermilk, and chocolate milk, the package was opened and then held upside down for 1 minute. brought to the starting position, panned five times, and held for 10 seconds, tilted again and finally held for 1 minute upside down. Chocolate milk in a beverage carton was emptied by pressing the package while the provided straw was inserted. Emptying Café Latte and liquid yoghurt was performed following the procedure for milk, with an additional shaking of five times before opening the package. Emptying cream and low-fat cream alternative in bottles followed the procedure of milk, while the low-fat cream alternative in a pouch was squeezed until no visible amounts of product could be emptied anymore.

Emptiability testing of yogurt, sour milk, fresh, and curd cheese differed greatly from the other products since the contents inside these packages could be accessed and thus emptied with a spoon with an additional scraping of the lid. It should be noted that a perfect consumer was simulated by this procedure, not necessarily reflecting the emptying behavior of consumers in practice. Thus, this type of emptiability is subsequently referred to as ‘technical’ emptiability.

The principal steps of quantification were:

1. Weighing of the package (food and packaging)
2. Following the emptying procedure of the respective product and weighing of the emptied package
3. Washing and air-drying the packaging for 48 hours at room temperature (22 ± 1 C°)
4. Weighing of the cleaned packaging

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Emptiability was then calculated as the mass of food residues (difference between mass of emptied package and cleaned packaging), divided by the mass of food contained originally in the package (difference between mass of package and cleaned packaging). Tests were repeated three times at room (22 ± 1 C°) and refrigerator temperature (7 ± 1 C°) respectively. Finally, the emptiability index (EMPT) was expressed as the arithmetic mean of the respective temperatures ($EMPT_{22°C}$ and $EMPT_{7°C}$), as well as a combined result ($EMPT_{22°C, 7°C}$). Variability was given as the product of the respective standard deviation and 3.26 for $EMPT_{22°C}$ and $EMPT_{7°C}$ and 1.44 for $EMPT_{22°C, 7°C}$, which follows from a desired statistical power of 0.80 and a confidence interval of 95%.

After the emptying procedure, all packaging components were weighed, and their material was determined by means of Fourier-transform infrared spectroscopy. Streamlined life cycle assessments were then carried out for every dairy product-packaging combination, omitting primary data collection, but using Ecoinvent 3.5 as a source of life cycle data. The PEF guidance[36] was followed in respect to allocation rules, selection of impact categories and their respective methods and indicators, as well as several types of default data such as transport distances, quantity and type of secondary packaging, as well as recycled content of primary packaging. The functional unit was defined as "one kg of consumed dairy product at room or refrigerator temperature in the home of the consumer" with system boundaries specified from cradle to grave, leading to an investigated foreground system starting at the agricultural production and ending at the end-of-life of the package (Figure 3).

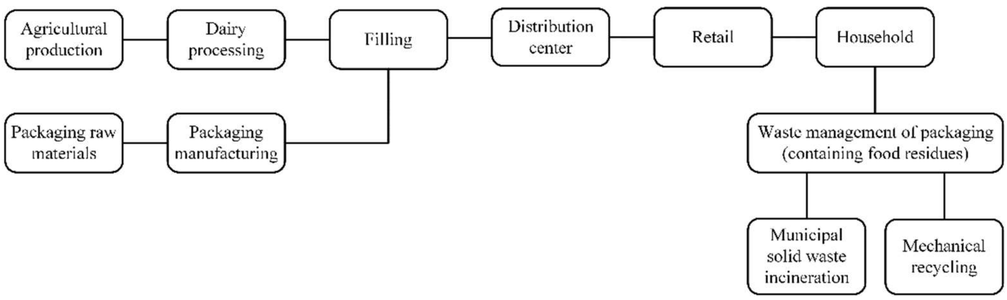


Figure 3: System boundaries of the foreground system, taken from Figure 1 in Paper II

To understand the influence of emptiability on the LCA, the difference between a functional unit of '1 kg consumed food' and '1kg distributed food' was calculated and expressed in relation to the impacts associated with the production and waste management of primary packaging for every impact category.

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### 4.2.2 Results and discussion

$EMPT_{22°C,\ 7°C}$ values of the investigated products ranged from 0.25% (± 0.11) for curd cheese in PS tubs to 5.79% (± 0.43) for liquid yogurt in PET bottles (Figure 4). In general, emptiability of dairy products in accessible packaging was better than in non-accessible packaging (Figure 5). From both figures, a high variability of EMPT is apparent for several types of products or packaging, while products investigated packed only in one type of packaging yield a lower variability in general, such as buttermilk. It can be concluded that EMPT is not only a function of packaging design or properties of food (such as viscosity) alone, but rather their interaction. It is further apparent that food with high viscosity (such as liquid yogurt) yields a comparatively poor emptiability if the associated packaging cannot be accessed.

While several investigated products were packed in different types of packaging, only low-fat cream alternative was identified as being the exact same product available in two types of packaging. For this product, $EMPT_{22°C,\ 7°C}$ was determined at 3.85% (± 0.08) for PET bottles, while emptiability was significantly better in a pouch (1.10% ± 0.55), resulting from the ability to squeeze the pouch efficiently compared to the non-accessible bottle. While there were differences between $EMPT_{22°C}$ and $EMPT_{7°C}$, no significant trend could be found ($p=0.94$).

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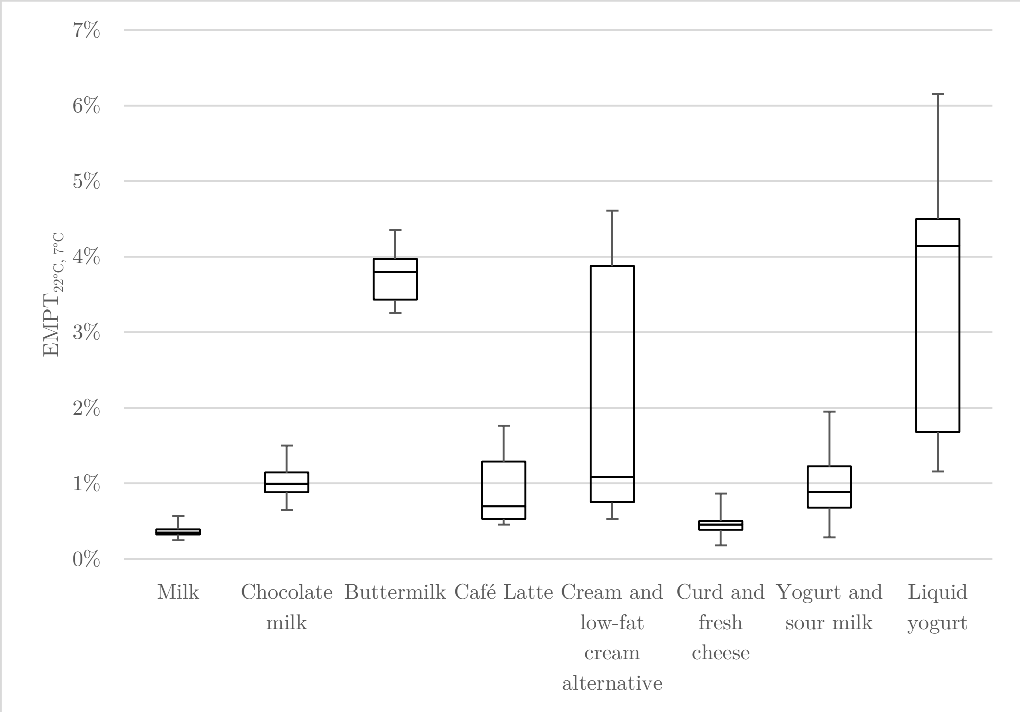


Figure 4: Emptiability results, grouped by types of dairy products (adapted from Figure 9 in Paper II)

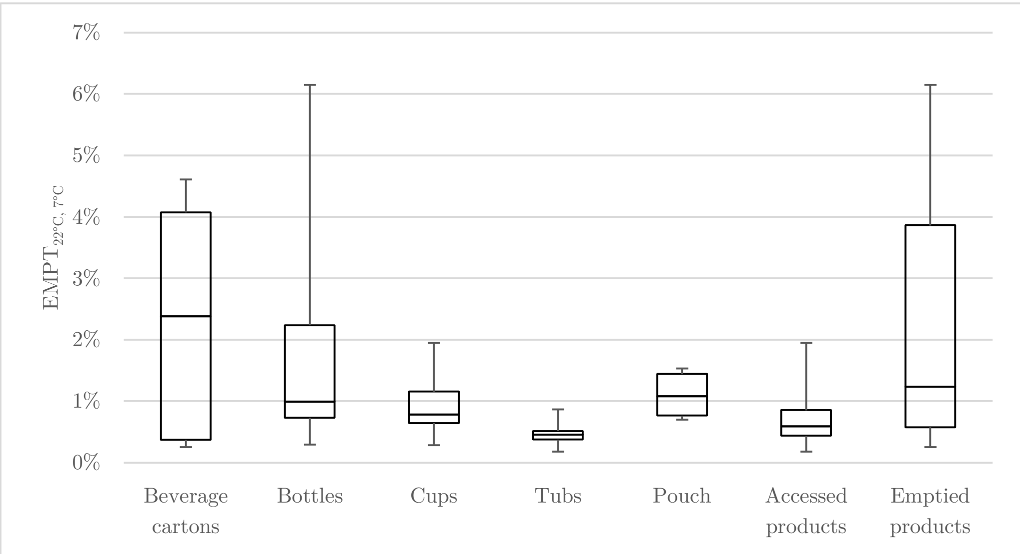


Figure 5: Emptiability results, grouped by types of packaging for dairy products (adapted from Figure 8 in Paper II)

Concerning the LCA results, the contribution of primary packaging ranged from 1.6% to 52.4% (mean 12.8%) for climate change. Naturally, after including emptiability in the LCA calculation, overall results increased. The associated implications varied greatly for every selected impact category, partly topping

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1000% for categories such as acidification (AC) and terrestrial eutrophication for some products such as cream (TEU) (Table 3).

Table 3: Percentage increase of selected products (product with the five highest and lowest increases in climate change) for primary packaging after including EMPT22°C, 7°C (adapted from Table 4 in Paper II). Abbreviations for impact categories are: AC, Acidification; PM, Particulate matter; CC, Climate change; TEU, Terrestrial eutrophication; FEU, Freshwater eutrophication; FRD, Fossil resource depletion

| **Dairy product** | **AC** | **RE** | **CC** | **TEU** | **FEU** | **FRD** |
|---|---|---|---|---|---|---|
| **Cream, 23% fat \| Beverage carton, flat top** | 1045 ± 81 | 426 ± 33 | 264 ± 20 | 1827 ± 141 | 208 ± 16 | 72 ± 6 |
| **Liquid yogurt \| Beverage carton, bottle top** | 390 ± 19 | 170 ± 8 | 87 ± 4 | 700 ± 33 | 121 ± 6 | 35 ± 2 |
| **Liquid yogurt \| Beverage carton, gable top** | 318 ± 28 | 134 ± 12 | 87 ± 8 | 555 ± 50 | 99 ± 9 | 34 ± 3 |
| **Buttermilk \| Beverage carton, bottle top, variant a** | 279 ± 31 | 125 ± 14 | 51 ± 6 | 512 ± 56 | 66 ± 7 | 19 ± 2 |
| **Buttermilk \| Beverage carton, bottle top, variant b** | 272 ± 27 | 121 ± 12 | 50 ± 5 | 498 ± 50 | 65 ± 6 | 19 ± 2 |
| **Yogurt, cereals \| PS cup** | 39 ± 3 | 31 ± 2 | 4 ± 0 | 103 ± 7 | 52 ± 4 | 2 ± 0 |
| **Sour milk \| PS cup** | 36 ± 7 | 27 ± 5 | 4 ± 1 | 91 ± 17 | 22 ± 4 | 3 ± 1 |
| **Cafe Latté \| PET bottle** | 22 ± 3 | 18 ± 3 | 3 ± 0 | 50 ± 7 | 3 ± 0 | 1 ± 0 |
| **Curd cheese, crumbly \| PS tub** | 25 ± 11 | 18 ± 8 | 3 ± 1 | 63 ± 28 | 10 ± 4 | 2 ± 1 |
| **Whole milk \| Glass bottle** | 5 ± 0 | 3 ± 0 | 1 ± 0 | 11 ± 1 | 1 ± 0 | 1 ± 0 |

Concerning climate change, the increases ranged from 1% for whole milk in glass packaging to 264% for cream (fat content of 23%) in a beverage carton. Thus, for cream in beverage cartons, technical emptiability was of even more importance than the production and waste management of its packaging. This was a result of the high environmental impacts associated with the production of this type of food, as well as the low impacts generated by beverage cartons

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compared to other types of packaging. This highlights the relevance of including EMPT when conducting comparative LCA studies of packaging.

## 4.3 Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup

### 4.3.1 Background, aim, and methods

An important conclusion from Paper II was the fact that packaging should be tested on its emptiability in comparative LCA studies. To support this even further, tomato ketchup was investigated in Paper III.

From Paper II it became apparent that if PFLW is included in studies of different packaging for a specific product category (e.g. tomato ketchup), but which does not contain the exact same product (i.e. hot tomato ketchup by company A), then packaging should not be compared without considering its contents as well. This is necessary since (i) viscosity of the products and thus their emptiability, as well as their (ii) composition and thus the environmental impact associated with its production could differ greatly from one another. Consequently, in Paper III the scope was not only on packaging but rather the entire food-packaging system, for which four different tomato ketchup products were examined (Figure 6).

The aim was to identify the most sustainable product by:

1. Testing emptiability
2. Conducting LCA and LCC including emptiability results
3. Assessing the total sustainability considering LCA and LCC results by means of MCDA (TOPSIS)

The functional unit was chosen as 3.8 kg consumed ketchup, the average consumption per capita in Austria in 2018[78]. Analogous to Paper II, the LCA was conducted without collection of primary data but was based on weighing and identifying the packaging material after testing for emptiability. Ecoinvent 3.5 was used as LCI database and the PEF guidance was followed for the selection of impact categories, allocation factors and procedures, as well as for default transport distances. The difference in conventional and organic agriculture of tomatoes could not be considered due to missing information in Ecoinvent. While organic tomatoes may have lower[79] or higher[80] yields, their

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LCA results can be higher[81,82] or lower as well. Still, organic agriculture is associated with several environmental benefits such as greater biodiversity and fewer negative effects on human health[83]. Thus, organic agriculture was considered as beneficial in TOPSIS as well and quantified as '1', compared to '0' for products of conventional agriculture. Weights for TOPSIS were determined by (i) equal weighting, as well as by means of (ii) Criteria Importance through Intercriteria Correlation (CRITIC) and (iii) Shannon's entropy.

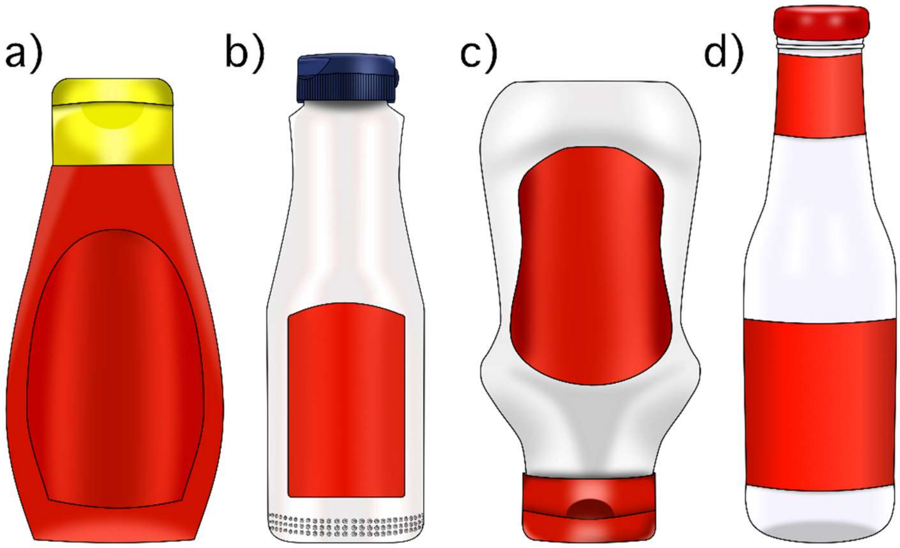


Figure 6: Ketchup products chosen as illustrative examples. a) Conventional ketchup, produced in Austria, 450 g indicated filling quantity, 29.99 g colored polypropylene (PP) bottle with 10.81 g colored PP cap, 0.28 g multilayer seal (assuming a composition of 52% polyethylene, 25% polyethylene terephthalate, 17% adhesive and 6% aluminum) and 0.97 g PP labels. 172 g tomatoes per 100 g ketchup. Sales price: 1.99 € (PP-450-CONV).
b) Organic ketchup, produced in Austria, 380 g indicated filling quantity, 22.30 g clear transparent PP bottle with 4.36 g colored PP cap, 0.29 g multilayer seal and 0.63 g PP labels. Sales price: 2.99€ (PP-380-ORG).
c) Organic ketchup, produced in the Czech Republic, 550 g indicated filling quantity, 30.96 g clear transparent PP bottle with 9.79 g colored PP cap, 0.32 g multilayer seal and 1.27 g paper labels. 210 g tomatoes per 100 g ketchup. Sales price: 1.99 € (PP-550-ORG).
d) Organic ketchup, produced in Italy, 480 g indicated filling quantity, 236.61 g flint packaging glass with 4.88 g tinplate screw cap and 1.29 g paper labels. 225 g tomatoes per 100 g ketchup. Sales price: 1.45 € (GL-480-ORG). Figure taken from Paper III.

For the selected products, not only technical but also practical emptiability was tested. The general calculation steps followed the methodology presented in Paper II. For simulating practical emptiability in plastic packaging, the bottles were shaken three times and then squeezed until air was released. Next, the bottles were swiveled and squeezed again until air was released. This process was repeated three times. By contrast, for products in glass packaging, the

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bottles were shaken three times, held upside down for 2 minutes, then shaken again three times and held upside down again for 1 minute. Additionally, technical emptiability was tested by scraping the bottles and their respective caps using a dedicated ketchup spoon with a length of 24.5 cm.

All tests were performed at room temperature (22°C ± 1) with a sample size of 6. The final indices for both practical and technical emptiability were expressed as arithmetic average ± confidence interval 95%. The results were analyzed by one-way ANOVA (Fisher's with Tukey post hoc test for samples with equality of variances and Welch's with Games-Howell post hoc test for samples without equality of variances).

### 4.3.2 Results and discussion

Practical emptiability (Figure 7) ranged from 13.12% (±2.05) to 28.80% (±3.30) for PP bottles, while the product in glass packaging performed significantly better at 3.85% (±0.41). These results are comparable to other studies reporting 0.5% to 26% in PP bottles[84] and 30% to 52% in PET bottles[85].

Nonetheless, emptiability of PP bottles can be significantly improved by using a spoon, resulting in technical emptiability indices of between 5.12% (±0.40) and 7.08% (±0.61). Since results of technical emptiability did not differ significantly, only practical emptiability was included in the subsequent TOPSIS analysis.

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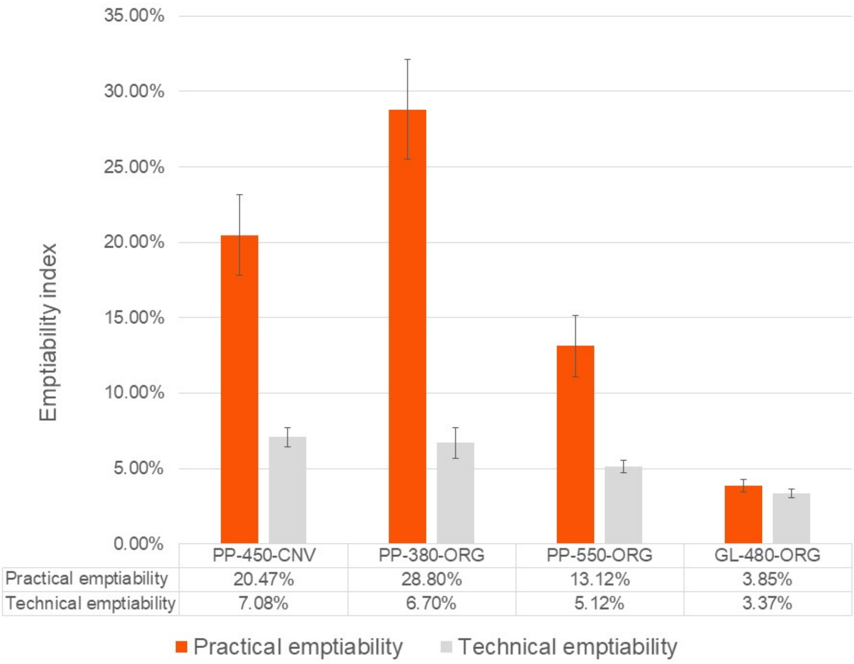


Figure 7: Emptiability results of examined products. Bars represent the mean, while error bars represent 95% confidence intervals. Abbreviations represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture. Figure taken from Paper III.

