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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

The environmental impact of packaging in food supply chains—does life cycle assessment of food provide the full picture?

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Abstract

Purpose Due to the urgency and the magnitude of the environmental problems caused by food supply chains, it is important that the recommendations for packaging improvements given in life cycle assessment (LCA) studies of food rest on a balanced consideration of all relevant environmental impacts of packaging. The purpose of this article is to analyse the extent to which food LCAs include the indirect environmental impact of packaging in parallel to its direct impact. While the direct environmental impact of food packaging is the impact caused by packaging materials' production and end-of-life, its indirect environmental impact is caused by its influence on the food product's life cycle, e.g. by its influence on food waste and on logistical efficiency.

Methods The article presents a review of 32 food LCAs published in peer-reviewed scientific journals over the last decade. The steps of the food product's life cycle that contribute to the direct and indirect environmental impacts of packaging provide the overall structure of the analytical framework used for the review. Three aspects in the selected food LCAs were analysed: (1) the defined scope of the LCAs, (2) the sensitivity and/or scenario analyses and (3) the conclusions and recommendations.

Results and discussion While in packaging LCA literature, there is a trend towards a more systematic consideration of the indirect environmental impact of packaging, it is unclear how food LCAs handle this aspect. The results of the review show that the choices regarding scope and sensitivities/scenarios made in food LCAs and their conclusions about packaging focus on the direct environmental impact of packaging. While it is clear that not all food LCAs need to analyse packaging in detail, this article identifies opportunities to increase the validity of packaging-related conclusions in food LCAs and provides specific recommendations for packaging-related food LCA methodology.

Conclusions Overall, we conclude that the indirect environmental impact of packaging is insufficiently considered in current food LCA practice. Based on these results, this article calls for a more systematic consideration of the indirect environmental impact of packaging in future food LCAs. In addition, it identifies a need for more packaging research that can provide the empirical data that many food LCA practitioners currently lack. In particular, LCA practitioners would benefit if there were more knowledge and data available about the influence of certain packaging characteristics (e.g. shape, weight and type of material) on consumer behaviour.

Keywords Food · Food supply chain · Food waste · Life cycle assessment · Packaging · Review

1 Introduction

Food supply chains are one of the main contributors to several pressing environmental problems such as climate change, eutrophication and loss of biodiversity (EEA 2016). The contribution of packaging to the overall environmental impact in food supply chains is controversial. On one hand, the environmental problems related to packaging waste have led to both legislation, e.g. European Council (1994), and research (Beitzen-Heineke et al. 2017; Tencati et al. 2016; Tua et al. 2017) that focus on packaging prevention. On the other hand, in the recent debate about food waste, the protective function

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of packaging has been highlighted as an important environmental benefit (Bertoluci et al. 2014; Verghese et al. 2015; Williams et al. 2008). Several studies have shown that the indirect environmental impact of packaging is of greater relative importance in many food supply chains than its direct environmental impact (Büsser and Jungbluth 2009; Silvenius et al. 2014; Wikström and Williams 2010). The direct environmental impact of food packaging is the impact caused by the production and end-of-life of the packaging materials used in the food product's life cycle. The indirect environmental impact of packaging is the impact caused by the influence that packaging has on the food product's life cycle. It includes the influence on the amount of food waste and the possibilities of recovering food waste (Verghese et al. 2015), the influence on transport efficiency in the food supply chain (García-Arca et al. 2014) and the influence on consumers behaviour affecting food transport, storage and preparation in households (Zampori and Dotelli 2014).

Life cycle assessment (LCA) appears to be a useful method for performing a complete analysis of the environmental impact of food packaging systems. For a long time, the common practice in packaging LCAs has been to focus on packaging only and to exclude the product inside the package (Williams and Wikström 2010). Many packaging LCAs concentrate on the comparison of packaging materials (e.g. Humbert et al. 2009b; Von Falkenstein et al. 2010) and of packaging waste management alternatives (e.g. Toniolo et al. 2013; Ferreira et al. 2014). Another frequently analysed topic in packaging LCAs is the comparison of one-way versus returnable packaging systems (e.g. Koskela et al. 2014; Levi et al. 2011). A common recommendation provided by packaging LCAs that focus on packaging material and its end-of-life is to minimise the amount of packaging material (Levi et al. 2011). Over the last 10 years, several authors (Pagani et al. 2015; Silvenius et al. 2014) have criticised LCAs on food packaging that exclude the packed product. These authors argue that many packaging LCAs neglect the influence of packaging on the overall environmental impact in the food supply chain, for example regarding its influence on food waste and on logistical efficiency. Thus, they call for the indirect environmental impact of packaging to be included in environmental assessments of packaging (Verghese et al. 2015; Williams and Wikström 2010). As a result, in packaging LCA literature, there are more and more published studies that follow these recommendations such as packaging LCAs that include food waste (Conte et al. 2015; Gutierrez et al. 2017; Manfredi et al. 2015). In this article, we refer to *packaging LCAs* if the main purpose is to analyse the impact of a packaging system. In contrast, we refer to *food LCAs* if the main purpose is to analyse the impact of a food product.