The product with the poorest emptiability (PP-380-ORG) was also the one with the highest tomato content. Since the viscosity of ketchup increases with its tomato content[86], this could be one of the reasons for this outcome.

PP-380-ORG could be identified as the product with the greatest environmental impact across all relevant impact categories (Figure 8). This was again a result of its poor emptiability, stemming from its high tomato content, naturally leading to a higher amount of tomatoes and energy demand in the manufacturing process. Consequently, for PP-380-ORG, FLW due to poor emptiability leads to even greater environmental impacts than its packaging. By contrast, the glass packaging of GL-480-ORG) yielded worse LCA results but can be considered better considering its good comparably good emptiability.

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Figure 8: LCA results of tomato ketchup products per functional unit. Figure taken from Paper III.

Concerning the results of LCC, or VA to be more precise, a very similar picture was presented (Figure 9). However, while for LCA results lower values are preferable, for VA a higher result and thus a greater contribution to the economy is desirable.

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Figure 9: VA results of ketchup products in Euro per functional unit. Figure taken from Paper III

Unsurprisingly, a higher FLW rate leads to an increase in profit along the supply chain. The more ketchup is wasted due to poor emptiability, the more the ketchup manufacturer can sell, which then also increases the profits of the respective suppliers of packaging or ingredients. Ultimately, the product with the poorest emptiability led to the best VA result. Conversely, looking only at the costs to the consumer, the product with the best emptiability (GL-480-ORG) would be the most beneficial.

After testing for emptiability and calculating the LCA and LCC, weights for the use in TOPSIS were determined by equal weighting, as well as CRITIC and Entropy (Table 4).

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Table 4: Weights of criteria, calculated using equal weighting (Equal), CRITIC and entropy. Abbreviations for criteria represent: CC (climate change), FRD (fossil resource depletion), WU (water use), FEU (eutrophication, freshwater), AC (acidification), PM (particulate matter), and VA (value added). Table adapted from Table 4 in Paper III.

| Category | Criteria | Equal (%) | CRITIC (%) | Entropy (%) |
|---|---|---|---|---|
| **Life cycle assessment** | CC | 12.5 | 6.8 | 14.4 |
| | FRD | 12.5 | 7.5 | 13.9 |
| | WU | 12.5 | 8.4 | 17.3 |
| | FEU | 12.5 | 6.8 | 14.3 |
| | AC | 12.5 | 8.0 | 14.2 |
| | PM | 12.5 | 15.2 | 13.3 |
| **Organic agriculture** | Yes/no | 12.5 | 32.2 | 7.5 |
| **Economic assessment** | VA | 12.5 | 15.2 | 5.1 |

The determined weights differed greatly between each set. Concerning CRITIC, organic agriculture was assigned 32.2%, but only 7.5% using entropy. In contrast, entropy assigned more weight to the LCA and less to LCC results.

After creating the decision matrix and following the TOPSIS procedure (as detailed in the full text of Paper III), final closeness values for all products were calculated with the best being the one closest to 1 (Figure 10).

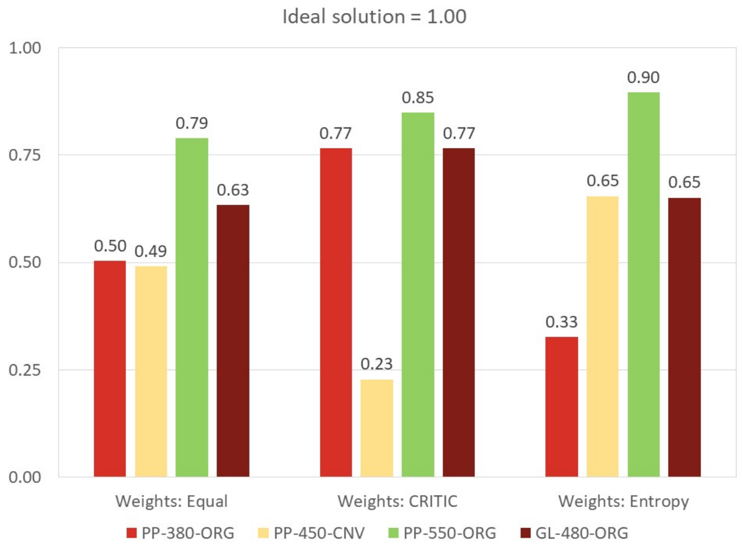


Figure 10: TOPSIS results (relative closeness values) of ketchup products. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

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Closeness values varied widely, resulting from the different computed emphasis. Nonetheless, PP-550-ORG was identified as the best and GL-480-ORG the second-best possible solution across all three weighting sets. The most striking differences were for PP-380-ORG and PP-450-CNV, following from the varying importance of organic agriculture.

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# 5 Conclusions and outlook

This thesis evaluated methods for the operationalization of packaging-related food loss and waste, its integration in life cycle and life cycle cost assessments and the proposal of a combined sustainability assessment using multi-criteria decision analysis. The following is a summary of the results of Papers I, II and III, in response to the research questions raised in section 2 (p. 5f)

## 5.1 Conclusions

### (i) What are the main drivers and issues of PFLW?

Packaging-related food loss and waste can occur at every stage of the food supply chain, beginning at the post-harvest and handling stage and ending with emptying the package. In general, food can be lost or wasted by either (i) the omission of packaging itself, (ii) the use of inappropriate packaging (e.g. under-packing or insufficient barrier properties) or by (iii) unoptimized packaging design (difficult to open or empty, no reclosability, too large package).

Since the production of food and thus its wastage is associated with a substantial consumption of resources and generation of emissions, the quantification of PFLW is highly relevant. However, it is still an under-researched issue and just not considered in the majority of LCA studies on food[70]. In total, 30% of all food produced is lost or wasted globally[10]. In relation to a households total FLW, packaging can be responsible for 20% to 25%[62].

### (ii) How can the quantification of PFLW be operationalized?

In the available literature, the following approaches for the quantification of PFLW could be identified:

- Surveying a household's FLW[62]

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- Simulating the emptying behavior of a package ('emptiability') and quantifying the resulting food remaining inside[65]

Testing packages on their emptiability was considered as most viable within the scope of this thesis. New approaches for its operationalization were proposed in Papers II and III.

In Paper II, 36 different dairy products and in Paper III, four different tomato ketchup products were examined. The resulting emptiability indices (ratio of food left in a package compared to original quantity) can be grouped and summarized as follows (Table 5):

Table 5: Summary of emptiability indices (arithmetic average) of examined products

| **Product category** | **Product** | **Technical emptiability (%)** | **Practical emptiability (%)** |
|---|---|---|---|
| **Dairy product** | Buttermilk | 3.36 – 3.97 | - |
| | Cream | 0.66 – 4.18 | - |
| | Curd cheese | 0.25 – 0.67 | - |
| | Fresh cheese | 0.40 – 0.48 | - |
| | Liquid yogurt | 1.43 – 5.79 | - |
| | Low-fat cream alternative | 1.10 – 3.85 | - |
| | Sour milk | 0.43 – 0.45 | - |
| | Yogurt | 0.68 – 1.72 | - |
| | Café Latté | 0.53 – 1.25 | - |
| | Chocolate milk | 0.80 – 1.26 | - |
| | Milk | 0.31 – 0.45 | - |
| **Condiment** | Tomato ketchup | 3.37 – 7.08 | 3.85 – 28.80 |

It is apparent that emptiability of tomato ketchup is substantially worse than that of dairy products. In summary, emptiability should be tested for (i) products with high viscosity and/or which are resource-intensive and (ii) packaging that is not accessible.

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### (iii) Are environmental impacts of PFLW relevant in comparative LCA studies of packaging?

Papers II and III highlight the importance of including PFLW, or emptiability to be more precise, in comparative LCA studies of packaging. Concerning climate change, emptiability of cream in a beverage carton leads to greenhouse gas emissions 2.64 greater than those of its primary packaging. PFLW is also highly relevant for buttermilk and liquid yogurt in beverage cartons, as well as for tomato ketchup in PP bottles. In other impact categories, particularly acidification and terrestrial eutrophication, emptiability can exceed 10 orders of magnitude compared to the impacts of packaging.

### (iv) What are the economic implications of PFLW?

In Paper III, poor emptiability of ketchup results in financial losses of 0.4 to 12.2 € per year for a consumer, depending on the type of product. However, the economic implications were calculated and considered from a system's perspective, showing that PFLW generates profits for all other actors along the food supply chain. Overall, poor emptiability leads to a greater contribution to the economy. This highlights the research need for environmental LCC methods depicting actual economic sustainability such as business diversity or long-term investments[87].

### (v) Does the consideration of PFLW influence the ranking of packaging in sustainability assessments?

Paper II and III highlighted that emptiability can have a substantial contribution to LCA and LCC results. In Paper III, the inclusion of emptiability altered the ranking of the products in both LCA, LCC and the final TOPSIS results, further supporting the claim of this thesis that PFLW can be highly relevant in comparative studies of packaging.

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## 5.2 Scientific contribution and outlook

This thesis showed that the quantification of PFLW is feasible by testing products on their emptiability. In some cases, emptiability-related FLW can even lead to greater environmental impacts than the production and waste management of the associated packaging. This is particularly true for resource-intensive food products (e.g. dairy products with high milk content such as cream) and resource-extensive packaging (such as beverage cartons). However, this approach is not without limitations, since the emptying procedure simulated in a laboratory setting could differ greatly from that in practice.

The present thesis contributes to the scientific discussion by operationalizing emptiability testing, as well as by comparing different packaging types combining life cycle assessments and life cycle costing with multi-criteria decision analysis. It highlights the importance of considering the entire food-packaging system, compared to only packaging itself. In the future, further research should focus on developing methods for collecting or estimating PFLW data at other supply chain stages, more particular while products are transported or stored between the manufacturer and the retail sector. Moreover, future comparative assessments considering PFLW could further include social aspects of sustainability, e.g. by using social life cycle assessments.

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# 7 Full text: Paper I

Wohner B, Pauer E, Heinrich V, Tacker M. Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues. *Sustainability* 2019; **11**(1).

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*Review*

# Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues

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**Abstract:** Packaging is often criticized as a symbol of today's throwaway society, as it is mostly made of plastic, which is in itself quite controversial, and is usually used only once. However, as packaging's main function is to protect its content and 30% of all food produced worldwide is lost or wasted along the supply chain, optimized packaging may be one of the solutions to reduce this staggering amount. Developing countries struggle with losses in the supply chain before food reaches the consumer. Here, appropriate packaging may help to protect food and prolong its shelf life so that it safely reaches these households. In developed countries, food tends to be wasted rather at the household's level due to wasteful behavior. There, packaging may be one of the drivers due to inappropriate packaging sizes and packaging that is difficult to empty. When discussing the sustainability of packaging, its protective function is often neglected and only revolves around the type and amount of material used for production. In this review, drivers, issues, and implications of packaging-related food losses and waste (FLW) are discussed, as well as the implication for the implementation in life cycle assessments (LCA).

**Keywords:** Packaging; food waste; food loss; sustainability; LCA

## 1. Introduction

Food production is associated with a significant consumption of resources. Today, approximately 30% of the earth's land and 70% of all extracted freshwater is used for growing crops. Additionally, the production and usage of pesticides and fertilizers can pollute air, water, and soil, and hence, poses a risk for human health and ecosystems as a whole [1]. Even worse is if this resource consumption is in vain when food misses its ultimate goal of human consumption and is lost or wasted instead.

According to the Food and Agriculture Organization of the United Nations (FAO), around 1.3 billion metric tons or approximately one-third of all food produced for humans is wasted worldwide each year [2]. In total, around 3.3 billion metric tons of $CO_2$ equivalent, 250 km$^3$ of blue water, and 1.4 billion hectares, which represents approximately one third of the world's agricultural area, is associated with not-consumed and, therefore, wasted food [3]. Further, other estimates point out that the amount of the world's food waste could be as high as 44% of the dry mass of agricultural crops [4]. In addition to environmental impacts, food waste also includes a social or ethical dimension, since 795 million or around 11% of the world's population suffer from hunger [5]. With the world's population projected to reach 10 billion people in 2050 [6], there is already a great deal of pressure on food availability and thus the urgency to reduce food waste.

At the international level, concern about food waste has been addressed by passing the Sustainable Development Goals (SDG). Goal 12.3 reads as follows: 'By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains,



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including post-harvest losses' [7]. With the amendment to the European Union (EU) Waste Directive adopted in 2018, which adopts the wording of SDG 12.3, this will indeed be legally binding for EU member states [8].

When referring to food waste, one has to highlight that there is currently no standardized definition of this term [9]. Frequently, a distinction is made between food waste and food loss, as well as between waste, which is edible or inedible, avoidable or (partially) unavoidable. For example, Parfitt et al. (2010) refer to 'food loss' as a 'decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption' and that it occurs at the stages before reaching the customer [10]. Here, and in FAO reports [2,3], losses at the end of the food chain are called 'food waste' and rather relate to human behavior, while in the reports of the British 'Waste Resources and Action Programme' (WRAP) [11] and in the *EU Food Use for Socian Innovation by Optmising Waste Prevention Strategies* (FUSIONS) project [12], there is no distinction made between 'food waste' and 'food loss'. Some authors do not declare food that was initially intended for human consumption, but then was fed to animals as waste [13]. However, some losses at the primary production, as well as at the post-harvest and handling stages, can also be seen as wasteful [14]. Furthermore, losses at one stage of the food supply chain could be caused in different stages [15,16]. Against this background, the present study uses the expression food loss and waste (FLW) to avoid confusion due to differing definitions.

A comparison of different regions shows that the stages of FLW hotspots along the supply chain vary strongly [2]. Apparently, in industrialized regions, such as Europe and North America, the amount of wasted food at the consumption stage is significantly higher than in developing regions, such as sub-Saharan Africa, South and Southeast Asia, and Latin America, where food is more likely to be lost or wasted at the stages between primary production and retail [2]. The FAO states that 'losses at almost every stage of the food chain may be reduced by using appropriate packaging' and that the higher losses at pre- and post-harvest stages in developing countries are 'underscoring the need to focus on packaging solutions' [17].

The present paper addresses the question about the direct and indirect effects of packaging in terms of the contribution to FLW across the supply chain. There has been relatively little research on whether more, less, or different types of packaging cause FLW in relation to the available literature on FLW. Furthermore, new approaches to the integration of these effects into life cycle assessments (LCA) are discussed. For this review, literature searches were performed in the online database, ScienceDirect. The keywords for the search were 'food waste' as well as the two keywords, 'food waste' and 'packaging', combined with the inclusion of the search operator, 'AND'. The search for literature about the integration of FLW into the LCA of packaging was performed with the additional keyword, 'LCA'. For the literature selection, peer-reviewed research articles were preferred. However, reports of highly renowned organizations (e.g., FAO, WRAP) were also included. In total, 88 references were identified as suitable for this review and 17 additional references, which were necessary for laying the framework of this review.

## 2. Functions and Sustainability Aspects of Packaging

The main functions of packaging are to contain, to protect, to facilitate handling, and to communicate information (Figure 1) [18,19]. The protective function includes FLW-related features, such as mechanical protection, barrier (e.g., against oxygen or water vapor), and thermal and sealing properties. The 'facilitate handling' function includes features, such as unitization, apportionment, resealability, and emptying. FLW-related features of the communication function consist mostly of product and packaging information and instructions, as in how to properly store, open, and dispose of the package [18]. Additionally, packaging can contain instructions on how to prolong the shelf life of the packaged food by encouraging consumers to freeze leftovers [20]. Furthermore, the communication function is responsible for the fulfillment of legal obligations, such as the provision of nutritional information, best before/use by dates, and ingredients [21].

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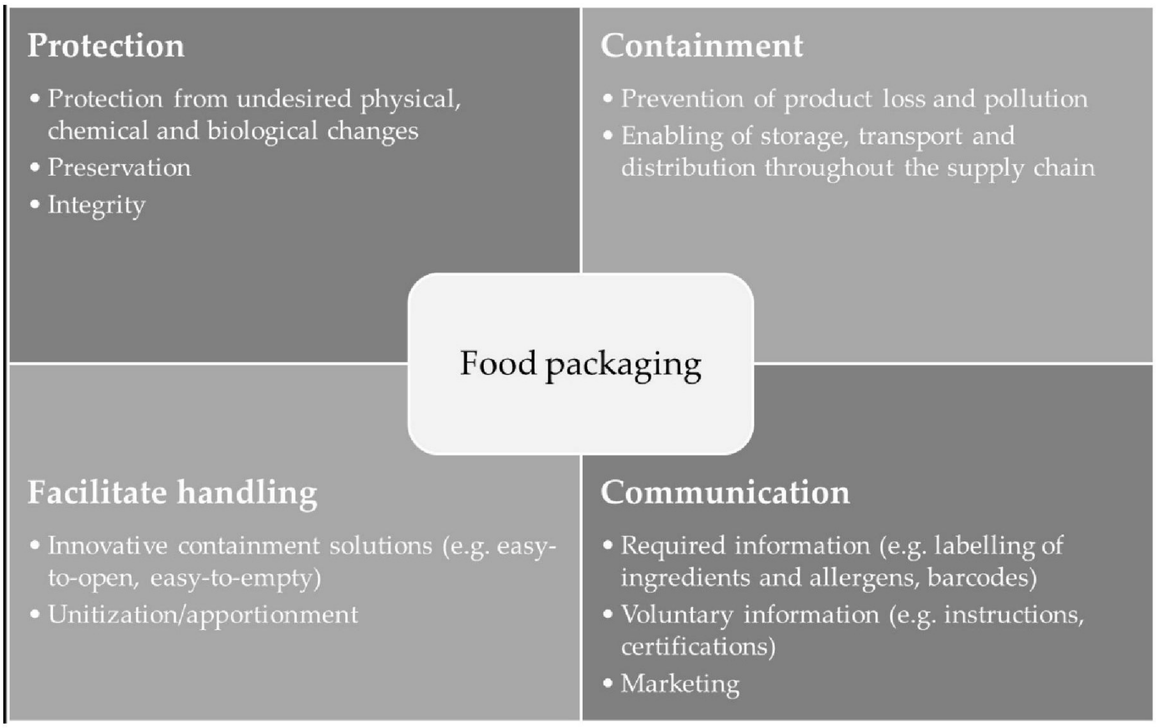


**Figure 1.** Packaging functions, based on [18,19].

However, while optimizing the protective function of a package, it is very important to pay particular attention to the needs and attitudes of consumers. As a survey in Norway shows, consumers with high amounts of food waste tend to be less environmentally aware with regard to packaging solutions (i.e., recyclability, material perceived as eco-friendly) than 'no-wasters', but show a higher willingness to pay more for packaging that helps to keep food fresh than no-wasters. One possible reason may be that high-wasting consumers buy bread more frequently, as well as more bread per shopping trip [22].

In a report by the American Institute for Packaging and the Environment (AMERIPEN), the authors emphasize the protective function and refer to packaging as an 'under-utilized solution that could significantly reduce food waste' [23]. One of the arguments is derived from a negative correlation between the proportion of packaged goods and the observed FLW. However, there is a growing public discourse about the environmental impact of using increased amounts of packaging and its actual contribution to sustainability. Globally, 348 million metric tons of plastic are produced each year [24], which gives rise to about 400 million tons of $CO_2$, including waste management [25]. In Europe, 39.7% of the plastic is used for packaging. However, only 40.8% of this plastic packaging is also recycled [24]. Every year, 4.8–12.7 metric tons of plastic waste enters the ocean, including plastic packaging [26]. In a business-as-usual scenario, by 2050, there could be more plastic than fish in the sea [25]. Another criticism of plastic packaging concerns impacts on human health. Particularly, some additives, such as bisphenol A or phthalates, are recognized as having endocrine effects [27,28].

Several environmental non-governmental organizations (NGOs) take an opposing position to the packaging industry in their report, 'Unwrapped' [29], which states that since 2005, the amount of food waste in European households has increased along with the amount of plastic packaging used. From this correlation, the authors of the study deduce that 'while some packaging has a role to play in protecting food and extending shelf life, many packaging practices increase wastefulness of both food and packaging'. Although the conclusions of both the AMERIPEN and the Unwrapped report are based on correlations and not on actual or implicit causalities, they hint at the importance of having a deeper look at the interrelation between food waste and packaging.

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However, consumers identify a food product's sustainability more with minimal or the complete absence of packaging rather than with packaging that keeps food fresh longer [30,31]. Furthermore, in a report by WRAP [32], half of the surveyed consumers stated that packaging is harmful to the environment and only a quarter agreed that packaging extends the shelf life of a product. Further, consumers identify the key benefits of packaging as 'keeps products safe and hygienic', 'provides important information on labels', and 'protects the food from the factory to the shop and on the way home', while only 13% think that packaging also protects the food at home. When asked whether packaging or food waste would be more environmentally harmful, opinion is divided. This is more or less in agreement with an Italian survey [33], where 60% of the consumers were convinced that packaging has a greater environmental impact than food waste. However, contrary to the conception of consumers, the contribution of FLW to the carbon footprint in a food packaging system is, in most cases, higher than that of the production and waste management of the packaging [34]. In general, the more resource-intensive the food production is, the more worthwhile is a more elaborate packaging [35]. In most cases, packaging accounts for only 1%–12% (typically around 5%) of greenhouse gas emissions in a life cycle assessment of a food packaging system [36]. Following this line of argument, prevention of FLW may arguably be seen as one, if not the most, important strategy for packaging optimization for most types of food [37,38]. Nevertheless, as long as consumers are not aware of the importance of FLW reduction by appropriate packaging, this represents a conflict of objectives and, hence, the main challenge for all stakeholders in the packaging design process.

## 3. Causes of Food Losses and Food Waste Related to Packaging

A first approach to determine packaging-related food loss or waste is to identify the stages in a food supply chain in which food is in a package. Once a product is packed—whether for transport or product packaging—this packaging can or may lead to a loss of contents. An estimate based on a survey of Swedish households' waste behavior showed that packaging-related FLW (PFLW) contributes to 20% to 25% of a household's total amount of food waste [39], but otherwise such data are scarcely available [40].

If FLW occurs, it does not necessarily mean that the food was originally inedible. Edible food may also be discarded only because the expiration date is exceeded. Hence, packaging-related FLW can refer to edible or inedible food. What is meant by a so-called expiration date are actually two dates, the 'best before' and the 'use by' date. The 'best before' date is a date of the minimum shelf life and signals the date until the food retains its quality, such as flavor and texture. Retailers are permitted to sell food after the best before date has passed. For food that is 'highly perishable' and, after a short period, is likely to 'constitute an immediate danger to human health', the best before date is to be replaced by a 'use by' date [21]. After the 'use by' date, food is deemed to be unsafe, in contrast to the exceedance of the 'best before'. Interestingly, 64% of consumers in the EU misinterpret the meaning of the best before date [41]. While consumers often confuse best before and use by dates, they state that they need more information about the shelf life of food once a package has been opened [42].

Looking at the food supply chain, there are many different stages and reasons why food may be wasted. As packaging is generally first introduced right after harvest, the identified stages of the food supply chain where PFLW can occur start with the post-harvest stage and end with the serving of food (see Table 1). Mechanical damage to food and/or its packaging and therefore the discarding of the product can occur during any stage of transportation while in transport packaging [17].

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**Table 1.** Packaging-related food loss and waste along the food supply chain.

| Stage | | Type of Packaging-Related Food Losses and Waste | References |
|---|---|---|---|
| Food in the supply chain | Primary production | - | - |
| | Post-harvest handling and storage | Damage of products due to contaminants, sharp edges or splinters of field containers, over-packing of field crates | [43,44] |
| | Processing and packaging | Problems in the filling process<br>Packaging failures while sealing<br>Packaging changes due to marketing reasons | [45–48]<br>[49]<br>[16] |
| | Distribution and retail | Packaging does not provide enough mechanical protection (inappropriate packaging material, poor stackability, no packaging at all) Damage to barcodes on packaging | [45,50,51] |
| Food in households | | Difficult to open packaging<br>Difficult to empty packaging<br>Inappropriate packaging size | [52,53]<br>[39,54]<br>[55–60] |

Source: Own elaboration, references for the different food supply stages: [10,61,62].

### 3.1. PFLW in the Supply Chain

As there is no packaging involved in the primary production of food, packaging-related FLW may start during the post-harvest handling and storage stage of food. If produce is harvested and packed in field containers, these should be properly cleaned beforehand to not introduce any contaminants into the food [43], as well as be free of any sharp edges or splinters that could damage the food [44].

At the processing stage, the main causes of FLW are overproduction, misshaped food, and packaging damage [63,64]. Technical malfunctions are mainly comprised of filling problems. During a manual filling process, food can be lost through bad handling due to poor work conditions [45]. In an automatic filling process, losses can occur when packaging and filling machines are not well matched or if there is a malfunction of the machinery, e.g., resulting in bottle overfilling [46]. As there are strict requirements for food companies on the filling level, companies tend to overfill rather than underfill their containers [48]. Furthermore, losses can occur due to the batch process itself and corrections that are needed before the filling machine can run correctly [47]. After filling, packaging may leak due to a failure in the closure (e.g., the heat seal) [49]. Another issue at the packaging stage, for which the retail sector is actually a key driver, is ongoing changes to the packaging of food products for marketing reasons [16]. As packaging is often bought in large amounts, this may lead to packaging waste, but could also contribute to FLW if already packed food is discarded.

While in distribution, food losses may occur due to damage of the packaging, the exceedance of expiration dates, or poor stock management [65]. Products may be packed poorly, e.g., without sufficient protection, or loaded without any packaging at all. Roads in bad condition increase the risk of damaging the food during transport [45]. An important packaging function to consider concerning PFLW while storing and distributing food is stackability. If crates cannot be well stacked, damages can lead to a collapse of the lower levels due to the pressure from high loads. This led to a loss of around 30% in the case of an investigated supply chain of citrus fruits [50]. Inappropriate stacking of trays was also one of the main causes of FLW reported in the case of strawberries in the UK [66]. In a comparative assessment of two different product and transport packages (corrugated cardboard and plastic crates) for eggs, an average breakage rate of 1.1% was observed while the results of the four different packaging scenarios varied between 0.56% and 2.38%. These damages were attributed to poorly stacked crates, as well as the inadequate quality of the corrugated board used and mismatched primary, secondary, and tertiary packaging [51].

After distribution, food is stored in the retail sector, a sector which is responsible for around 5% of FLW in Europe [67]. As reported by the retail chains, expired shelf life is the main reason for the generation of FLW [37,68]. This may be due to delays at the pre-distribution stages, while premature spoilage may occur due to improper packaging and storage temperatures or rough handling [37]. Packaging damage is rather rare and may just mean that the imprinted barcodes are unreadable [45].

Since it is time-consuming to remove food from a package, some supermarkets may forgo this procedure [49,69]. If a package contains only partly spoiled food, this may lead to the disposal of otherwise saleable goods [70]. Food and packaging are then disposed of as a whole as residual waste instead of as separated organic waste for food, and plastic or municipal waste for the packaging. The separation does not necessarily occur in the downstream waste treatment either and even if it does, food-contaminated packaging reduces the possibility of a potential mechanical recycling of the packaging, further contributing to a higher environmental impact [71].

### *3.2. Packaging-Related FLW at the Consumer*

#### 3.2.1. Effects of Packaging Design

Besides the primary function of protecting its content, a package has also to be able to facilitate handling. Therefore, the packaging manufacturer has to enable the easiness of unpacking, openability, and emptying of a package with the design [18]. Poor openability can lead to FLW as consumers may spill food or beverages if the opening of a package proves difficult. This is particularly true for elderly people or for those with disabilities [52,53].

When talking about the ability to empty the packaging entirely a distinction can be made between the terms, 'easy-to-empty' and 'easy-to-access', according to Plastics Recyclers Europe. In their online recyclability assessment tool for plastic packaging, *RecyClass* [72], the easy-to-empty index is intended for 'packaging where the content is not accessible for emptying (i.e., bottles, tubes)' and the easy-to-access index for packaging 'where the content is accessible for emptying (i.e., pots)'. 'Easy to empty' means that a package can be emptied without force (i.e., flipping and holding the open package vertically for a period of time) and 'easy to access' simulates a regular use by a consumer (i.e., using a spoon to empty a yogurt cup). Plastics recyclers are concerned about food residues, as these may interfere with the recycling process of the packaging [73].

Food residues in packaging were addressed in an exploratory study with Swedish households [39]. In this study, yogurt and sour milk in liquid packaging board contributed 75%, liquid margarine, jam, porridge, mayonnaise, and soups in plastic, glass, fiber-based, or metal packaging 25% to the 'difficult-to-empty' waste. The viscosity of the food is likely to play an important role, as products with high viscosity were more inclined to stick to the inside of the packaging. In total, waste due to the poor emptiability of packaging led to approximately 4% of the total amount of FLW generated by the surveyed households. The process of emptying a package is not only influenced by the packaging design, but also the person responsible for opening it, particularly in the case of the 'easy to access' function. As the authors state, the waste associated with emptying a yogurt package was very different between the two surveyed groups, one with education about environmental issues and one without [39]. This was further substantiated with a test of the emptying behavior of 1000 mL milk packages, where residues of 4.7–14.7 mL were found. The authors point out that the simulation of a final stirring process by the consumer significantly influenced the resulting waste. Further important factors that influenced the emptying behavior could be attributed to the presence of a fold at the bottom of the package and corrugations in its internal wall, as well as the shape of the package itself [54].

#### 3.2.2. Effects of Packaging Size

At the household level, spoiled food may be seen as a symptom of many different problems and not as a reason for waste per se. Hence, one has to look at the root causes of what leads to a household not eating purchased food in time [68]. Of course, this may be due to unexpected events, however, there is evidence to suggest that inadequate packaging sizes are a key factor in the generation of FLW. Packaging size is a growing concern for consumers as well as retailers, but for the latter, more in the context of packaging waste instead of FLW [16].

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The potential amount of FLW may be dependent on the packaging function 'apportionment', i.e., when a product is divided from the large-scale production units into the desired amount and size. If a product is offered in two packs of 75 g that can be separately opened instead of one 150 g pack, there is a greater amount of packaging used per packed food. This may result in a higher environmental impact of packaging, as consumers have to buy multiple packages in a single visit [55], but also may result in a higher chance of consuming food in time [18]. An optimized apportionment not only helps households in reducing FLW, but also the retail sector by enabling a better management of stock [50]. Only 17% of surveyed consumers in Italy state that portions 'generally reflect their needs' [60]. At the same time, consumers who buy larger packages also waste more food. As the household size has a strong influence on the total amount of generated food waste, it is clear that packaging size has too. Single households generate the most food waste per capita and by comparison, people in four-person households waste less than half than a person in a single household [56].

When asked about which activities or interventions would help to reduce food waste in their homes, most households state meal planning, the change of preferences and food habits, and of the need for different packaging options at retail [58]. Interestingly, households that state that purchasing too large packages is 'at least sometimes a reason for wasting food' have greater amounts of food waste than others. This is even more significant in households that say it is the reason 'most of the time' or 'always'. Households that believe they may be able to reduce food waste by buying smaller packages waste more food than others [59]. All in all, a third of the households claim that they would generate less food waste if the packaging size of food products would be more suited to their needs [60].

Furthermore, consumers in Germany and Italy point out that the packaging sizes of many types of fresh produce, as well as dairy products, baking ingredients, meat products, and pasta, are too big, while complaining about the higher price of smaller packages in comparison to larger ones [56]. Buying large packages contributes significantly to excessive purchasing, which is true in particular for low-income households, where this leads to over-preparing and thus to the generation of FLW [57]. The simple solution would be to just shrink packages then, but understanding the impact of packaging size on FLW is anything but trivial [74].

That is to say, it is hard to estimate how much consumers waste due to packaging size or apportionment [75], as long as there is a lack of empirical studies.

#### 3.2.3. Effects of Packaging Technology

Currently, both packaging and future developments in material technology have a huge potential to minimize FLW [15,17] and to contribute to food safety and security [45]. In the context of technology, packaging potentially prolongs shelf life. As material technology is always making advances, more and more polymer-based multilayer packaging is used, which extends the shelf life of food while reducing packaging weight [76]. Due to good barrier properties, multilayer materials are suitable for modified atmosphere packaging (MAP). Such packages contain a modified gas composition, mainly nitrogen, carbon dioxide, or oxygen, which aims to reduce microbial growth and chemical deterioration of the packaged food and therefore increases its shelf life [77]. The downside of multilayer packaging is that it is usually landfilled or incinerated due to poor recyclability [78].

Another promising technology is active and intelligent packaging, which is set to become more prevalent in the future. Active packaging contains 'deliberately incorporated components intended to release or absorb substances into or from the packaged food or from the environment surrounding the food' [79] and has, therefore, the purpose to extend the shelf life of food [80,81]. Intelligent packaging is comprised of 'materials and articles that monitor the condition of packaged food or the environment surrounding the food' [79] and may be able to reduce FLW by abandoning the system of a fixed best before data by providing dynamic information about the actual condition of the food [82].

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## 4. Integration of FLW in LCA of Packaging

As elaborated upon, it is important to emphasize the aspect of packaging-related FLW when talking about the environmental performance of packaging. A well-known and commonly used method to investigate environmental impacts of food across the supply chain is LCA [83]. However, in relation to available food LCAs, only a few studies integrate packaging-related FLW [84]. The studies investigated for this review include the calculation of the environmental impacts of (i) food loss probabilities dependent on the shelf life, (ii) break-even rates of FLW compared to packaging, (iii) scenarios of FLW amounts based on expert opinion, and (iv) a (e.g., protection) function-based approach in ex-ante LCA.

Most LCA studies of food use 1 kg produced or packaged food as a functional unit, a quantified performance in a system for use as a reference unit [85]. In contrast, a functional unit of 1 kg consumed food allows an accounting for the impact of packaging-related FLW [86–90]. This enables a comparison between packaging that wastes more and packaging that wastes less food. As a result, in some cases, the total carbon footprint of the respective food-packaging system may be lower with resource-intensive compared to resource-efficient packaging (Figure 2).

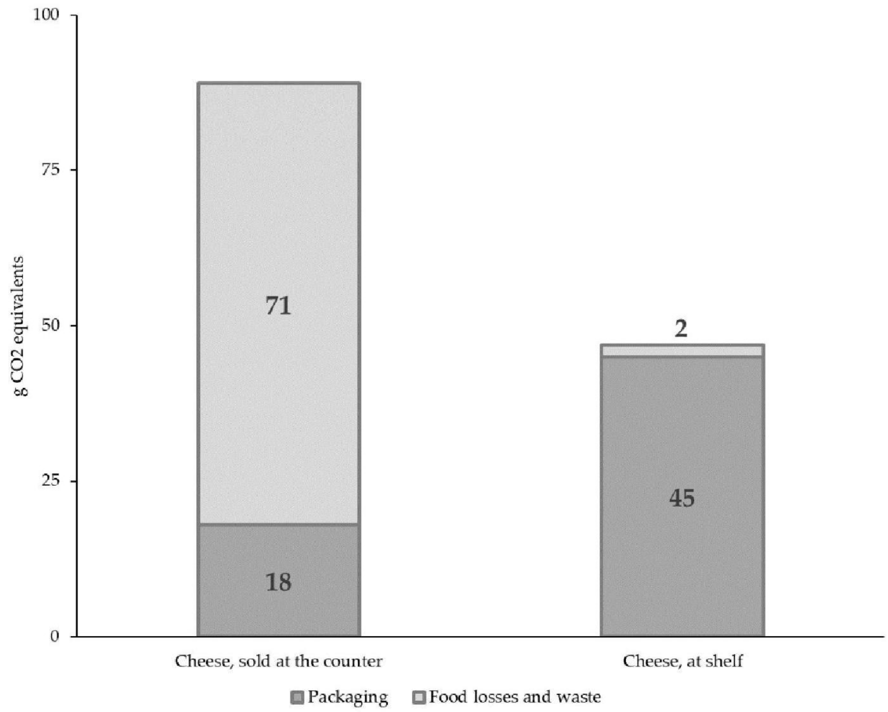


**Figure 2.** Carbon footprint of two packaging options for cheese, per 150 g cheese, adapted from [35].

Unfortunately, in most cases, there is no actual FLW data available for a specific food-packaging system [90]. To that end, methods have to be developed for estimating packaging-related FLW. A novel approach is the calculation of food loss probabilities of packages due to different best before dates [91,92]. For instance, by extending the shelf life of specific products, such as yogurt and cream, a considerable reduction of FLW can be reached [93]. There is, however, no direct relationship between a longer shelf life and FLW generation [94], meaning that an extended shelf life does not automatically translate to less FLW for every food product. The best before date can have a significant impact on the purchase decision [95] and depends not only on the product category, but also on the size of the retailer. Medium and larger supermarkets can benefit from faster turnovers, while for smaller supermarkets, it is better to place fewer orders and have products with a longer shelf life [96]. The issue of quantifying FLW reduction in relation to its shelf life is therefore challenging. If a packaging is already on the

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market, research suggests that the integration of the emptying behavior of a package in its LCA is feasible as well as advisable [54].

The calculation of break-even rates could be one way to deal with uncertainties about packaging-related FLW amounts. This means that packaging designers or LCA analysts could calculate when an increase in packaging would pay off in return for less FLW [97,98]. In addition, an LCA analyst may calculate scenarios with different packaging-related FLW rates based on expert opinion [99]. Another example is a function-based approach, to be used when altering or redesigning food packaging. An ex-ante LCA of food packaging may compare two different packaging design decisions by looking at parameters, such as stackability and oxygen or water vapor transmission rates, and calculate the LCA by adjusting the required amounts accordingly [100].

## 5. Discussion

Thirty percent of all food produced becomes waste. The use of appropriate packaging may be one way to reduce this percentage. Particularly in developing countries, a lack of packaging is stated as one of the main drivers of food losses or waste by the FAO [17].

In industrialized countries, the contribution of packaging to FLW is less clear-cut. Packaging plays an essential part in food protection and thus can reduce FLW. Examples include non-adequate packaging (too large packaging sizes, inappropriate material, contaminated packaging, technical failures in the packaging process) [43–45,48,50,51,55–60] or packaging that is too difficult to open [52,53] or to empty [39,54] so that its contents spill or are left in the package. Packaging saves food by mechanical protection or prolong its shelf life by a material with good barrier properties [76], through the use of modified atmosphere packaging [77] and, in the future, by intelligent or active packaging through the dynamic display of its microbiological status [82]. As increasingly more food is consumed outside the home [101], the food service sector contributes a significant share to the amount of FLW [12]. Here, an easy way to reduce FLW may be the use of a so-called ‘doggy-bag’, which can be used to take leftovers to be eaten at a later date [45].

Packaging designers should focus on the influence of the packaging design choices on FLW prevention. In order to reduce packaging-related FLW, packaging has to be designed with the interrelations between primary, secondary, and tertiary packaging in mind [51]. Although a systematic analysis and quantification of packaging design aspects has not yet been performed, optimal product protection and optimization of the shelf life can be considered essential. In addition, packaging may offer design features, such as compartments, that can be opened individually or packaging, which is easily reclosable. A design for easy portioning and small package sizes are further important assets [20,102]. Furthermore, packaging can contain instructions about how best to store the food and to encourage people to freeze leftovers [20], as well as how to serve food to avoid residues in the package [54].

Although FLW and packaging are getting attention in the scientific literature, packaging-related FLW (PFLW) is largely unexplored. As this review shows, there is no reliable data on quantities of PFLW. Furthermore, the quantification of PFLW proves to be difficult, whether with household surveys or waste analysis. Household surveys can lead to wrong quantifications of FLW because answers are often biased by social desirability, a lack of motivation for documenting waste, or simply due to forgetfulness [39]. Waste composition analyses have limitations on information about specific waste quantities by food category and do not include alternative disposal routes of households, such as a separate bio-waste collection, home composting, or the use as pet food [103], but above all, there is no generation of information about the causes of the FLW. These causes are rather complex and are often the result of multiple interacting activities [104] so it is challenging to identify FLW as (at least partially) packaging-related, even when interviewing consumers directly about whether their FLW is connected in any way with packaging [39]. Future research is needed to develop new methods for determining PFLW.

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This review has identified further research needs in the implementation of PFLW into the LCA of packaging. Resource-intensive packaging can have an overall lower carbon footprint compared to FLW if its PFLW is lower than a resource-efficient packaging (Figure 2). As a result, the assessment of the contribution of packaging to a sustainable food system can be turned upside down. Therefore, the quantification and implementation of PFLW into the LCA of packaging is of great importance. However, there is a lack of LCA studies on packaging considering PFLW [84]. However, in the reviewed research articles, there is agreement on the importance of PFLW and a number of authors already support the call for further research on this topic [39,40,84,87,92,97].