The consideration of the indirect environmental impact of packaging seems to be becoming more common in packaging LCA practice. Another frequent source of information on the environmental impact of food packaging is in the results of food LCAs. Commonly, LCAs on food products include packaging in their scope. Accordingly, one might draw the conclusion that food LCAs automatically include both the direct and the indirect environmental impacts of packaging and that packaging recommendations found in food LCAs are more reliable than those in traditional packaging LCAs. While many food LCAs provide recommendations for packaging, it is unclear to what extent they consider the interrelationship between the direct and indirect environmental impacts of packaging. Our hypothesis is that most food LCAs base their packaging recommendations on an analysis of its direct environmental impact without considering its indirect impact. Due to the high relative importance of the indirect environmental impact of packaging in many food supply chains, there is a great risk that recommendations for food packaging that do not consider this will lead to packaging developments that increase the overall environmental impact of the food supply chain. This contradicts one of the main ideas behind the application of LCA methodology, i.e. to avoid burden shifting (European Commission 2010). Due to the urgency and the magnitude of the environmental problems in food supply chains (including packaging), it is important that the recommendations for packaging improvements in food LCAs rest on a balanced consideration of all relevant environmental impacts of packaging.

While several authors have highlighted the importance of considering both the indirect and the direct environmental impact of packaging in environmental assessments of packaging (Verghese et al. 2015; Williams and Wikström 2010), there is a lack of knowledge about how this recommendation has influenced LCA methodology. In packaging LCA literature from the last decade, several studies (e.g. Conte et al. 2015; Manfredi et al. 2015) analyse the indirect environmental impact of packaging in parallel to its direct. To our knowledge, there is no study that analyses if the indirect effects of packaging are considered in food LCA literature and, especially, if packaging recommendations in this literature take indirect effects in consideration. If not, the packaging recommendations in food LCAs may lead to an increased environmental impact. To address this knowledge gap, this article presents a review of 32 food LCAs published in peer-reviewed scientific journals over the last decade. The purpose of this article is:

a) To analyse the extent to which food LCAs from the past decade include the indirect environmental impact of packaging alongside its direct impact
b) To analyse whether recommendations for packaging improvements are made without consideration of their indirect environmental impact
c) To provide recommendations for a balanced consideration of both direct and indirect environmental impacts of packaging in food LCAs

The article is organised as follows: The first section provides an overview of the direct and indirect environmental impacts of packaging in food supply chains based on current literature. It is followed by a description of the review method including descriptions of the literature search and the applied analytical framework. After this, we present the results. The next section discusses the results and provides recommendations for the development of packaging-related food LCA methodology. The article ends with a brief conclusion section that summarises the main findings and identifies opportunities for future research.

2 The direct and indirect environmental impacts of food packaging

The following sections provide a brief overview of the direct and indirect environmental impacts of packaging in food supply chains. For a more detailed description and discussion with regard to the indirect environmental impact of packaging, see Lindh et al. (2016). Packaging systems are commonly described in a hierarchy of three levels: primary, secondary and tertiary packaging (Jönson 2000). The primary packaging (e.g. a bottle) is in direct contact with the product, the secondary (e.g. a corrugated cardboard box) contains several primary packages and the tertiary (e.g. a pallet or roll container) contains a number of primary or secondary packages.

2.1 Packaging material (primary, secondary and tertiary)

An important part of the direct environmental impact of packaging is the impact from production of the packaging materials used for primary, secondary and tertiary packaging. For products with relatively low environmental impact ingredients, e.g. soft drinks (Amienyo et al. 2013), packaging production can be the main contributor to the overall environmental impact. In contrast, for products with high-impact ingredients, e.g. cheese (Berlin 2002), the relative contribution from packaging to the overall environmental impact is usually small. Packaging LCAs frequently highlight the interrelationship between primary, secondary and tertiary packaging and the need to include all relevant packaging levels into LCAs (Silvenius et al. 2014). Furthermore, it has been recommended that all levels of a packaging system should be developed in parallel (Hellström and Nilsson 2011; Olsmats and Dominic 2003).