## 6. Conclusions

Future packaging developments should focus on further advancements in packaging technology, but should not neglect the importance of indirect effects of packaging. Stakeholders in the packaging design should understand the demands of the packaging across the whole supply chain to optimize their product in reducing food losses and waste. This should be done by undertaking studies on consumer behavior as well as the provision of education and the collaboration between producers, manufacturers, and retailers [105]. More research is required to quantify packaging-related food loss and waste so that life cycle assessments can incorporate the direct as well as the indirect environmental effects of packaging to help facilitate the environmentally preferable choice.

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# 8 Full text: Paper II

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Streamlined LCA results: https://doi.org/10.7717/peerj.7578/supp-3

Life cycle inventory of Austrian fat-protein corrected milk (FPCM): https://doi.org/10.7717/peerj.7578/supp-4

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# Technical emptiability of dairy product packaging and its environmental implications in Austria

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## ABSTRACT

**Background:** Food waste is a major ecological concern around the globe. While the main function of packaging is to contain and protect food, it may also lead to food waste if residues remain in a package after emptying. Such residues could be attributed to wasteful behavior of consumers, but also to properties of packaging (e.g., geometry, surface tension) and food (e.g., surface tension, viscosity).
**Methods:** In this study, the technical emptiability (ability of packaging to be emptied entirely) of 36 dairy products is analyzed. Firstly, the amount of food residues in packaging after emptying at room and refrigerator temperature was weighed and set in relation to the original filling quantity. Secondly, streamlined life cycle assessments (LCAs) based on the Product Environmental Footprint guidance with a functional unit of "one kg of consumed dairy product at room or refrigerator temperature in the home of the consumer" are conducted. Finally, technical emptiability was included in the streamlined LCA and attributed to the primary packaging in order to evaluate its environmental impact.
**Results:** Technical emptiability for both temperatures combined was found to be between 0.25% (±0.11) and 5.79% (±0.43) for the analyzed dairy products. While there were differences in emptiability results of the same product and different temperatures, no significant trend ($p$ = 0.94) between emptiability and temperature could be observed. Liquid yogurt, cream, and buttermilk in beverage cartons and plastic bottles yielded the highest amounts, while milk in beverage cartons and glass bottles yielded the lowest amounts regarding food residues. Looking at global warming potential, poor technical emptiability of cream in a beverage carton leads to even higher environmental impacts than the production and waste management of its packaging.
**Discussion:** The streamlined LCA results show that food residues can contribute substantially to the footprint of packaging and can have similar or even higher environmental impacts than packaging production and waste management.
Yet, emptiability is remarkably under-researched to this day. Future studies should further develop the methods presented in this paper, while LCA analysts should include technical emptiability when assessing the sustainability of packaging, particularly for those containing resource-intensive goods.

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## INTRODUCTION

Worldwide, 1.3 billion metric tons or approximately one-third of the food produced is lost or wasted every year (Gustavsson, Cederberg & Sonesson, 2011). Food losses and waste (FLW) account to the emission of 3.3 billion tons of $CO_2$ equivalents and, when compared to countries, is ranked as the third top emitter after USA and China (Food and Agriculture Organization of the United Nations (FAO), 2013).

In theory, optimized packaging can reduce both food and packaging waste across the supply chain (Food and Agriculture Organization of the United Nations (FAO), 2014; Verghese et al., 2015), for example, by providing mechanical protection (Oki & Sasaki, 2000) or by using modified atmosphere packaging and thus prolonging the shelf life of its contents (Kirtil & Oztop, 2016). In low and middle-income countries, missing or inappropriate packaging is stated as one of the major contributors to FLW (Food and Agriculture Organization of the United Nations (FAO), 2014). In contrast, in Europe or North America more food is wasted at the consumption stage (Gustavsson, Cederberg & Sonesson, 2011). Here, packaging can be directly responsible for FLW due to various reasons (Wohner et al., 2019), for example:

- Inappropriate packaging size, that is, too large packages
- Packaging that is difficult to open
- Packaging that is not reclosable
- Packaging that is difficult to empty

However, how exactly and to what extent packaging functions influence FLW is still largely unexplored (Wikström et al., 2019). In total, packaging may be responsible for up to 25% of FLW in households (Williams et al., 2012). According to this study, packaging that is "difficult to empty" is identified as a major driver of FLW. Further, "emptiability" (ability of emptying a package completely) is stated as particularly important for reducing FLW of yogurt (Wikström et al., 2019).

Several consumer protection agencies and companies are already concerned with emptiability (Markert, 2016; Austrian Association for Consumer Information (VKI), 2017; LiquiGlide Inc, 2018). Still, existing scientific literature on this subject is scarce. For instance, Meurer et al. (2017) detail their approach of emptying UHT milk, while in other literature the emptiability of yogurt (Williams et al., 2012) and minced meat in trays or tubes (Wikström, Williams & Venkatesh, 2016) are stated, yet without the description of a reproducible methodology for quantification. Despite the aforementioned studies, emptiability can be considered under-researched, even though it may lead to relevant environmental impacts. More specifically, by food residues interfering with the recycling of packaging (Packaging SA, 2017; Maris et al., 2018), as well as by the unnecessary resource consumption and emissions related to the production of food (Food and Agriculture Organization of the United Nations (FAO), 2013). As a rule, food production has considerably higher environmental impacts than its packaging (Silvenius et al., 2011; Licciardello, 2017). Therefore, a resource-intensive packaging can actually have a lower environmental impact than a resource-extensive one if it leads to less FLW

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(*Denkstatt, 2014*). Yet, many life cycle assessment (LCA) studies of packaging exclude packaging-related FLW, while the awareness of its importance is fortunately increasing (*Molina-Besch, Wikström & Williams, 2018*).

To fill the identified literature gap, this paper addresses the question on how to quantify emptiability, or more precisely, technical emptiability. In this context, technical emptiability is considered as the sole product of the respective food packaging combination while excluding any wasteful behavior a consumer might practice. Furthermore, the study discusses if the attribution of food residues leads to the conclusion that technical emptiability testing should be carried out and included in the LCA of packaging. For this purpose, streamlined LCAs of all products are performed, that is, refraining from the collection of primary data.

The present research is restricted to dairy products since these are particularly resource-intensive (*Clune, Crossin & Verghese, 2017*) and are consumed in large quantities in Austria (*Statistik Austria, 2018*).

# MATERIALS AND METHODS

## Testing of technical emptiability

A total of 36 dairy products were purchased from various brands in several Austrian supermarkets.

In addition to the packaging geometry, emptiability is mainly influenced by the surface tension of food and packaging, along with the viscosity of food (*Schmidt, 2011*). Moreover, viscosity changes with temperature (*Gonçalves et al., 2017*) and dairy products are usually consumed both directly after removal from the refrigerator, as well as on the go after they have gained room temperature. Therefore, tests were performed at room (22 ± 1 °C) and refrigerator temperature (7 ± 1 °C).

While the testing for milk was based on *Meurer et al. (2017)*, due to the lack of scientific literature a new methodology for emptying dairy products other than milk had to be adapted or rather newly developed. A pre-test was carried out to observe how long the content actually flows and then drips out, similar to *Meurer et al. (2017)*. After this preliminary test, a total emptying time of 2 min including a shake of the package was chosen, since after that no more dripping of milk occurred. While emptying, the "perfect consumer" was simulated, that is, emptying with meticulous precision, so that the derived emptiability could actually be attributed to the packaging and not to a potentially wasteful consumer behavior. As a result, the emptying of packaging was carried out until it became apparent that no more food could be removed from the packaging without damaging it.

The principal steps of testing were (i) weighing of the package (food and packaging), (ii) emptying the contents, (iii) weighing the emptied package, (iv) washing and air drying of the packaging for 48 h at room temperature (22 ± 1 °C) and (v) weighing of the cleaned packaging.

The mass of food residues in a package ($FR_i$) was then calculated as:

$$FR_i = \text{Emptied package}_i - \text{Cleaned packaging}_i$$

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Due to time and resource restraints resulting from the analysis of 36 products, a number of three tests per temperature and package was chosen. The emptiability index (EMPT) of the respective temperature was the arithmetic mean of all three emptiability tests per package and temperature, expressed as the ratio of $FR_i$ to the mass of the food in a package ($F_i$):

$$\mathrm{EMPT}_{\mathrm{Temp}}(\%) = \frac{\sum_{i=1}^{3} \mathrm{FR}_i}{\sum_{i=1}^{3} \mathrm{F}_i} \times 100$$

Since it is not known at which temperature the dairy products are consumed in practice, the discussion focuses more on the mean of both temperatures. As a result from the formula, a lower emptiability index means a better emptiability of packaging. Subsequently, statistical reliability of the derived emptiability results were analyzed by power tests (*Cohen, 1988*) in order to calculate variability. First, a desired statistical power of 0.80 with a confidence interval of 95% was defined. This resulted in effect sizes (Cohen's d) of 3.26 for three samples and of 1.44 for six samples. Finally, variability regarding emptiability indices was defined as these values multiplied with the respective standard deviation (Data S1).

### Emptiability testing of different types of milk, buttermilk, and chocolate milk

For the emptying of milk (whole milk, low-fat milk, lactose-free skimmed milk), buttermilk and chocolate milk, the packaging was held upside down and kept in this position for 1 min. The packaging was then brought to the starting position, panned five times and held for 10 s. Finally, it was tilted again and held for 1 min upside down. For chocolate milk in a beverage carton, the emptying was carried with the provided straw by pressing the package.

### Emptiability testing of café latte

For café latte, the cup was shaken five times and then opened, whereby the intended drinking lid was put on for emptying. Further emptying followed the same procedure as for milk.

### Emptiability testing of cream and low-fat cream alternative

Cream and low-fat cream alternative in bottles were emptied similar to milk variations. The multilayer polymer pouch for low-fat cream alternative was cut open at the designated area and its contents were squeezed out.

### Emptiability testing of liquid yogurt

In addition to the emptying method of milk, the packages of liquid yoghurt were shaken five times before being opened.

### Emptiability testing of yogurt, sour milk, fresh, and curd cheese

For all yogurt, sour milk, and cheese products, both the packaging was spooned out and the lid scraped off with a spoon. For the emptying process always the same spoon was used, which was washed and dried between each measurement.

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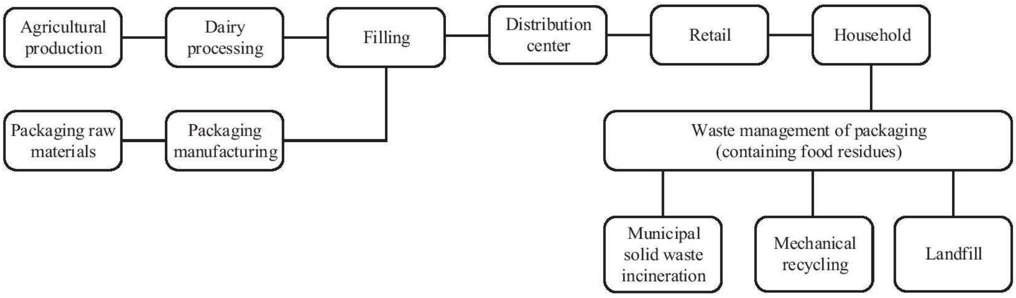


**Figure 1** System boundaries of streamlined life cycle assessment.
Full-size DOI: 10.7717/peerj.7578/fig-1

## Streamlined life cycle assessment

### *Goal and scope definition*

The goal of the streamlined LCA is to understand the relative impact of including emptiability in LCA of primary packaging. In contrast to full LCAs, streamlined LCA omit the collection of primary data.

As the dairy products are sold, consumed and disposed of in Austria and generally contain Austrian dairy, the geographical area chosen is also Austria.

The methodology for carrying out LCA is based on the current guidance (version 6.3) for the product environmental footprint (PEF) (*European Commission, 2017*) and the product environmental footprint category rules (PEFCR) for dairy products (*Bengoa, Dubois & Humbert, 2018*) in particular. The calculations are performed with OpenLCA 1.7.4 and the Ecoinvent 3.5 database. All used datasets are listed in the Data S2.

### *Functional unit and reference flow*

The functional unit chosen is "one kg of consumed dairy product at room or refrigerator temperature in the home of the consumer." The reference flow is the amount of product needed to fulfil the functional unit. As an example, this results in a reference flow of 1,010 g for a product with a filling quantity of 1,000 g and an emptiability-related loss of 10 g.

### *System boundaries*

The system boundaries of the streamlined LCA include the raw materials, manufacturing and transport of packaging with all its components, the agricultural production and processing of milk and other ingredients, as well as the disposal of the packaging including the food residues inside (Fig. 1).

The included transports are those of the packaging and the ingredients to the filling plant, as well as those of the product from the dairy plant to the distribution center, then to the supermarket and finally to the consumer. Transport distances are taken from the PEFCR and are listed in the Data S2.

Not included in the streamlined LCA are the final assembly of the packaging (e.g., application process of an aluminum lid to a plastic cup) and the use phase (e.g., energy consumption of the refrigerator), as well as FLW at other food supply chain stages.

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The refrigeration process in the household has not been considered since the packaging design does not affect the energy consumption of the refrigerator. Therefore, according to the PEF guidance, this is to be classified as a product-independent use stage process and shall thus be excluded from the system boundary.

### Life cycle stages

Life cycle stages are calculated and listed separately (Data S3) for

- Primary packaging (PRP): raw materials, production, transport, and waste management
- Food production (F): production of dairy products
- Waste management of food residues (FW): waste management (incineration) of food residues in packaging after emptying
- Secondary/tertiary packaging (STP): raw materials, production, transport, and waste management
- Transport to home: transportation of packages from the supermarket to the home of the consumer

The attribution of food residues to the LCA of the respective primary packaging follows a similar approach detailed in *Wikström, Williams & Venkatesh (2016)*. Subsequently, a newly derived result of each impact category for the respective primary packaging after including food residues ($PRP_{FRi}$) is calculated. For this, the environmental impacts regarding the production and waste management of (i) STP, (ii) the production of food, (iii) the transport of the products to the home of the consumer ($TH_i$) (iv) and that of the waste management of food residues ($FW_i$) was attributed to the production and waste management of primary packaging ($PRP_i$).

$$\mathrm{PRP}_{\mathrm{FR}_i} = \mathrm{PRP}_i + \frac{\mathrm{PRP}_i + \mathrm{STP}_i + \mathrm{TH}_i + F_i}{1 - \mathrm{EMPT}_i} \times \mathrm{EMPT} + \mathrm{FW}_i$$

For EMPT, the mean of all six emptiability tests was used, since the temperature at which the products are consumed was not known. Finally, $PRP_{FR}$ was compared to the LCA results based purely on production and waste management of the primary packaging ($PRP_i$).

### Selection of impact categories

All 16 impact categories of the PEF (ILCD 2.0 2018 impact categories set) were calculated and listed for all investigated life cycle stages in Data S3. For the interpretation, however, only the most relevant impact categories were used. For this purpose, first the results of all impact categories are normalized and weighted (Data S3). Next, the absolute values of all but the toxicity categories are added to obtain the PEF single score. Toxicity categories were excluded since they are not yet robust enough (*Bengoa, Dubois & Humbert, 2018*; *Sala, Cerutti & Pant, 2018*). Finally, the most relevant impact categories were those which contribute at least 80% to the PEF single score. For this study, this results in a list of the following six categories, ranked by their contribution:

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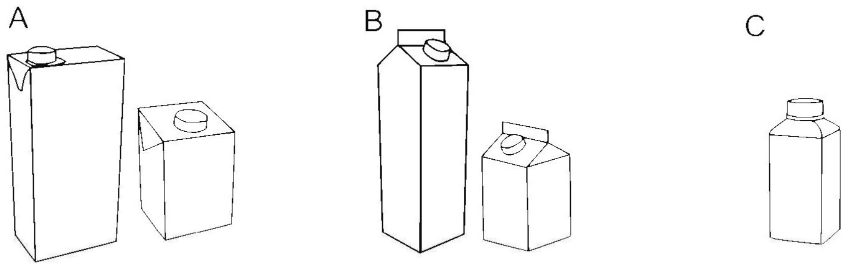


**Figure 2 Emptied beverage cartons.** (A) Cartons with flat tops. (B) Cartons with gable tops. (C) Cartons with bottle-shaped tops. Full-size DOI: 10.7717/peerj.7578/fig-2

- Freshwater and terrestrial acidification (Accumulated Exceedance, in mol $H^{+}_{eq}$)
- Respiratory effects, inorganics (Impact on human health, in disease incidence)
- Climate change (Global Warming Potential over 100 years, in kg $CO_{2eq}$)
- Terrestrial eutrophication (Accumulated Exceedance, in mol $N^{-}_{eq}$)
- Freshwater eutrophication (EUTREND model, in kg $P_{eq}$)
- Resource use, fossils (Abiotic Resource Depletion, in $MJ_{eq}$)

### *Life cycle inventory of packaging*

First, each packaging was disassembled after the emptying process. Then, the packaging components were weighed and, finally, their material determined. Whenever the polymer type of plastic packaging was not recognizable by the label, its identification was carried out with Fourier-transform infrared spectroscopy.

Tested packaging consisted of:

- Aseptic and non-aseptic beverage cartons: with bottle-shaped, gable and flat tops (Fig. 2)
- Plastic bottles: high-density polyethylene (HDPE) and polyethylene terephthalate (PET) (Fig. 3)
- Plastic cups: polypropylene (PP), polystyrene (PS); single and twin-chamber cups (Fig. 4)
- Plastic tubs: PP and PS (Fig. 5)
- Pouch: multilayer polymer pouch (PP, PE, calcium carbonate, and ethylene vinyl alcohol (EVOH) (Fig. 6)
- Glass bottle: white packaging glass (Fig. 7)

Detailed packaging descriptions are listed in the Data S2. The composition of non-aseptic beverage cartons was assumed to be 80% cardboard and 20% low density polyethylene (LDPE), that of aseptic beverage cartons to be 75% cardboard, 21% LDPE and 4% aluminum (*Fachverband Kartonverpackungen für flüssigkeits Nahrungsmittel eV (FKN), 2007*). Zero recycled content was assumed for all materials, except for packaging glass, where 60% of recycled content was chosen (*Austria Glas Recycling GmbH, 2018*). The composition of the multilayer polymer pouch was taken from its environmental product

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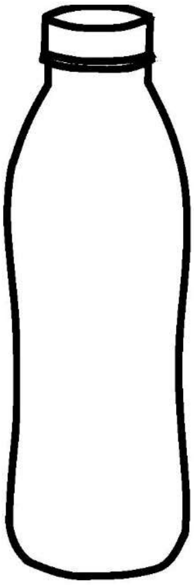

Figure 3 **Emptied plastic bottles.** Full-size DOI: 10.7717/peerj.7578/fig-3

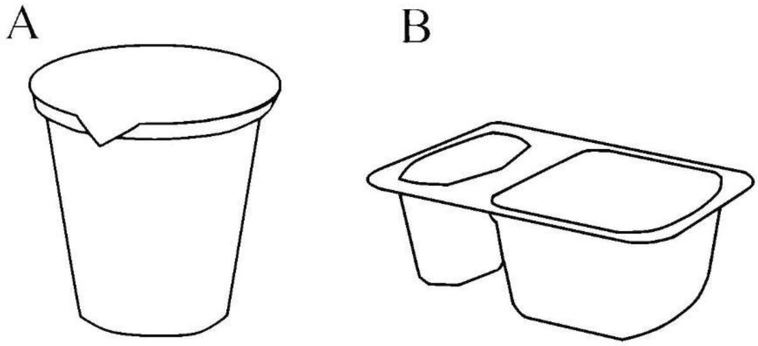


Figure 4 **Emptied plastic cups.** (A) Single chamber cups. (B) Twin-chamber cups. Full-size DOI: 10.7717/peerj.7578/fig-4

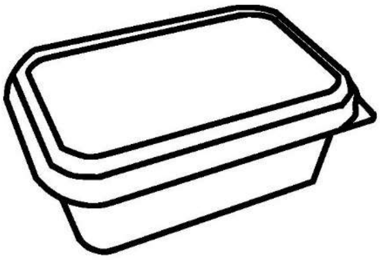

Figure 5 **Emptied plastic tubs.** Full-size DOI: 10.7717/peerj.7578/fig-5

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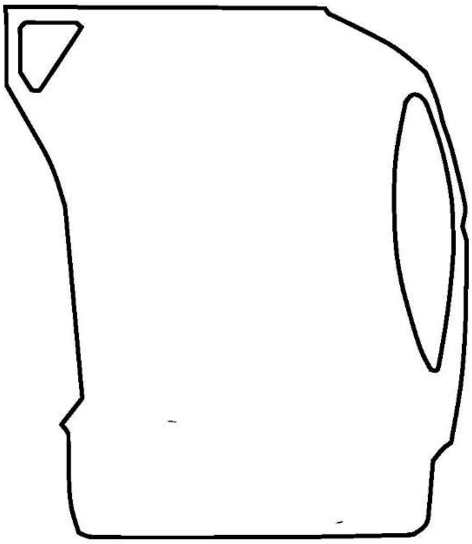

**Figure 6** **Emptied plastic pouches.**

Full-size DOI: 10.7717/peerj.7578/fig-6

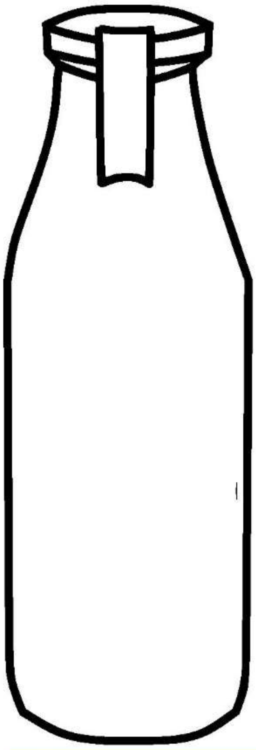

**Figure 7** **Emptied glass bottles.**

Full-size DOI: 10.7717/peerj.7578/fig-7

declaration (*Ecolean, 2018*). Transport distances for glass and non-glass packaging to the filling plant were taken from *Bengoa, Dubois & Humbert (2018)* (Data S2), as well as default data for secondary and tertiary packaging (25.6 g corrugated board, 1.5 g LDPE film, and 6.0 g wooden pallet per kg dairy product).