2.2 Transport

The influence of packaging on transport efficiency (for the transport from production facility to retail) is an interesting aspect that has been highlighted by several authors, e.g. García-Arca and Prado-Prado (2014). At the same time, the relative contribution of the packed product transport is reported as small in many food supply chains (Molina-Besch 2016). However, there are examples of products such as wine (Wrap 2007), where the use of more transport-efficient packaging solutions results in a significant environmental improvement. The relative importance of transport-efficient packaging depends on many different factors: the food ingredients, the type and amount of packaging materials used, the transport distance between producer and retail as well as the mode(s) of transport (Molina-Besch 2016). Guiso et al. (2016) conclude, in an LCA of olive oil packaging, that glass bottles are preferable for local distribution while tin plate cans are better for long-distance distribution.

2.3 Food waste

In an ideal world, packaging waste would be the only waste that has to be taken care of at the food product's end-of-life. In reality, approximately one third of all globally produced food is actually not consumed but lost before consumption (Gustavsson et al., 2011). In this article, the term food waste is used for all food losses "that take place at retail and consumer stages" (Corrado et al. 2017). For many food products, the packaging decision directly influences the amount of food waste in distribution, in retail (Svanes et al. 2010; Verghese et al. 2015) and in consumers' homes (Williams et al. 2012). In food packaging LCAs, the relationship between the environmental impact of packaging and its ability to reduce food waste has been discussed to some extent (Silvenius et al. 2014; Wikström et al. 2014). Several studies show that for certain products, the environmental benefit of decreased food waste outweighs the environmental impact caused by the use of additional packaging material (Conte et al. 2015; Wikström and Williams 2010). In recent packaging LCAs, it is often shelf life-prolonging packaging that is analysed in relation to food waste (Conte et al. 2015; Gutierrez et al. 2017; Zhang et al. 2015). Corrado et al. (2017) provides a summary of different types of food loss that occurs in food supply chains. Based on Corrado's summary and some other studies, Table 1 lists types of food waste that are influenced by packaging.

2.4 Food transport, storage and preparation by households

Consumer behaviour during the product use phase has been identified as an important driver for the overall environmental impact of many products (Polizzi di Sorrentino et al. 2016). The use phase of food products is not only relevant with regard to the amount of food waste (as described above) but contributes significantly to the energy and water use of private households. Use phase assessment in LCAs is more common for consumer products with long durability (such as electronic

Table 1 Food waste types that are influenced by packaging. Adapted from Corrado et al. (2017)

Food waste in transport, distribution and retail	• Food damage by inappropriate packaging (Corrado et al. 2017) • Expired food (Corrado et al. 2017) • Unsold food (Corrado et al. 2017)
Food waste in households	• Food not eaten due to preparation of excess food (Corrado et al. 2017) • Food not eaten due to passed best-before date (Corrado et al. 2017) • Food not eaten due to inappropriate packaging size (Corrado et al. 2017; Williams et al. 2012) • Food spilled due to inappropriate opening devices of packaging (Duizer et al. 2009) • Food not eaten due to difficulty of completely emptying packaging (Williams et al. 2012) • Food not eaten due to decrease in quality (insufficient protection) (Verghese et al. 2015)

appliances) than for food. At the same time, it has been highlighted that variations in the way products are being used may have a significant impact on LCA results for all products "where the use phase is responsible for a large share of the total environmental impact" (Daae and Boks 2015, p. 148). LCAs of pasta (Bevilacqua et al. 2007) and coffee (Humbert et al. 2009a) have identified the energy use of preparation as a hotspot in the products' life cycles. Energy consumption of refrigerated food storage is another relevant contributor to energy use in the food life cycle (Büsser and Jungbluth 2009). Packaging can indirectly influence how consumers transport, store and prepare food (for example through its information function). Other use phase-related packaging attributes include product dosage and type of packaging material that influence the chosen food preparation technology (e.g. microwave or electric stove). While it has become more common to consider food waste in packaging LCAs, only a handful of studies discuss packaging's influence on food preparation and storage. Zampori and Dotelli (2014) recommend considering the cooking stage of food in the design of new packaging for food that requires cooking before consumption. Wikström et al. (2016) highlight in general the importance of including product user behaviour in packaging LCAs.