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### Life cycle inventory of milk and dairy products

For the LCA of Austrian milk, methane ($CH_4$) and nitrous oxide ($N_2O$) emissions, as well as feed rations, were taken from the GLEAM tool provided by the *Food and Agriculture Organization of the United Nations (FAO) (2018)*. The Austrian Air Pollution Inventory was used for information on ammonia ($NH_3$) emissions from dairy cows (*Anderl et al., 2018*). A distance of 60 km was used for the transport of raw milk between dairy farms and processing units (*Bengoa, Dubois & Humbert, 2018*). Finally, a life cycle inventory for one kg of fat-protein corrected milk (FPCM) for Austria was modeled (Table S1). One kg of FPCM consists of 4.00% fat, 3.30% protein content and 4.85% lactose content (*International Dairy Federation (IDF), 2015*), which sums up to 12.15% milk solids.

The milk quantity required for each dairy product was then calculated according to the milk solids allocation (*International Dairy Federation (IDF), 2015*; *Bengoa, Dubois & Humbert, 2018*). Thus, the required amount of milk for the respective dairy product was calculated as the sum of its fat, protein and lactose content divided by 0.1215.

Recipes of processed products had to be estimated (Data S2) as the information on the package did not indicate exact quantities in most cases. Estimates were based on the imprinted list of ingredients and the nutrition labeling of the packed food. Information on energy and resource consumption for the processing of (i) milk, (ii) fermented products, and (iii) cheese was taken from *Bengoa, Dubois & Humbert (2018)*. For café latte, the Ecoinvent dataset for green coffee beans was supplemented with data on grinding and roasting of coffee (*Phrommarat, 2019*).

### End-of-life assumptions of analyzed products

The assumption that packaging is recycled can only be made if it is recyclable by design and if the packaging is actually collected, sorted and recycled in the respective country. Only then, a country-specific recycling rate for a type of packaging may be used. For these assessments, recyclability guidelines were used to determine the expected recycling rate of the specific products. As an illustration, while the recycling rate for PET bottles in Austria is 45% (*Van Eygen, Laner & Fellner, 2018*), the end-of-life assumption for white PET bottles is incineration, since such opaque bottles are not recyclable (*Plastics Recyclers Europe, 2018*). All examined PET bottles have opaque colors and are, therefore, not recycled in Austria. The HDPE bottle for cream (36% fat) has a full-body sleeve made of oriented PS and is therefore also not recyclable (*Institute cyclos-HTP, 2017*).

For plastic cups and tubs, it can be assumed that these are not recycled in Austria, as are small foils or pouches due to their size (*Van Eygen, Laner & Fellner, 2018*). Plastic cups that are wrapped with cardboard are seen as a multilayer packaging and hence, not recyclable, since the separation of the cardboard from the cup cannot be expected from the consumer (*Tschachtli et al., 2018*). Besides the packaging design, food residues of more than 1% by volume also affect the recycling of plastic bottles, cups, and foils (*Packaging SA, 2017*).

Thus, all analyzed plastic primary packaging is assumed to be incinerated. The only primary packaging that can be classified as both recyclable and recycled in practice are beverage cartons and glass bottles, with recycling rates of 30% (*Getränkekarton*

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*Austria, 2019*) and 86% (*Altstoff Recycling Austria, 2018*) respectively. Further, recycling rates of aluminum lids and closures are assumed to be 38% (*Warrings & Fellner, 2018*).

For the secondary and tertiary packaging, a recycling rate of 85% is assumed for cardboard (*Altstoff Recycling Austria, 2018*) and 39% for large LDPE films (*Van Eygen, Laner & Fellner, 2018*).

As there is a landfill ban on untreated waste in Austria (*Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW), 2008*), it was assumed that no packaging, with the exception of glass and metal packaging, would be landfilled if it is not recycled.

#### Allocation rules

Allocation procedures follow the rules of the Circular Footprint Formula presented in the PEF guidance. Credits are awarded for the thermal and electrical energy gained from the incineration of the products, as well as for the recyclate resulting from recycling. Allocation and quality factors used in the PEF Circular Footprint Formula to calculate end-of-life burdens and credits are taken from the PEF default data (*European Commission, 2019*) and are also listed in the Data S2.

#### Robustness of the streamlined LCA results

For including technical emptiability in the streamlined LCA, the mean of all six EMPT tests was used. Subsequently, sensitivity analysis was carried out to evaluate potential implications resulting from emptiability indices that vary from the derived means. As a consequence, the calculations were repeated with the upper and lower limits of the determined variability of emptiability indices.

## RESULTS

### Technical emptiability results

The determined emptiability results (7 and 22 °C combined) of all analyzed products amount to values between 0.25% (±0.11) and 5.79% (±0.43). Liquid yogurt in beverage cartons and PET bottles, as well as cream and buttermilk in beverage cartons have the poorest emptiability results (Table 1), while whole milk (Table 2) and crumbly curd cheese have better results in comparison. Emptiability indices (EMPT) for the various types of milk are found to be similar to the results of *Meurer et al. (2017)*, with 0.31–0.45%. The derived variability of emptiability ranges between 0.03 (whole milk in a glass bottle) and 0.55% points (low-fat cream alternative in a polymer pouch), with a mean of 0.21. In percent, these values are between 2% (low-fat cream alternative in a PET bottle) and 70% (sour milk in a PP cup), with a mean of 20% (Data S1).

From comparing different food products and types of packaging it is obvious that the range of technical emptiability of the same packaging with different filling goods (Fig. 8), as well as of the same food in different packaging (Fig. 9) has a wide range of margin. This indicates that technical emptiability is a result of a food-packaging combination rather than of food or packaging properties solely. However, from Fig. 8 it is apparent that

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**Table 1** Technical emptiability results for dairy products other than milk.

| Dairy product | $EMPT_{22\,°C}$ (%) | $EMPT_{7\,°C}$ (%) | $EMPT_{22\,°C,\,7\,°C}$ (%) |
|---|---|---|---|
| Buttermilk \| Beverage carton, bottle top, variant a | 3.77 ± 0.77 | 4.18 ± 0.63 | 3.97 ± 0.42 |
| Buttermilk \| Beverage carton, bottle top, variant b | 3.74 ± 0.44 | 4.13 ± 0.66 | 3.93 ± 0.38 |
| Buttermilk \| Beverage carton, gable top | 3.32 ± 0.29 | 3.41 ± 0.17 | 3.36 ± 0.12 |
| Cream, 23% fat \| Beverage carton, flat top | 4.10 ± 0.05 | 4.27 ± 1.00 | 4.18 ± 0.31 |
| Cream, 36% fat \| HDPE bottle | 0.86 ± 0.13 | 0.80 ± 0.12 | 0.83 ± 0.07 |
| Cream, 36% fat \| PS cup | 0.72 ± 0.12 | 0.60 ± 0.20 | 0.66 ± 0.11 |
| Curd cheese, creamy \| PS tub | 0.79 ± 0.28 | 0.56 ± 0.20 | 0.67 ± 0.21 |
| Curd cheese, crumbly \| PS tub | 0.27 ± 0.35 | 0.23 ± 0.17 | 0.25 ± 0.11 |
| Fresh cheese, herbs \| PP tub | 0.53 ± 0.39 | 0.39 ± 0.19 | 0.46 ± 0.16 |
| Fresh cheese, radish \| PP tub, variant a | 0.47 ± 0.32 | 0.48 ± 0.32 | 0.47 ± 0.13 |
| Fresh cheese, radish \| PP tub, variant b | 0.49 ± 0.11 | 0.44 ± 0.20 | 0.46 ± 0.07 |
| Fresh cheese, sweet pepper \| PP tub | 0.41 ± 0.10 | 0.40 ± 0.29 | 0.40 ± 0.09 |
| Fresh cheese, sweetened \| PS cup | 0.44 ± 0.18 | 0.52 ± 0.20 | 0.48 ± 0.10 |
| Liquid yogurt \| Beverage carton, bottle top | 4.40 ± 0.33 | 4.35 ± 0.62 | 4.38 ± 0.20 |
| Liquid yogurt \| Beverage carton, gable top | 4.18 ± 1.13 | 4.18 ± 0.62 | 4.18 ± 0.36 |
| Liquid yogurt, blueberries \| PET bottle | 5.95 ± 0.68 | 5.63 ± 1.06 | 5.79 ± 0.43 |
| Liquid yogurt, strawberry \| PET bottle | 1.50 ± 0.26 | 1.36 ± 0.57 | 1.43 ± 0.21 |
| Liquid yogurt, vanilla \| PET bottle | 1.66 ± 0.32 | 2.24 ± 0.25 | 1.95 ± 0.47 |
| Low-fat cream alternative \| PET bottle | 3.86 ± 0.08 | 3.85 ± 0.28 | 3.85 ± 0.08 |
| Low-fat cream alternative \| Polymer pouch | 1.44 ± 0.46 | 0.77 ± 0.32 | 1.10 ± 0.55 |
| Sour milk \| PP cup | 0.35 ± 0.28 | 0.52 ± 0.03 | 0.43 ± 0.36 |
| Sour milk \| PS cup | 0.40 ± 0.21 | 0.51 ± 0.26 | 0.45 ± 0.14 |
| Yogurt, cereals \| PS cup | 0.67 ± 0.07 | 0.68 ± 0.16 | 0.68 ± 0.05 |
| Yogurt, chocolate \| PS cup | 1.31 ± 0.93 | 1.04 ± 0.20 | 1.18 ± 0.34 |
| Yogurt, fruits \| Twin-PP cup | 1.71 ± 0.89 | 1.72 ± 0.63 | 1.72 ± 0.30 |
| Yogurt, vanilla \| PS cup | 0.94 ± 0.19 | 1.20 ± 0.53 | 1.07 ± 0.26 |

**Note:**
Results are given in percent, variability of results in percentage points.

**Table 2** Technical emptiability results for milk and milk-based drinks.

| Dairy product | $EMPT_{22\,°C}$ (%) | $EMPT_{7\,°C}$ (%) | $EMPT_{22\,°C,\,7\,°C}$ (%) |
|---|---|---|---|
| Cafe Latté \| PET bottle | 0.48 ± 0.08 | 0.57 ± 0.10 | 0.53 ± 0.08 |
| Cafe Latté \| PP cup | 0.96 ± 0.81 | 1.54 ± 0.64 | 1.25 ± 0.54 |
| Chocolate milk \| Beverage carton, flat top | 1.13 ± 0.19 | 1.40 ± 0.46 | 1.26 ± 0.25 |
| Chocolate milk \| PET bottle, variant a | 0.86 ± 0.17 | 0.74 ± 0.36 | 0.80 ± 0.15 |
| Chocolate milk \| PET bottle, variant b | 0.92 ± 0.11 | 1.06 ± 0.22 | 0.99 ± 0.13 |
| L-free skimmed milk \| Beverage carton, gable top | 0.35 ± 0.08 | 0.35 ± 0.12 | 0.35 ± 0.04 |
| Low-fat milk \| Beverage carton, flat top | 0.35 ± 0.04 | 0.52 ± 0.16 | 0.43 ± 0.14 |
| Low-fat milk \| Beverage carton, gable top | 0.40 ± 0.10 | 0.51 ± 0.09 | 0.45 ± 0.09 |
| Whole milk \| Beverage carton, gable top | 0.28 ± 0.11 | 0.34 ± 0.07 | 0.31 ± 0.06 |
| Whole milk \| Glass bottle | 0.31 ± 0.05 | 0.33 ± 0.05 | 0.32 ± 0.03 |

**Note:**
Results are given in percent, variability of results in percentage points.

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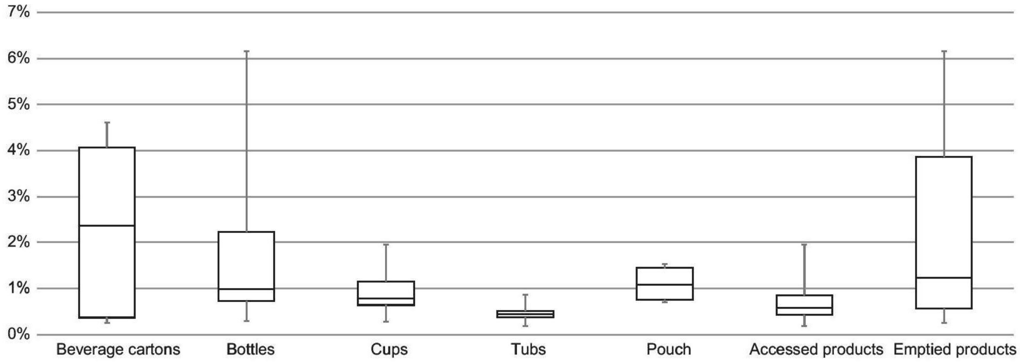


**Figure 8** **Emptiability results, grouped by types of packaging.**
Full-size DOI: 10.7717/peerj.7578/fig-8

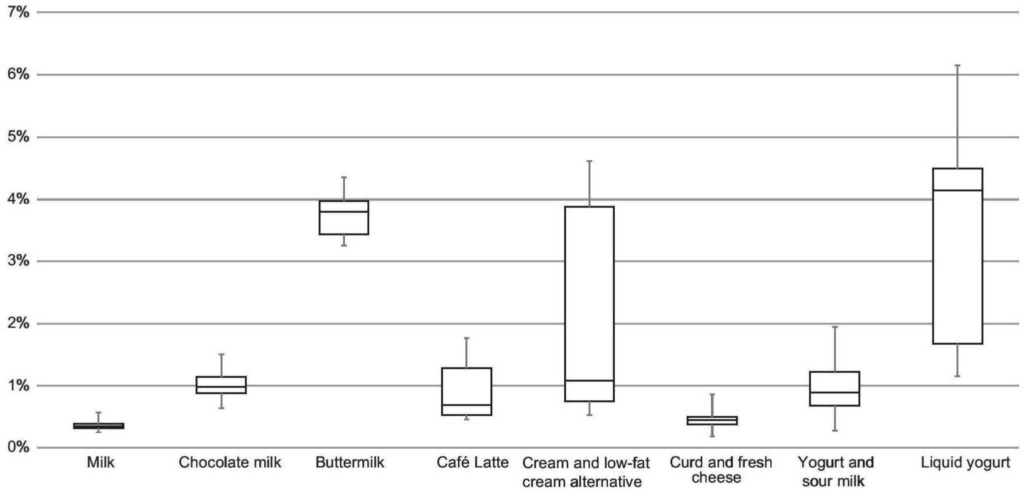


**Figure 9** **Emptiability results, grouped by types of dairy products.**
Full-size DOI: 10.7717/peerj.7578/fig-9

technical emptiability of dairy products in packaging that was emptied is better than in packaging that was accessed (i.e., spooned out).

In the case of low-fat cream alternative, the exact same food product is available in two different types of packaging (bottle and pouch). Here, the emptiability of the pouch is distinctly better due to its ability to be squeezed after pouring out the contents. Furthermore, buttermilk in beverage cartons with gable tops seems to have slightly better emptiability than in those with bottle-shaped tops.

For the most part, there are differences in emptiability results for 22 and 7 °C, particularly for café latte in a cup and low-fat cream alternative in a pouch. Nevertheless, no clear positive or negative trend between temperature and emptiability can be observed (Mann–Whitney-U test: $U = 641$; $p = 0.94$).

## Streamlined LCA results

Food comprises the largest percentage of each package examined, whereas primary packaging generally has a small contribution to the overall results, ranging from 1.6% to

**Table 3 Percentage increase in streamlined LCA results of primary packaging for milk and milk-based drinks due to technical emptiability.**

| Dairy product | Acidification | Respiratory effects, inorganics | Climate change | Eutrophication, terrestrial | Eutrophication, freshwater | Resource use, fossils |
|---|---|---|---|---|---|---|
| Cafe Latté \| PET bottle | 22 ± 3 | 18 ± 3 | 3 ± 0 | 50 ± 7 | 3 ± 0 | 1 ± 0 |
| Cafe Latté \| PP cup | 78 ± 34 | 45 ± 19 | 10 ± 4 | 164 ± 72 | 13 ± 6 | 4 ± 2 |
| Chocolate milk \| Beverage carton, flat top | 103 ± 21 | 44 ± 9 | 28 ± 6 | 181 ± 37 | 24 ± 5 | 8 ± 2 |
| Chocolate milk \| PET bottle, variant a | 41 ± 7 | 37 ± 7 | 6 ± 1 | 89 ± 16 | 5 ± 1 | 2 ± 0 |
| Chocolate milk \| PET bottle, variant b | 45 ± 6 | 37 ± 5 | 7 ± 1 | 100 ± 13 | 6 ± 1 | 3 ± 0 |
| L-free skimmed milk \| Beverage carton, gable top | 43 ± 5 | 18 ± 2 | 9 ± 1 | 77 ± 9 | 9 ± 1 | 3 ± 0 |
| Low-fat milk \| Beverage carton, flat top | 38 ± 13 | 18 ± 6 | 8 ± 2 | 74 ± 24 | 7 ± 2 | 3 ± 1 |
| Low-fat milk \| Beverage carton, gable top | 33 ± 7 | 15 ± 3 | 7 ± 1 | 63 ± 13 | 6 ± 1 | 2 ± 1 |
| Whole milk \| Beverage carton, gable top | 46 ± 9 | 20 ± 4 | 9 ± 2 | 83 ± 16 | 10 ± 2 | 3 ± 1 |
| Whole milk \| Glass bottle | 5 ± 0 | 3 ± 0 | 1 ± 0 | 11 ± 1 | 1 ± 0 | 1 ± 0 |

**Note:**
Results are given in percent, variability of results in percentage points.

52.4% for climate change (Data S3) (mean 12.8%, median 9.9%). The obtained streamlined LCA results of primary packaging are in line with other studies that report average climate change values of 5.0% (*Silvenius et al., 2011*), or between 7.0% and 13.9% in the case of milk packaging (*Licciardello, 2017*).

For all six impact categories identified as relevant, the impacts of primary packaging increase after including technical emptiability (Tables 3 and 4). These range from +1% (±0) for the fossil use of fresh cheese to +1,827% (±141) for the terrestrial eutrophication of cream in a beverage carton.

For climate change, the highest increase can be found for cream 23% fat (264% ± 20), liquid yogurt (87% ± 8) and buttermilk (51% ± 6) in beverage cartons. Regarding the impact on climate change, the inclusion of emptiability is of less relative importance for curd cheese, fresh cheese, and yogurt (3% ± 1 to 8% ± 2). This also applies to milk, particularly for whole milk in a glass bottle (1% ± 0), as well as to low-fat and skimmed milk in beverage cartons (7% ± 1 to 9% ± 1). For milk and milk-based drinks, emptiability is of higher importance for café latte in a PP cup (10% ± 4) and particularly for chocolate milk in a beverage carton (28% ± 6).

Acidification was identified as the most relevant impact category for the defined functional unit. In this category, beverage cartons with buttermilk, liquid yogurt and cream (1,045% ± 81) are again the packaging for which technical emptiability leads to the highest relative increase in impacts.

Different from the six relevant impact categories, also reductions of environmental impacts due to emptiability were calculated. This concerns the categories ozone layer depletion, land use and human toxicity (non-carcinogenic effects) (Data S3). The (imputed) decreases in ozone layer depletion and land use result mainly from the credits awarded by the incineration of packaging and thus the substitution of fossil fuels or biomass. The decrease in human toxicity is due to the heavy metal uptake of crops cultivated for animal feed contributing more to the overall impact than the generation of

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**Table 4 Percentage increase in streamlined LCA results of primary packaging for dairy products other than milk due to technical emptiability.**

| Dairy product | Acidification | Respiratory effects | Climate change | Eutrophication, terrestrial | Eutrophication, freshwater | Resource use, fossils |
|---|---|---|---|---|---|---|
| Buttermilk \| Beverage carton, bottle top, variant a | 279 ± 31 | 125 ± 14 | 51 ± 6 | 512 ± 56 | 66 ± 7 | 19 ± 2 |
| Buttermilk \| Beverage carton, bottle top, variant b | 272 ± 27 | 121 ± 12 | 50 ± 5 | 498 ± 50 | 65 ± 6 | 19 ± 2 |
| Buttermilk \| Beverage carton, gable top | 243 ± 9 | 106 ± 4 | 49 ± 2 | 437 ± 16 | 55 ± 2 | 17 ± 1 |
| Cream, 23% fat \| Beverage carton, flat top | 1,045 ± 81 | 426 ± 33 | 264 ± 20 | 1,827 ± 141 | 208 ± 16 | 72 ± 6 |
| Cream, 36% fat \| HDPE bottle | 99 ± 8 | 68 ± 5 | 8 ± 1 | 245 ± 20 | 34 ± 3 | 3 ± 0 |
| Cream, 36% fat \| PS cup | 165 ± 28 | 123 ± 21 | 15 ± 2 | 431 ± 73 | 60 ± 10 | 7 ± 1 |
| Curd cheese, creamy \| PS tub | 65 ± 20 | 47 ± 15 | 8 ± 2 | 166 ± 52 | 25 ± 8 | 4 ± 1 |
| Curd cheese, crumbly \| PS tub | 25 ± 11 | 18 ± 8 | 3 ± 1 | 63 ± 28 | 10 ± 4 | 2 ± 1 |
| Fresh cheese, herbs \| PP tub | 62 ± 22 | 44 ± 15 | 6 ± 2 | 152 ± 53 | 19 ± 7 | 3 ± 1 |
| Fresh cheese, radish \| PP tub, variant a | 41 ± 11 | 30 ± 8 | 5 ± 1 | 95 ± 25 | 10 ± 3 | 2 ± 1 |
| Fresh cheese, radish \| PP tub, variant b | 44 ± 7 | 32 ± 5 | 5 ± 1 | 104 ± 16 | 17 ± 3 | 3 ± 0 |
| Fresh cheese, sweet pepper \| PP tub | 44 ± 9 | 31 ± 7 | 5 ± 1 | 108 ± 23 | 14 ± 3 | 2 ± 0 |
| Fresh cheese, sweetened \| PS cup | 36 ± 7 | 28 ± 6 | 4 ± 1 | 93 ± 18 | 37 ± 7 | 2 ± 0 |
| Liquid yogurt \| Beverage carton, bottle top | 390 ± 19 | 170 ± 8 | 87 ± 4 | 700 ± 33 | 121 ± 6 | 35 ± 2 |
| Liquid yogurt \| Beverage carton, gable top | 318 ± 28 | 134 ± 12 | 87 ± 8 | 555 ± 50 | 99 ± 9 | 34 ± 3 |
| Liquid yogurt, blueberries \| PET bottle | 86 ± 7 | 73 ± 6 | 18 ± 1 | 184 ± 15 | 21 ± 2 | 13 ± 1 |
| Liquid yogurt, strawberry \| PET bottle | 37 ± 5 | 29 ± 4 | 6 ± 1 | 82 ± 12 | 8 ± 1 | 4 ± 1 |
| Liquid yogurt, vanilla \| PET bottle | 76 ± 19 | 61 ± 15 | 12 ± 3 | 172 ± 42 | 14 ± 3 | 6 ± 1 |
| Low-fat cream alternative \| PET bottle | 29 ± 1 | 25 ± 1 | 7 ± 0 | 61 ± 1 | 7 ± 0 | 5 ± 0 |
| Low-fat cream alternative \| Polymer pouch | 62 ± 31 | 51 ± 25 | 6 ± 33 | 146 ± 73 | 24 ± 12 | 3 ± 2 |
| Sour milk \| PP cup | 28 ± 20 | 14 ± 10 | 5 ± 1 | 57 ± 40 | 7 ± 5 | 3 ± 2 |
| Sour milk \| PS cup | 36 ± 7 | 27 ± 5 | 4 ± 1 | 91 ± 17 | 22 ± 4 | 3 ± 1 |
| Yogurt, cereals \| PS cup | 39 ± 3 | 31 ± 2 | 4 ± 0 | 103 ± 7 | 52 ± 4 | 2 ± 0 |
| Yogurt, chocolate \| PS cup | 36 ± 10 | 26 ± 8 | 5 ± 2 | 88 ± 26 | 12 ± 3 | 3 ± 1 |
| Yogurt, fruits \| Twin-PP cup | 49 ± 9 | 36 ± 6 | 7 ± 1 | 111 ± 20 | 11 ± 2 | 4 ± 1 |
| Yogurt, vanilla \| PS cup | 63 ± 15 | 47 ± 11 | 8 ± 2 | 162 ± 39 | 32 ± 8 | 5 ± 1 |

**Note:**
Results are given in percent, variability of results in percentage points.

emissions or waste. Apart from this, too much emphasis should not be placed on toxicity indicators since they are currently not very robust and therefore excluded from being communicated or added to the PEF single score (*Sala, Cerutti & Pant, 2018*).

# DISCUSSION

## Implications of technical emptiability

For the evaluation of the relevance of technical emptiability, existing LCA guidance documents may be used. ISO 14044 allows for a cut-off of inputs in LCA that contribute less than 1% to the total system regarding mass or energy (*ISO 14044, 2006*) while the PEF does not recommend any kind of cut-off in advance (*European Commission, 2017*). Additionally, the PEFCR for dairy products are encouraging the inclusion of primary data

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on FLW in LCA whenever available (*Bengoa, Dubois & Humbert, 2018*). According to ISO 14044 and its mass-related cut-off, food residues in the analyzed packages should be included except for milk, cream, cheese, sour milk, yogurt with cereals, and café latte in a PET bottle. However, following this approach would mean that the $GWP^{100}$ of, for example, a beverage carton for cream would be understated by the factor 2.6. Defining relevance as a percentage increase of under 5% after including food residues, then only the technical emptiability of four out of 36 analyzed products could be seen as insignificant for climate change results of primary packaging. However, after including more impact categories besides climate change, technical emptiability is relevant for every analyzed packaging and thus should definitely be considered in future studies.

The results show clearly that food residues are particularly important for resource-intensive foods and for packaging, which is resource-friendly, such as the beverage carton. Thus, for whole milk in a glass bottle, the relative contribution of food residues to the overall environmental impact of packaging is of less importance.

Additionally, it should be stated that while the increase of environmental impacts is certainly relevant when looking at packaging alone, the picture is different for the whole life cycle of the products, that is, after the food production is included. Here, the difference in environmental impacts between "one kg distributed food" and "one kg consumed food" only ranges from 0% to +2% for all products (Data S3). This shows once again that the production of food leads to much greater environmental impacts than that of packaging.

## Limitations regarding emptiability testing

In this study, a method to operationalize technical emptiability was proposed, a packaging attribute that clearly distinguishes itself from the potentially wasteful behavior of a consumer. Yet, while the results for products which are to be emptied (e.g., bottles) do not depend on the meticulousness of the person performing the tests, this may be different for spooned out products.

The temperature at which dairy products are consumed could be either room temperature, refrigerator temperature or somewhere in between. Therefore, the mean of both $EMPT_{22\ ^{\circ}C}$ and $EMPT_{7\ ^{\circ}C}$ was used, thus disregarding differences between temperatures. In future studies of products that are consumed only at a specific temperature, emptiability testing should also focus on this temperature.

The aim of this explorative study was to cover a broad range of products. With $n = 3$, this already resulted in 216 tests for the 36 products analyzed at both temperatures. As a result, the variability of technical emptiability for some products was quite large.

In future emptiability studies, the sample size should be increased if results with lower variability are required.

## Limitations regarding the evaluation of environmental impacts

No primary data was used for the calculations of the streamlined LCA of packaging and dairy products. Therefore, the actual environmental impacts of the investigated products may actually be lower or higher, depending on the energy and resource efficiency

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of the respective companies. Furthermore, the exact composition of dairy products was not known. Particularly, the amount of milk required for the production of these was estimated by dry mass allocation. Due to the fact that milk is the most environmentally substantial input in dairy products (*Famiglietti et al., 2019*), an over- or underestimation could have a major impact on the results.

For the assessment of EVOH used in the multi-layer polymer pouch, the dataset of ethylene vinyl acetate (EVA) was used as a proxy, hence not considering an otherwise additionally necessary production process. However, EVOH accounts for only 3% of its mass. Furthermore, a previous LCA study reports using EVA as a proxy as acceptable (*Humbert et al., 2009*).

Another limitation of this study is that only a generic dataset for the incineration of food was used, thus neglecting differences of food properties (i.e., lower heating values). Still, this life cycle stage only contributes a maximum of 0.24% to the overall climate change results and even less to other impact categories.

## CONCLUSIONS

The present results show that in the food-packaging system of dairy products in Austria, the food contents always account for the highest percentage in LCA results. Surprising is that for some products, food residues are responsible for even higher environmental impacts than their primary packaging. It should be noted that the goal of this study was to represent the "ideal consumer." Thus, the results for "practical emptiability" are probably even higher than for the derived technical emptiability, since it can be assumed that consumers are not emptying packages as meticulously as did the authors of this paper. Future research should be concerned with not only extending the method on testing technical emptiability in this paper, but also on finding approaches on how to measure practical emptiability.

Furthermore, it was not the focus of the study to investigate the relationship between packaging design and technical emptiability, which should also be addressed in future research. Nevertheless, the results of this study indicate that food products are at greater risk of causing higher amounts of food residues if there are contained in packaging where the contents are not easy to access (i.e., bottles and beverage cartons).

Presumably, food residues in packaging cause severe economic and ecological implications as food lost due to poor emptiability may add up to vast quantities for whole markets. Furthermore, European countries are obliged to introduce plastic packaging which is 100% recyclable to the market and to drastically increase the recycling rate of plastic packaging by 2030 (*European Commission, 2018*; *European Parliament, 2018*). Hence, packaging designers should develop packaging with good emptiability in addition to good recyclability due to the interference of food residues with the recycling process (*Meurer et al., 2017*; *Maris et al., 2018*). Measuring technical emptiability is only possible with already existing packaging, hence making a priori evaluation difficult. However, some packaging features can already be considered by

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designers, such as the use of wide necks or designing packaging that can be stood upside down (*Packaging SA, 2017*).

Several LCA analysts (*Flysjö, 2011*; *Williams & Wikström, 2011*; *Grant, Barichello & Fitzpatrick, 2015*; *Manfredi et al., 2015*; *Verghese et al., 2015*; *Gruber et al., 2016*; *Heller, Selke & Keoleian, 2018*) already incorporate FLW into their work on packaging. Food residues can have substantial environmental impacts, and in some cases even greater than that of the respective packaging. Thus, it is crucial that future comparative studies of packaging also include emptiability, since this could change the identification of the most environmentally friendly option.

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## ADDITIONAL INFORMATION AND DECLARATIONS

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The authors received no funding for this work.

### Competing Interests

The authors declare that they have no competing interests.

### Author Contributions

- Bernhard Wohner conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Nicole Schwarzinger conceived and designed the experiments, performed the experiments, analyzed the data, approved the final draft.
- Ulla Gürlich conceived and designed the experiments, performed the experiments, analyzed the data, approved the final draft.
- Victoria Heinrich conceived and designed the experiments, approved the final draft.
- Manfred Tacker conceived and designed the experiments, contributed reagents/materials/analysis tools, approved the final draft.

### Data Availability

The following information was supplied regarding data availability:

Tables with descriptions of all dairy products regarding food (nutritional values, list of ingredients) and packaging (material and mass of individual packaging components) are available in the Supplemental Files.

### Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.7578#supplemental-information.

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# 9 Full text: Paper III

Wohner B, Gabriel VH, Krenn B, Krauter V, Tacker M. Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup. *Science of The Total Environment* 2020; **738**: 139846.

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# Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup

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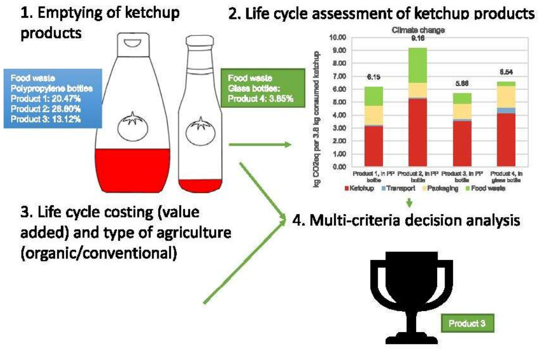
## HIGHLIGHTS

- Ketchup waste due to poor emptiability ranged from 3.85% (±0.41) to 28.80% (±3.30).
- Emptiability of ketchup in glass packaging is better than in polypropylene bottles.
- Glass packaging has greater environmental impacts than polypropylene bottles.
- Including packaging-related FLW can alter the ranking of products.
- Poor emptiability increases costs to the consumer but also economic value added.

## GRAPHICAL ABSTRACT

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## ABSTRACT

In this paper, a sustainability evaluation method for food-packaging systems is proposed. First, food waste due to poor emptiability was determined. Then, these quantities were included in life cycle assessments (LCA) and life cycle costing (value added, VA) of the products. Finally, LCA and VA results were combined using multi-criteria decision analysis, Technique for Order by Similarity to Ideal Solution (TOPSIS), in order to identify the most sustainable food packaging system.

As a case study, four different ketchup products were examined. For ketchup in polypropylene bottles, FLW resulting from poor emptiability ranged from 13.12% (±2.05) to 28.80% (±3.30) respectively, while this was only 3.85% (±0.41) for ketchup packaged in glass. After integrating the emptiability results into life cycle assessments, this resulted in greenhouse gas emissions of 5.66 to 9.16 kg $CO_{2eq}$ per 3.80 kg consumed ketchup, the average consumption per capita in Austria. Importantly, poor emptiability of the examined products led to greater environmental impacts than the associated packaging. While greater product loss also pushes up the costs for consumers, it contributes to more value added to the economic system, which is in stark contrast to the goal of decoupling the economy from resource consumption.

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*Abbreviations:* AC, acidification; CC, climate change; CNV, conventional agriculture; CRITIC, Criteria Importance through Intercriteria Correlation; EMPT, emptiability; FEU, eutrophication, freshwater; FLW, food losses and waste; FRD, resource use, fossils; FU, functional unit; GL, glass; LCA, life cycle assessment; MCDA, multi-criteria decision analysis; PP, polypropylene; ORG, organic agriculture; PEF, product environmental footprint; PM, particulate matter; TOPSIS, technique for order by similarity to ideal solution; VA, value added; WU, water use.

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## 1. Introduction

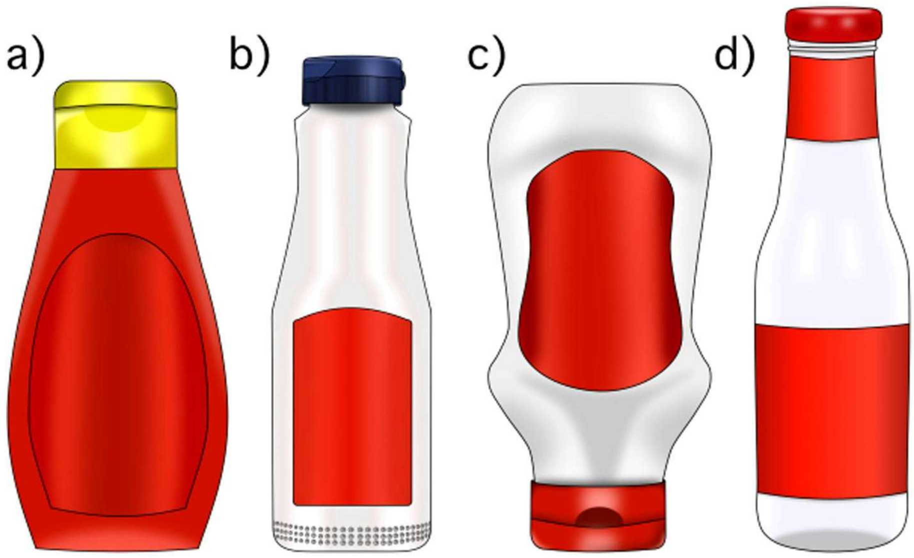
Today, the world's economy is mainly based on a linear model. Recent studies suggest that globally, only 9% of all raw materials are reused, recycled or composted after their use (de Wit et al., 2018). Concerning the European Union (EU), only 67% of packaging and 46% of municipal waste is currently recycled (eurostat, 2019a). As a result, initiating a transformation towards a circular economy by adopting the ‘Circular Economy Package’ has become one of the top priorities of the EU (European Commission, 2019b).

This package includes goals such as requiring full recyclability or reusability of packaging (European Commission [DG ENV - Directorate C], 2018), increased recycling quotas of packaging as well as halving food waste by 2050 or 2030 respectively (The European Parliament and the Council, 2018). In Austria, only 25% of plastic packaging is currently recycled (Altstoff Recycling Austria AG, 2018), meaning that this must be approximately doubled by 2030 to fulfill the mandatory quota of 55%.

As a possible solution, in addition to increasing the recyclability of plastic packaging, a general reduction of plastic is highly discussed. Such a reduction has further gained fresh prominence due to increasing public disdain concerning plastic. This has been addressed by several Austrian food retailers, who declared the reduction of plastic packaging in their mission statements (HOFER, 2018; REWE Group, 2018; SPAR, 2019). Furthermore, the reduction of plastic packaging by 20% to 25% was officially declared a goal of the Austrian government in 2018 (Bundeskanzleramt, Bundesministerium Öffentlicher Dienst und Sport, Bundesministerium Nachhaltigkeit und Tourimus, 2018). However, environmental benefits of reducing the quantity of plastic packaging could even lead to greater environmental impacts when it is substituted by other materials such as paper, glass or metal (Pilz et al., 2010). Furthermore, a reduction or substitution of plastic packaging could increase the generation of food loss and waste (FLW) (Pauer et al., 2019; Wohner et al., 2019a). While much research has been carried out on the evaluation of direct environmental impacts of packaging by conducting life cycle assessments (LCA), there is still very little scientific understanding of indirect effects (Molina-Besch et al., 2018; Wohner et al., 2019a). Since protecting food is in fact the main function of packaging (Lindh et al., 2016; Pauer et al., 2019), sustainability evaluations of packaging should not be carried out without considering its impact on the filling good and thus of holistic evaluations of food together with its associated packaging (food-packaging systems) (Pauer et al., 2019). With 14% of food being lost between post-harvest and retail level (FAO, 2019) together with older estimates of 30% being lost across the whole supply chain (Gustavsson et al., 2011), it is clear however that FLW and therefore indirect effects of packaging are a pressing concern. Several authors already focus on assessing FLW by using LCA (Beretta and Hellweg, 2019; Scherhaufer et al., 2018), with an increasing number of authors integrating FLW into the LCA of packaging (Molina-Besch et al., 2018). Among other aspects, this includes (i) FLW related to packaging being difficult to empty (Meurer et al., 2017; Williams et al., 2012; Williams and Wikström, 2011; Wohner et al., 2019b), (ii) calculation of break-even rates between the volume of packaging material and FLW (Bacenetti et al., 2018; Yokokawa et al., 2018) or (iii) modelling the quantity of FLW based on shelf life (Conte et al., 2015).

According to Pauer et al. (2019), evaluations of food-packaging systems should include direct and indirect environmental effects, in addition to circularity assessments, yet without proposing a combined evaluation method. Niero and Kalbar (2019) already combined direct environmental effects (LCA results) of packaging and circularity metrics using multi-criteria decision analysis (MCDA). In context of this research, however, we argue that circularity parameters such as recycled content or recycling quotas may affect LCA results, thus violating the rules of using only independent attributes in MCDA (Belton and Stewart, 2003).