2.5 Packaging waste end-of-life

The end-of-life phase of the packaging waste constitutes another direct environmental impact of food packaging. A review of food LCAs (Molina-Besch 2016) concludes that for Global Warming Potential, the relative contribution of packaging waste management did not exceed 10% in most of the reviewed studies. However, the relative importance of the environmental impact of packaging end-of-life in food LCAs depends on the waste management processes (Wikström et al. 2014) and the methodological choices regarding allocation of emissions and potentially recovered materials and/or recovered energy (Zampori and Dotelli 2014). Another critical aspect is that packaging attributes can influence consumer behaviour with regard to sorting of packaging waste (Wikström et al. 2016); therefore, it might not be wise to base LCA's end-of-life modelling solely on average recycling rates of packaging materials.

2.6 Food waste end-of-life

Just as packaging attributes influence how consumers sort packaging waste, they indirectly influence the waste fraction in which the food waste is sorted (Wikström et al. 2016). For example, if the chosen packaging solution is difficult to empty, it is more probable that the food waste and the package are discarded together in mixed household waste (Quested and Murphy 2014), which means that the packaging material cannot be recycled and the nutrients and energy of the food waste cannot be recovered.

3 Methods

3.1 Literature search and selection

Literature searches in the databases *Scopus* and *Web of Science* were performed. Keywords divided into three different categories were combined to identify a high number of relevant food LCAs (see Table 2). Keywords of type 1 aimed to identify research based on LCA methodology. Keywords of type 2 aimed to identify LCAs performed on food (or beverage) products. Keywords of type 3 aimed to limit the search to food LCAs that include packaging. The keywords were combined with "AND" between keyword categories and with "OR" within each keyword category. Articles published during the last 10 years (from 2007 to 2017) were included in the review. The indirect environmental impact of packaging is a relatively new concept in the literature on environmental

Table 2 Keywords used for the electronic database search

Keyword category	Type 1	Type 2	Type 3
Purpose	To identify research based on LC assessment methodology	To identify LCAs on food products	To limit the search to food LCAs that include packaging
List of keywords	Life cycle assessment, life cycle analysis, LCA, carbon footprint	Food, meal, dish, beverage, meat, fish, poultry, seafood, dairy, cereal, fruit, vegetable, pork, beef, lamb, chicken, egg, cheese, milk, yoghurt, salmon, cod, sardine, tuna, bread, pasta, rice, sugar, flour, beer, wine, "soft drink", juice, nectar, "still drink", coffee, tea, "mineral water", spirits, apple, orange, banana, pear, melon, berries, berry, cherry, pineapple, citrus, plum, apricot, grapes, peach, nuts, tomato, cucumber, lettuce, pepper, potato, carrot, maize, cabbage, root, peas, spinach, onion, garlic, leek, butter, fat, pulses, cocoa	Packaging, package, container

optimization of packaging. Accordingly, it was assumed that most food LCAs before 2007 did not consider the indirect environmental impact of packaging. The literature search was limited to peer-reviewed scientific articles (in English) to assure a high quality of research to review. The search in both databases resulted in 721 hits.

To select relevant LCA research for the review, the articles from the electronic literature search were analysed based on the following selection criteria:

1. The article must present results from an LCA study of a food or beverage product.
2. The LCA study should preferably have a cradle-to-grave scope but must at least include life cycle steps from cradle-to-retail plus packaging end-of-life. Cradle-to-gate LCAs are not relevant for the purpose of this review since they do not allow for an analysis of both the direct and the indirect environmental impact of packaging in the food product's life cycle.
3. The article must include some conclusions about packaging or provide some recommendation for packaging improvement based on the LCA results. The reason for excluding food LCA studies that do not provide conclusions or recommendations about packaging is that the identification of packaging improvement opportunities does not have to be included in the goal of all food LCAs.
4. The performed LCA must follow an attributional LCA approach because it is the most suitable method for examining the environmental impact in existing supply chains (Jensen and Arlbjørn 2014).

For the literature selection, duplicates were removed and the article titles were analysed based on the selection criteria 1. Afterwards, the abstracts of the 127 remaining articles were analysed for criteria 1 and 2 and, if fulfilled, the complete text of the articles were analysed for criteria 3 and 4. Thirty-two articles fulfilled the selection criteria (see Table 3).

3.2 Analytical framework

The different steps of the food product's life cycle that contribute to the direct and to the indirect environmental impact of packaging described in Sections 2.1 to 2.6 provide the overall structure of the analytical framework (see Table 4). The analytical framework contains eight (instead of six) packaging-related life cycle steps for two reasons: Primary packaging material is considered separately from secondary and tertiary packaging material in the analytical framework due to the importance of primary packaging for the shelf life and safety of food products. Following the division of food waste in the different parts of the supply chain suggested by Corrado et al. (2017) (see Table 1), food waste in transport, distribution and retail of packed products is separated from food waste in households in the analytical framework.