In summary, the aim of the present paper is to analyze packaging-related FLW of food-packaging systems in order to integrate it into environmental and economic assessments. Against this background, a case study on tomato ketchup is conducted. Emptiability is quantified, which is then integrated into LCA and life cycle costing (LCC) of the products. Finally, the most sustainable product is identified by using multi-criteria decision analysis (MCDA).




g. 1. Ketchup products chosen as illustrative examples. a) Conventional ketchup, produced in Austria, 450 g indicated filling quantity, 29.99 g colored polypropylene (PP) bottle with .81 g colored PP cap, 0.28 g multilayer seal (assuming a composition of 52% polyethylene, 25% polyethylene terephthalate, 17% adhesive and 6% aluminum) and 0.97 g PP labels. 2 g tomatoes per 100 g ketchup. Sales price: 1.99 € (PP-450-CONV). b) Organic ketchup, produced in Austria, 380 g indicated filling quantity, 22.30 g clear transparent PP bottle ith 4.36 g colored PP cap, 0.29 g multilayer seal and 0.63 g PP labels. Sales price: 2.99 € (PP-380-ORG). c) Organic ketchup, produced in the Czech Republic, 550 g indicated filling quantity, .96 g clear transparent PP bottle with 9.79 g colored PP cap, 0.32 g multilayer seal and 1.27 g paper labels. 210 g tomatoes per 100 g ketchup. Sales price: 1.99 € (PP-550-ORG). d) Organic tchup, produced in Italy, 480 g indicated filling quantity, 236.61 g flint packaging glass with 4.88 g tinplate screw cap and 1.29 g paper labels. 225 g tomatoes per 100 g ketchup. Sales ice: 1.45 € (GL-480-ORG).

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## 2. Materials and methods

In this section, we first present the case study. Based on this, selected criteria and their quantification is discussed. Finally, the selection and calculation of a suitable method for the sustainability evaluation is presented.

### 2.1. Case study: tomato ketchup

Tomato ketchup was chosen as a case study. Ketchup is made from fresh tomatoes or tomato puree, sugar and/or sweetener, spices and seasoning, salt and vinegar. The final product must have a minimum of 28% dry mass (Bundesministerium für Arbeit, Soziales, Gesundheit und Konsumentenschutz, 2015). In Austria, 3.8 kg of ketchup is consumed per capita and year (Statista GmbH, 2019).

The following products of different brands were purchased at various supermarket chains (Fig. 1):

### 2.2. Life cycle assessment

Life cycle assessment is a well-known method to assess environmental impacts across the life cycle of a product, frequently used in food and food packaging studies (Fraval et al., 2019). LCA for this article was based on ISO 14040 (ISO, 2006a) with additional guidance from the Product Environmental Footprint (PEF) (European Commission, 2017), which is being currently developed by the European Commission. In contrast to ISO 14040, the PEF guidance includes stricter recommendations. For this study, the PEF guidance was used for:

- Selection of life cycle impact categories
- Identification of the most relevant life cycle impact categories
- Default transport distances
- Allocation regarding input and output of secondary materials

Calculations were performed using OpenLCA and the Ecoinvent 3.5 database. LCA for the case study was limited to secondary data only. This type of LCA method can be considered as 'streamlined LCA', which has the benefit of reducing the expenditure of time and resources (Speck et al., 2015).

#### 2.2.1. Functional unit, reference flow and system boundaries

The functional unit (FU) was defined as 'consumption of 3.8 kg ketchup'. This led to different reference flows for the examined products, determined by the loss of ketchup due to poor emptiability. As an example, if 50% of food loss and waste (FLW) occurs at the consumer, all environmental impacts up to the point of loss are doubled (Wikström et al., 2014). System boundaries and the resulting presented life cycle stages include:

- Packaging: Raw materials, manufacturing of glass and plastic bottles, transport of empty bottles to the ketchup production site, disposal of packaging
- Ketchup processing: Cultivation of tomatoes and sugar, thermal and electrical energy used in the production of ketchup
- Transport of the final product to an Austrian supermarket
- Transport of the final product from the supermarket to the home of the consumer
- Food loss and waste: Calculated as the difference between provisioned and consumed ketchup

#### 2.2.2. Life cycle inventory of packaging manufacturing

Ketchup bottles were first emptied (see Section 2.2.8) before the packaging was disassembled and weighed. Packaging manufacturing was then modelled using Ecoinvent datasets, taking the respective datasets for the raw materials and their manufacturing processes. No recycled content was assumed for plastic packaging and 40% for flint glass bottles (European Commission, 2019a). Transport distances between the packaging manufacturers to the ketchup production site were assumed to be (i) 230 km by truck, (ii) 280 km by train and (iii) 87 km by ship for plastic bottles. For glass bottles a transport of (i) 350 km by truck, (ii) 39 km by train and (iii) 87 km by ship was chosen (European Commission, 2017).

#### 2.2.3. Life cycle inventory of agricultural production

For the life cycle inventory of ketchup, the quantity of tomatoes used in processing was taken from the label. From this, the quantity of added sugar was calculated after subtracting the stated sugar content from the sugar contained in the tomatoes, assuming a sugar content of 2.6% and a water content of 95% of the average fruit (USDA, 2019). Among the examined products were ones of organic and conventional agriculture. Organic farming is often associated with reduced farm inputs and higher soil carbon sequestration, therefore reducing environmental impacts compared to conventional agriculture. However, there is an ongoing debate concerning the actual sustainability of organic agriculture, since this agricultural practice often leads to lower yields, which increases greenhouse gas emissions in some cases (Smith et al., 2019). Regarding tomatoes, organic agriculture may have lower (He et al., 2016; Ronga et al., 2019) or higher yields (Stanhill, 1990), which in turn leads to lower (He et al., 2016) or higher (Ronga et al., 2019; Vermeulen and CJM, 2011) environmental impacts compared to conventional tomatoes. Moreover, comparative LCA studies of organic and conventional agriculture are not always able to capture the differences (Meier et al., 2015). For this paper, it was assumed that organic agriculture is a beneficial concerning sustainability due to it having multiple ecological and social benefits, such as greater biodiversity and fewer potential negative effects on human health (Shennan et al., 2017). Nonetheless, there is no Ecoinvent dataset available for organic tomatoes. Since the impact of organic agriculture could not be considered in the LCA, it was included as an additional criterion. Quantification of organic agriculture was carried out by assigning a value of '1' for products of organic, and a value of '0' for products of conventional agriculture. Other ingredients of tomato ketchup such as vinegar and spices were excluded from the analysis due to their small and unknown quantities.

#### 2.2.4. Life cycle inventory of ketchup processing

In the manufacturing process of ketchup, tomatoes are heated with steam to up to 99 °C (Amón et al., 2015). Thermal energy consumption of this process was calculated as the product of the latent heat of vaporization of water at 100 °C (2.26 MJ/kg) and the volume of water needed to be evaporated to achieve the final water content of the respective ketchup. This water content was estimated as the difference between 100% and the sum of carbohydrates, fat, protein and assumed average ash content of 3% (Sharoba et al., 2005). It was assumed that waste heat is not recovered (Amón et al., 2015). The electricity consumption of ketchup manufacturing was taken from existing literature (Andersson et al., 1998). Country-specific electricity mixes and transport distances to Austria were considered, with a modal split of 75% lorry and 25% freight train (eurostat, 2019b) (eurostat, 2019b) for international transports. The following distances for the transport of the final products between productions sites and Austrian retail were estimated:

- Ketchup produced in Austria: 200 km
- Ketchup produced in the Czech Republic: 375 km
- Ketchup produced in Italy: 950 km

#### 2.2.5. Transports of final products

The transport of the final products between the supermarket and the home of the consumer was assumed to be 5 km, of which 62% were allocated to a passenger car with a trunk of load of 200 l, 5% to a van and 33% were not allocated (Castellani et al., 2018; European Commission, 2019a). As a result, the distribution of 1 l ketchup is associated with 0.0155 km driven by passenger car.

A summary of data concerning the modelled foreground system is presented in Table 1.

### 2.2.6. Selection of impact categories

Initially, all 16 impact categories recommended by PEF (Castellani et al., 2018) were calculated. Then, the PEF guidance was followed for the selection of the most relevant impact categories.

First, all impact categories were normalized, meaning that their magnitude of relative to a reference information (ISO, 2006b) (in the context of PEF the impacts of an average world citizen per year) were calculated. Next, the normalized values were weighted using the values provided by the PEF guidance. Accordingly, the three toxicity impact categories shall not be used for benchmarking with assigned weights of 0%, since their methodology is not yet considered as robust enough. Finally, the most relevant impact categories were identified based on the ones that contribute at least 80% to the total sum (European Commission, 2017). Relevant impact categories were the same for all products. This is also true for their order of contribution except for GL-480-ORG, where the ranks of particulate matter and acidification are swapped (Table 2).

Consequently, results of the most relevant impact categories per functional unit are used as criteria in the MCDA. Normalized and weighted results were only used for the procedure of selecting the most relevant impact categories. Results of all impact categories, their respective contribution to the total, as well as normalization and weighting factors are listed in the supplementary material.

### 2.2.7. End-of-life and allocations

The use of recycled content and the disposal of the packaging was modelled according to the Circular Footprint Formula listed in the PEF guidance (European Commission, 2017). Energy savings of 2.5% per 10% recycled content are assumed for the production of glass bottles (Stettler et al., 2016). Life cycle inventory data of plastic recycling processes in Austria was taken from literature (van Eygen et al., 2018b), with quality factors of recyclate of 1.00 for glass and metal (European Commission, 2019a), as well as 0.67 for polypropylene (calculated as the average ratio of market prices between September 2018 and 2019 (plasticker et al., 2019)).

For this article, it was assumed that PP bottles contaminated with ketchup can be recycled. However, this might not be true since ketchup residues may affect the sorting and/or recycling process as has been shown for PET bottles (Boesveld, 2011). It was assumed that all PP bottles consist of 5% by weight of ethylene vinyl alcohol (Hedenqvist, 2018), which still allows the bottle to be recycled (FH Campus Wien, 2019). Consequently, the only non-recyclable packaging components were multilayer seals and paper labels.

Recycling rates in Austria are 14% for polypropylene bottles (van Eygen et al., 2018a), 84% for glass and 86% for metal packaging (eurostat, 2019c). Polypropylene caps are currently not recycled in Austria (van Eygen et al., 2018a). Due to landfill restrictions in Austria (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2008), only non-recycled quantities of metal and glass packaging were assumed to be landfilled, while non-recycled plastic packaging was assumed to be incinerated.

### 2.8. Indirect environmental effects due to FLW

Quantifying packaging-related FLW is challenging (Wohner et al., 2019a) and therefore often omitted in studies of food-packaging systems (Molina-Besch et al., 2018). In a previous study we proposed a method for testing dairy products on their 'technical emptiability' and its integration in LCA studies (Wohner et al., 2019b) as a possibility to measure packaging-related FLW. For the present case study, not only technical but also practical emptiability was tested. Finally, the results of practical emptiability were taken to calculate the respective reference flows of the investigated products associated with the functional unit.

Practical emptiability simulates an average emptying behavior by the consumer. For plastic bottles, first the bottles were shaken three times and squeezed until air was released. Next, the bottles were swiveled and then squeezed again until air was released. This step was repeated three times. Glass bottles were shaken three times and then held upside down for 2 min. Subsequently, the bottles were shaken three times and then held upside for 1 min.

Technical emptiability represents the best possible emptying procedure without damaging the packaging. For this, both glass and plastic bottles including their caps were scraped with a dedicated ketchup spoon (length of 24.5 cm) after practical emptiability tests.

Finally, the emptiability index was expressed as the ratio of ketchup left in the bottle to the original filling quantity. Testing was performed at room temperature (22 °C ± 1). Based on previous studies, a sample size of 6 was taken to assure significant results (Meurer et al., 2017; Wohner et al., 2019b).

## 2.3. Economic assessment

Life cycle costing is an approach often used for the economic evaluation of a product. 'Conventional' LCC represents the historic practice of economic assessments, which includes costs associated with a product and which are generally presented only from one, the producer's or consumer's, perspective (Hunkeler et al., 2008). Further, conventional LCC is often performed not all along the entire supply chain, often excluding End-of-Life operations. In contrast, 'environmental LCC' is performed alongside LCA, using the same system boundaries and models and thus covering the whole life cycle of a product. Moreover, by including the full life cycle, environmental LCC enables the economic evaluation of a product from a system's perspective. Therefore, according to Hunkeler et al. (2008), environmental LCC should be the approach of choice for sustainability assessments. Hence, the economic evaluation in this paper is conducted taking the 'value added' approach (VA). Generally, the revenues (R) for selling a product are higher than its production costs (C) (Heijungs et al., 2013), resulting in a margin which is referred to as "added value", given in a monetary unit, in this study Euro (€).

$$VA = R - C$$

Consequently, the total life cycle cost is the "sum of all value added over the life cycle" (Moreau and Weidema, 2015). Since environmental impacts are already covered by the LCA, their associated costs are not included in VA, as this would be considered as double-counting.

In this paper, VA is calculated following the same principles as for the LCA. Therefore, the final VA result is the sum of value added by the production and disposal of ketchup, its packaging and all related transport, with additional consideration of the final sales price. This can be expressed as follows:

$$VA_{Total} = VA_{IN} - C_{IN} + VA_{EN} - C_{EN} + VA_{PA} - C_{PA} + VA_{TR} - C_{TR} + R_{PU} - C_{PU} + VA_{EoL}$$

where:

- $VA_{Total}$: Total VA of the respective product
- $VA_{IN}$: VA of agricultural production of ingredients (tomatoes and sugar) (calculated as the total of the difference between costs for producing and revenues of selling tomatoes or sugar, and the VA for all upstream processes)
- $C_{IN}$: Costs to the ketchup producer for purchasing ingredients
- $VA_{EN}$: VA of thermal and electrical energy production (calculated as the total of the difference between costs for producing and revenues of selling energy, and the VA for all upstream processes)
- $C_{EN}$: Costs to the ketchup producer for purchasing energy

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**Table 1**
Summary of data for modelling the foreground system. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture. Data are given per kg produced and distributed ketchup. Remaining abbreviations represent: PP, polypropylene; vkm, vehicle-kilometer; tkm, ton-kilometer.

| | | Unit | PP-450-CNV | PP-380-ORG | PP-550-ORG | GL-480-ORG |
|---|---|---|---|---|---|---|
| Ingredients | Tomatoes | kg | 1.72 | 2.85 | 2.10 | 2.25 |
| | Added sugar | kg | 0.14 | 0.15 | 0.09 | 0.16 |
| Energy consumption for processing | Electricity | MJ | 0.38 | 0.38 | 0.38 | 0.38 |
| | Thermal energy (steam) | MJ | 2.34 | 4.82 | 2.97 | 3.62 |
| Packaging | PP bottle (blow moulded) | g | 66.50 | 59.17 | 55.60 | 0 |
| | Glass bottle | g | 458.84 | 0 | 0 | 0 |
| | PP cap (injection moulded) | g | 23.97 | 11.57 | 17.58 | 0 |
| | Tinplate cap | g | 0 | 0 | 0 | 9.46 |
| | Multilayer seal | g | 0.62 | 0.77 | 0.57 | 0 |
| | PP label | g | 2.15 | 1.67 | 0 | 0 |
| | Paper label | g | 0 | 0 | 2.28 | 2.50 |
| Transport from manufacturer to retail | Lorry | tkm | 0.22 | 0.21 | 0.30 | 1.03 |
| | Freight train | tkm | 0 | 0 | 0.10 | 0.37 |
| Transport from retail to consumer | Passenger car | vkm | 0.014 | 0.019 | 0.014 | 0.014 |
| | Van | tkm | 0.0001 | 0.0001 | 0.0001 | 0.0002 |

- $VA_{PA}$: VA of packaging production (calculated as the total of the difference between costs for producing and revenues for selling packaging, and the VA for all underlying processes)
- $C_{PA}$: Costs to the ketchup producer for purchasing packaging
- $VA_{TR}$: VA of transports (calculated as the total of difference between costs and revenues for providing transport, and the VA for all upstream processes)
- $C_{TR}$: Costs to the ketchup producer for the transport of products
- $R_{PU}$: Revenue to the ketchup producer for selling ketchup to the consumer
- $C_{PU}$: Costs to the consumer for purchasing ketchup from the producer
- $VA_{EOL}$: VA of disposal of ketchup and packaging (calculated as the total of the difference between costs and revenues of recycling or incineration of ketchup or packaging, and the VA for all upstream processes)

For the calculation, default values available in the Ecoinvent 3.5 database version of OpenLCA were taken (Ciroth, 2016a). In OpenLCA, prices already contained but hidden in several Ecoinvent datasets were made visible by the software publisher, with information on costs added to further datasets (Ciroth, 2016b). Similar to the conducted LCA, a major limitation is that possible differences between organic and conventional tomatoes could not be considered due to a lack of data in Ecoinvent.

### 2.4. Multi-criteria decision analysis

#### 2.4.1. Selection and calculation

The examined products show different results between LCA impact categories, as well as between LCA and VA results in general. Hence, the need for a method to decision making tool arises, able to solve multi-dimensional issues. In this context, multi-criteria decision analysis methods are increasingly used to identify the best possible solution out of several alternatives (Wątróbski et al., 2019a). Based on the listed criteria, a suitable MCDA method was defined as being able to (i) take different weights into account, (ii) compare criteria on a quantitative scale and (iii) generate a ranking. Using the MCDA tool (Wątróbski et al., 2019b), TOPSIS (Hwang et al., 1993) was identified as a method meeting these requirements. The following terms are defined for better readability and are frequently used in MCDA:

- Alternative: Several predetermined, limited and independent alternatives. For this study, these are the four examined products (Alinezhad and Khalili 2019).
- Criterion: A particular perspective according to which alternatives may be compared (Belton and Stewart, 2003). In the context of this study, these are comprised of the six chosen LCA impact categories and the VA.
- Attribute: a "quantitative or qualitative measure of performance associated with a particular criterion" (Belton and Stewart, 2003), which can be either beneficial (with the goal of maximization) or non-beneficial (with the goal of minimization). In this study, the attributes are the results of VA and the chosen LCA impact categories, with the former considered as being beneficial, and the latter as being non-beneficial.
- Normalization: Converting attributes into non-dimensional form to allow their aggregation into a final score (Jahan and Edwards, 2015; Vafaei et al., 2016)

The general calculation steps of TOPSIS can be summarized as follows (ÇELEN, 2014; Hwang et al., 1993; Kumar et al., 2017):

**Table 2**
Most relevant life cycle impact categories, in descending order of their relevance.

| Impact category | Indicator | Unit | Life cycle impact assessment method |
|---|---|---|---|
| Climate change (CC) | Radiative forcing as Global Warming Potential (GWP100) | kg $CO_{2eq}$ | IPCC 2013 (IPCC, 2013) |
| Resource use, fossils (FRD) | Abiotic resource depletion – fossil fuels (ADP-fossil) | MJ | CML 2002 (Bruijn et al., 2004) |
| Water use (WU) | User deprivation potential (deprivation-weighted water consumption) | $m^3$ $world_{eq}$ | Available Water Remaining (AWARE) (UNEP, 2016) |
| Eutrophication, freshwater (FEU) | Fraction of nutrients reaching freshwater end compartment (P) | kg $P_{eq}$ | EUTREND model (Goedkoop et al., 2013) |
| Acidification (AC) | Accumulated Exceedance (AE) | mol $H+_{eq}$ | Accumulated Exceedance (Posch et al., 2008) |
| Particulate matter (PM) | Impact on human health | Disease incidence | PM method (UNEP, 2016) |

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1. Creation of a decision matrix

$$X = (x_{ij})_{mxn}$$

consisting of $m$ alternatives ($A_1, A_2, \ldots, A_m$) and $n$ criteria ($C_1, C_2, \ldots, C_n$), with the intersection of each alternative and criteria given as $x_{ij}$.

2. Normalization of the decision matrix:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}$$

where $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$

3. Calculation of the weighted normalized decision matrix by multiplication of the normalized matrix with the attribute's weights ($w_j$):

$$v_{ij} = w_j * r_{ij},$$

$i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$where $w_j = \frac{W_j}{\sum_{i=1}^{n} W_i}$ j = 1, 2, …, n

4. Determination of worst alternative $A_w$ (or negative ideal solution) and best alternative $A_b$ (or positive ideal solution):

$$A_w = \{\langle \max(v_{ij} | i = 1, 2, \ldots, m) | j \in J_-\rangle, \langle \min(v_{ij} \mid i = 1, 2, \ldots, m) | j \in J_+\rangle\}$$
$$\equiv \{v_{wj} \mid j = 1, 2, \ldots, n$$

$$A_b = \{\langle \min(v_{ij} | i = 1, 2, \ldots, m) | j \in J_-\rangle, \langle \max(v_{ij} \mid i = 1, 2, \ldots, m) | j \in J_+\rangle\}$$
$$\equiv \{v_{bj} \mid j = 1, 2, \ldots, n,$$

where for beneficial attributes:

$$J_+ = \{j = 1, 2, \ldots, n \mid j,$$

and for non-beneficial attributes:

$$J_- = \{j = 1, 2, \ldots, n \mid j$$

5. Calculation of the Euclidean distance of each alternative to the worst ($d_{iw}$) and best solution ($d_{ib}$):

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{wj})^2}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_{bj})^2}$$

where $i = 1, 2, \ldots, m$

6. Calculation of the relative closeness ($CC_i$) of each alternative to the ideal solution:

$$CC_i = \frac{d_{iw}}{d_{iw} + d_{ib}}$$

7. Ranking of the alternatives according to $CCi$ (i = 1, 2, …, $m$)

Individual calculation steps of TOPSIS for the case study are listed in the supplementary material.

*2.4.2. Determination of weights*

Determination of criteria weights is equally crucial and controversial since there is an abundant number of methods regarding this procedure which all produce different results and thus considerably influence the outcome of an MCDA. Such methods can be classified either (i) a priori, where weights are determined before data is collected, or (ii) a posteriori, were the determination of weights occurs after data collection. While a priori weights are generally elicited by expert interviews or questionnaires, a posteriori weights are calculated based on the collected data for each alternative (Kao, 2010).

For this paper, three weighting sets were calculated and used for TOPSIS, namely (i) equal weighting, (ii) Criteria Importance through Intercriteria Correlation (CRITIC) (Diakoulaki et al., 1995) and (iii) entropy (Li et al., 2011), similar to a sustainability assessment of biodiesel (Anwar et al., 2019).

*2.4.2.1. Equal weighting.* Equal weighting is the simplest type of weighting method, in which each criterion is given the same importance. In this study, 8 criteria were selected, which results in a weight ($w_j$) of 12.5% per criteria.

$$w_j = \frac{1}{8}$$

*2.4.2.2. Weights of criteria using CRITIC.* Calculating weights using CRITIC is performed by characterizing each vector by its standard deviation and a subsequent construction of a symmetric matrix with linear correlation coefficients between the vectors (Alinezhad and Khalili 2019).

First, the decision matrix is normalized as follows:

$$x_{ij} = \frac{r_{ij} - r_i^-}{r_i^+ - r_i^-}$$

$$x_{ij} = \frac{r_{ij} - r_i^+}{r_i^- - r_i^+},$$

where $i = 1, \ldots, m$ and $j = 1, \ldots, n$ and $x_{ij}$ representing the normalized value for alternative $i$ and attribute $j$, with

$$r_i^+ = \max(r_1, r_2, \ldots, r_m)$$

$$r_i^- = \min(r_1, r_2, \ldots, r_m)$$

Then, the correlation coefficient between attributes is calculated as follows:

$$\rho_{jk} = \frac{\sum_{i=1}^{m} (x_{ij} - \overline{x_j})(x_{ik} - \overline{x_k})}{\sqrt{\sum_{i=1}^{m} (x_{ij} - \overline{x_j})^2 \sum_{i=1}^{m} (x_{ik} - \overline{x_k})^2}}.$$

with $\overline{x_j}$ and $\overline{x_k}$ representing the mean of jth and kth attributes, calculated as

$$\overline{x}_j = \frac{1}{n} \sum_{j=1}^{n} x_{ij}$$

$$\overline{x}_k = \frac{1}{n} \sum_{k=1}^{n} x_{ik},$$

where i = 1, 2, …, m.

After that, the standard deviation of each attribute is calculated as

$$\sigma_j = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_{ij} - \overline{x}_j) 2},$$

where $i = 1, \ldots, m$.

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Next, the index (C) is calculated as:

$$C_j = \sigma_j \sum_{k=1}^{n} \left(1 - \rho_{jk}\right)$$

Finally, the weight of attributes is derived by:

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j}$$

*2.4.2.3. Weights of criteria using entropy*. First, the decision matrix is normalized as follows:

$$\overline{r_{ij}} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}},$$

where $j = 1, 2, \ldots, n$ and $\overline{r_{ij}}$ is the normalized value of the decision matrix.

Then, the degree of entropy is determined:

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \overline{r}_{ij} \ln \overline{r}_{ij},$$

where $j = 1, 2, \ldots, n$ and $0 < E_j < 1$.

Next, the deviation rate is calculated by:

$$d_j = 1 - E_j,$$

where $j = 1, 2, \ldots, n$.

Finally, weights of attributes are derived by:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

## 3. Results and discussion

### 3.1. Emptiability

Practical emptiability of the examined bottles ranges from 3.85% (± 0.41) to 28.80% (±3.30), while this can be substantially reduced to between 3.37% (±0.29) and 7.08% (±0.61) when a spoon is used ('technical emptiability') (Fig. 2). Variability was calculated as 95% confidence intervals.

In previous studies, the emptiability index of ketchup was reported as 0.5% to 26% (Andersson et al., 1998) in PP bottles and 30% to 52% (Boesveld, 2011) in PET bottles, which shows that the quantity of ketchup remaining in the package can even be higher.

From the figure above (Fig. 2), it is apparent that the product in a glass bottle (GL-480-ORG) has the best emptiability. In contrast, PP-380-ORG has the poorest. Important to emphasize is that emptiability is a function of both product and packaging, thus not allowing the generalization of glass being better than plastic packaging, since the products in different packages were not identical. Emptiability is mainly influenced by the packaging geometry, the surface tension of food and packaging, and particularly by the viscosity of food (Schmidt, 2011). Besides processing conditions, viscosity of ketchup increases with its tomato content. Since the product with the highest tomato content yielded the worst emptiability, this may result in being one of the major drivers of FLW. One major limitation here is that the portioning behavior of the products could not be considered. With the glass bottle, dosing may be more difficult than with the plastic bottles. This could lead to the consumer emptying more ketchup than required which may ultimately result in disposing of it.

Statistical analysis was performed using one-way ANOVA (Fisher's with Tukey post hoc test for samples with equality of variances and Welch's with Games-Howell post hoc test for samples without equality

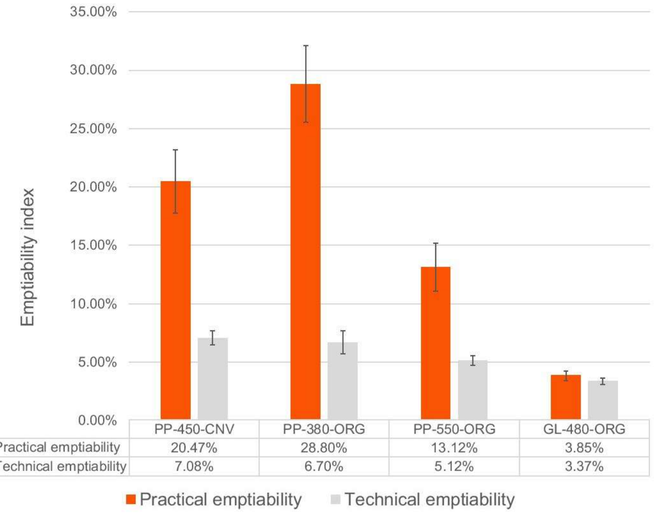


**Fig. 2.** Emptiability results of examined ketchup products. Bars represent the mean, while error bars are 95% confidence intervals ($n = 6$). Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

of variances), after testing for normality with Shapiro Wilk tests. All statistical tests were performed with the software 'Jamovi' (version 1.1.7) (The jamovi project, 2019) and can be found in the supplementary material.

### 3.2. LCA results

Climate change results of all products (Fig. 3a) range from 5.66 to 9.16 kg $CO_{2eq}$ per functional unit (FU) respectively. Packaging is responsible for 24% to 26% of the total for PP-450-CNV, PP-550-ORG and GL-480-ORG, but only 12% for PP-380-ORG due to its high tomato content and poor emptiability (Fig. 3a-f). In other impact categories, plastic packaging contributes 7% to 13% and glass packaging 29% to 31% to the overall result. Obviously, direct environmental impacts of glass packaging are associated with greater environmental impacts than plastic bottles, which is well in line with results of other LCA studies (Boesen et al., 2019; Humbert et al., 2009; Niero and Kalbar, 2019). Nonetheless, this is compensated for by its good emptiability.

Concerning the total LCA results, the most influential factors are FLW, the tomato content and the resulting thermal energy required for water vaporization. Regarding water use, cultivation of tomatoes is almost solely responsible for environmental impacts. Taken together, production and loss of food is substantially more relevant than its associated packaging concerning environmental impacts. By contrast, transport is of relatively low importance. One interesting outcome is that LCA results of PP-550-ORG are better than PP-450-CNV, which would not be the case if FLW would have been excluded. This finding underlines the value of quantifying and integrating packaging-related FLW into life cycle assessments.

Detailed LCA results and results of the remaining calculated impact categories are listed in the supplementary material.

### 3.3. Value added results

Value added results for the investigated products (Fig. 4) show a similar picture to that of the LCA results with the important difference that here, higher values are considered as beneficial. Therefore, VA results are in fact diametrically opposed to most of the impact categories of the performed LCA. This arises mostly from the effect that a greater material intensity leads to more value added along the supply chain,

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**Fig. 3.** Life cycle assessment results of most relevant impact categories for ketchup. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) e content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

hich contradicts the goal of eco-economic decoupling (European ommission, 2011).

Consequently, since the sales price of a product is higher than its roduction costs, poorer emptiability also leads to a greater VA result. or PP-380-ORG, this is particularly clear, since it has the highest tomato ontent as well as the poorest emptiability. Furthermore, the calculated argin regarding the sales price for this product is substantially greater compared to the others. This is confirmed by other studies indicating that smaller packages generally generate higher revenues than larger ones (Yonezawa and Richards, 2016).

In contrast, GL-480-ORG, is not only the one with the lowest sales price per kg, but also the one with the best emptiability, leading to the worst VA results in comparison. Using conventional LCC and taking the consumer's perspective, the results would be exactly the other

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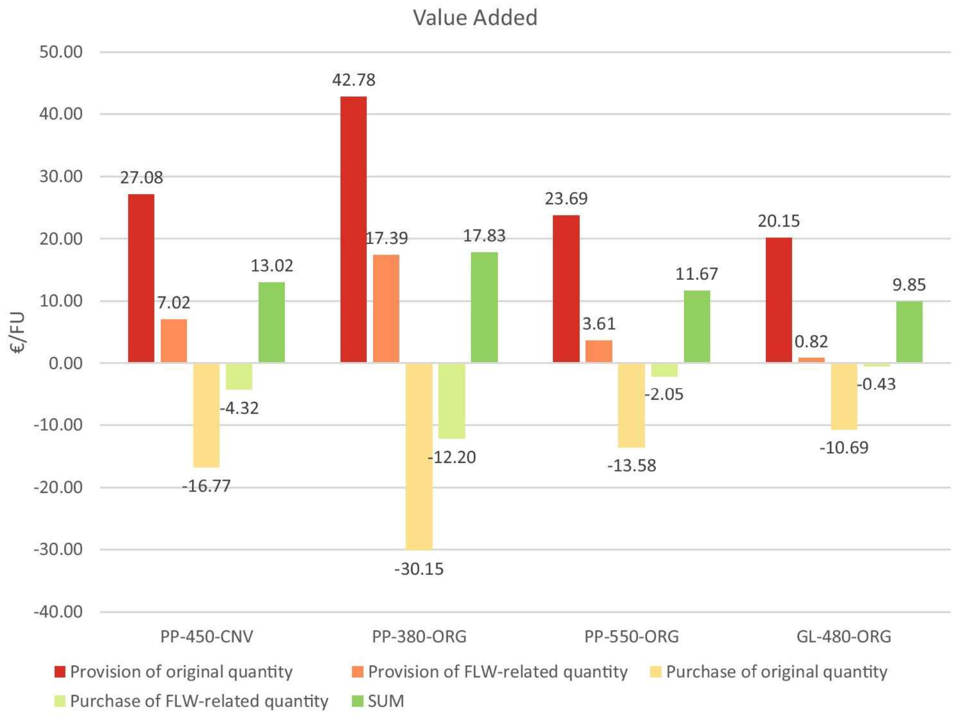


**Fig. 4.** Value added results. Original quantity is 3.8 kg of ketchup, while the quantity due to food loss and waste (FLW) is generated by the respective emptiability of the products. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

way around. Costs to the consumer for eating 3.8 kg ketchup would be 42.35 € for PP-380-ORG, but only 11.12 € for GL-480-ORG. In turn, from the manufacturer's point of view, a higher loss would be preferable as the quantity sold would increase. As Wood and Hertwich (2013) point out, life cycle costing results should generally be maximized from society's perspective to generate economic growth but minimized from an individual's perspective to save costs. Consequently, we agree with Heijungs et al. (2013) who raised the question: "What do we in fact want to learn from life cycle costing"?

We conclude that taking a system's perspective is more relevant in the context of sustainability assessments than taking an individual's perspective. Thus, despite its limitations, we still consider VA as a suitable method for performing environmental LCC together with LCA. Nonetheless, ff this debate is to be moved forward, methods portraying a broader economic scope should be developed. Previous research has already demonstrated how not only economic growth, but also characteristics such as consumer satisfaction, business diversity or long-term investments could be considered in new methods concerning life cycle costing (Neugebauer et al., 2016).

### 3.4. Sustainability evaluation using TOPSIS

After determining LCA and VA results, the decision matrix for TOPSIS was created (Table 3).

Next, weights were calculated based on the approaches of equal weighting, CRITIC and entropy (Table 4) described in Section 2.4.2.

Using CRITIC, VA and organic agriculture are given more, LCA results less weight compared to equal or entropy weights.

Finally, after following the calculation steps laid out in Section 2.4.1, the final closeness values using TOPSIS were determined, with the most sustainable food-packaging system being the one closest to '1.00' (Fig. 5).

Closeness values of the products differ greatly depending on the chosen weighting set. Nonetheless, PP-550-ORG performs best concerning all three weighting sets, which is followed by GL-480-ORG. The most striking observation is the difference in performance of PP-380-ORG and PP-450-CNV, which is the consequence of the higher importance of LCA results in the entropy and organic agriculture in the CRITIC weighting set. As discussed in Section 3.3, VA increases with material intensity and FLW. If TOPSIS were calculated with life cycle costs from the consumer's perspective, this would have a positive impact on the results of GL-480-ORG and a negative impact on PP-380-ORG.

Since the study was limited to the use of secondary data, generalization of these results is limited. Furthermore, these results are only applicable to Austria, due to recycling rates of packaging and costs of these products are only viable for this country. Depending on the country of marketing, the evaluation could change substantially. Furthermore, the difference of organic and conventional agriculture could not be captured in the calculation of LCA and VA, which however was addressed by considering it as an additional criterion in the MCDA.

## 4. Conclusions

The main aim of this study was to combine environmental and economic assessments of food-packaging systems, including and putting the focus on indirect effects of food loss. Historically, most LCA studies of packaging did not consider FLW (Molina-Besch et al., 2018), predominantly due its quantification being challenging (Wohner et al., 2019a). In this study, FLW was quantified by testing the emptiability of products, which was then integrated into the LCA and VA calculations of the examined products. As a result, environmental impacts increased, and more surprisingly, also the value added to the economy, which is, however, inherent in the respective method (Wood and Hertwich, 2013).

A further limitation is the exclusion of criteria of taste or quality. A point could be made that PP-380-ORG is the product with the highest tomato content and thus the one with the highest quality. However, this is highly subjective and would have to be the subject of sensory testing which was outwith the scope of this study.

We conclude and agree with authors of similar previous studies that TOPSIS assists in overcoming the limitations inherent in LCA

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**Table 3**
Decision matrix of TOPSIS for case study. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.
Abbreviations for criteria represent, beneficial (B) or non-beneficial (NB): CC (climate change), FRD (resource use, fossils), WU (water use), FEU (Eutrophication, freshwater), AC (acidification), PM (Particulate matter), and VA (Value Added).

| | | Type of criterion | Unit | PP-450-CNV | PP-380-ORG | PP-550-ORG | GL-480-ORG |
|---|---|---|---|---|---|---|---|
| LCA | CC | NB | kg $CO_{2eq}$/FU | 5.97E+00 | 9.16E+00 | 5.66E+00 | 6.54E+00 |
| | FRD | NB | MJ/FU | 9.40E+01 | 1.37E+02 | 8.62E+01 | 9.65E+01 |
| | WU | NB | $m^3_{eq}$/FU | 1.23E+01 | 2.15E+01 | 1.28E+01 | 1.29E+01 |
| | FEU | NB | kg $P_{eq}$/FU | 1.40E-03 | 2.11E-03 | 1.26E-03 | 1.58E-03 |
| | AC | NB | mol $H^+_{eq}$/FU | 3.90E-02 | 6.06E-02 | 3.54E-02 | 4.95E-02 |
| | PM | NB | disease incidence/FU | 3.02E-07 | 4.72E-07 | 2.82E-07 | 4.51E-07 |
| Organic agriculture | | B | yes (1) / no (0) | 0 | 1 | 1 | 1 |
| Value added | | B | €/FU | 13.02 | 17.83 | 11.67 | 9.85 |

**Table 4**
Weights of criteria, calculated using equal weighting ('EQUAL'), CRITIC and entropy. Abbreviations for criteria represent: CC (climate change), FRD (resource use, fossils), WU (water use), FEU (eutrophication, freshwater), AC (acidification), PM (particulate matter), and VA (value added).

| Category | Criteria | Equal | Critic | Entropy |
|---|---|---|---|---|
| Life cycle assessment | CC | 12.5% | 6.8% | 14.4% |
| | FOSSILS | 12.5% | 7.5% | 13.9% |
| | WATER | 12.5% | 8.4% | 17.3% |
| | FW_EUTROPH | 12.5% | 6.8% | 14.3% |
| | FW_ACID | 12.5% | 8.0% | 14.2% |
| | RESP | 12.5% | 15.2% | 13.3% |
| Organic agriculture | Yes/no | 12.5% | 32.2% | 7.5% |
| Economic assessment | VA | 12.5% | 15.2% | 5.1% |

studies (Maxim, 2014; Niero and Kalbar, 2019), such as only considering environmental performance, while excluding assessments of other sustainability dimensions (Zimek et al., 2019) or compliance with environmental regulations (Levy, 2017). The proposed sustainability assessment of food-packaging systems can solve multi-dimensional issues, particularly of conflicting sustainability goals. TOPSIS provides a single score and therefore an easy to understand indication of the best possible solution. However, it is not without its limitations. TOPSIS does not provide a 'final word' since the selection of criteria and weights strongly influence the results, again shown in this study. Furthermore, sustainability may be considered as a social construct and, arguably, weighting sets should then only be determined subjectively (Mollayosefi et al., 2019). While this may be a benefit due to it being highly adaptable to the preferences of one decision maker, it is then challenging to compare the results of one such study to those of others (Maxim, 2014). A natural progression of this work would be to apply this method to an increasing number of different food-packaging systems. Furthermore, future studies could incorporate social life cycle assessments to depict all three pillars of sustainability. Additionally, the economic assessment could be enhanced by developing environmental LCC methods which cover a more extensive scope of economic sustainability. Finally, while admittedly challenging, a greater focus on quantifying FLW besides emptiability and the integration into such assessments would produce a better and broader insight into the sustainability of food-packaging systems.


Fig. 5. Relative closeness values of products. Abbreviations for products represent (i) the packaging material as polypropylene (PP) or glass (GL), (ii) the content of bottles of 380, 450, 480 or 550 g and (iii) if the ketchup is a product of conventional (CNV) or organic (ORG) agriculture.

## CRediT authorship contribution statement

**Bernhard Wohner:** Conceptualization, Formal analysis, Validation, Writing - original draft, Writing - review & editing, Visualization. **Viktoria Helene Gabriel:** Conceptualization, Writing - review & editing. **Barbara Krenn:** Conceptualization, Formal analysis. **Victoria Krauter:** Conceptualization, Validation, Writing - review & editing, Supervision. **Manfred Tacker:** Conceptualization, Validation, Resources, Writing - review & editing, Supervision.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

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