As Table 4 shows, three particular aspects in the selected food LCAs were analysed: (1) The defined scope of the LCAs, (2) the sensitivity and/or scenario analyses and (3) the conclusions and recommendations. Thus, our analysis relates to the LCA phases *Goal and Scope* and *Interpretation* (International Organization for Standardization (ISO) 2006a, b). Our analysis does not consider the phases *Inventory analysis* and *Impact assessment* because these phases relate to LCA methodology in general and do not require any specific consideration of the packaging-related data. The following sections describe and motivate the three parts of our analysis.

3.2.1 Review of the food LCAs' scope

Firstly, for each of the eight packaging-related life cycle steps, it was analysed whether the step is included in the LCA's scope. While most food LCAs can be expected to include packaging in their overall goal and scope definition, an important pre-condition for considering its indirect environmental impact is that the relevant packaging-related life cycle steps are part of the LCA's scope. Food LCAs that exclude, e.g. the consumption phase from their scope, can logically not

Table 3 Overview of the food LCA studies included in the review

Reference	Analysed food product	Analysed primary packaging type(s)
1. Amienyo et al. (2013)	Carbonated soft drinks	Glass bottles, aluminium cans and PET bottles
2. Amienyo et al. (2014)	Red wine	Glass bottles
3. Amienyo and Azapagic (2016)	Beer	Glass bottles, steel cans and aluminium cans
4. Bonamente et al. (2016)	Red wine	Glass bottles
5. Bevilacqua et al. (2007)	Pasta	Cardboard and plastic
6. Calderón et al. (2010)	Ready meal	Steel cans, glass jars and plastic pouches
7. Cellura et al. (2012)	Vegetables	Cardboard boxes, wooden and plastic crates
8. Cordella et al. (2008)	Beer	Glass bottles and steel kegs
9. Davis and Sonesson (2008)	Complete dinner meal	Cardboard, laminated cardboard and plastics
10. Dalla Riva et al. (2017)	Mozzarella cheese	Plastic bags
11. Espinoza-Orias et al. (2011)	Bread	Paper and plastic bags
12. Flysjö (2011)	Butter and margarine	Flexible polymer packaging
13. Fusi et al. (2014)	White wine	Glass bottles
14. Garofalo et al. (2017)	Whole peeled tomato	Steel cans
15. Gazulla et al. (2010)	Wine	Glass bottles
16. Girgenti et al. (2013)	Blueberry and raspberry	Plastic trays with wrapping
17. Girgenti et al. (2014)	Strawberry	Plastic trays with wrapping
18. Hassard et al. (2014)	Coffee products	Steel can, plastic bag, glass bottle
19. Hanssen et al. (2017)	Complete dinner meal	Paper and plastics
20. Humbert et al. (2009)	Coffee	Glass jars
21. Iribarren et al. (2010)	Mussels	Steel cans with carton wrap
22. Jeswani et al. (2015)	Breakfast cereals	Folding carton boxes
23. Laso et al. (2017)	Anchovy	Aluminium and tinplate cans, glass and plastic jars
24. Manfredi and Vignali (2014)	Tomato purée	Glass jars
25. McCarty et al. (2014)	Peanut butter	PET jars
26. Point et al. (2012)	Wine	Glass bottles
27. Rinaldi et al. (2014)	Olive oil	Glass bottles
28. Schmidt Rivera et al. (2014)	Ready meal	Plastics and cardboard
29. Tasca et al. (2017)	Endive salad	Plastic bags
30. Teixeira et al. (2013)	Breton pâté	Steel cans, aluminium cans and glass jars
31. Thoma et al. (2013)	Milk	Plastic containers and beverage cartons
32. Zufia and Arana (2008)	Tuna dish with tomato sauce	Plastic trays

consider the influence of packaging on food waste rates in households. It is clear that in practice, cut-offs have to be made in all LCAs (Van den Berg et al. 1999), but it is important to consider that the selected scope influences what kind of conclusions a food LCA study can draw about packaging.

3.2.2 Review of sensitivity and scenario analyses

Secondly, it was analysed whether the data and assumptions used to model each packaging-related life cycle step are included in the performed sensitivity and/or scenario analyses. In addition, the sensitivities/scenarios were examined as to whether or not they considered the influence of packaging on this particular life cycle step. Due to the uncertainties in LCA results created by the use of secondary data and by assumptions, it is important to include sensitivity analyses in LCAs. In sensitivity analyses, selected input data or assumptions are systematically altered to analyse how much these data inputs affect the overall results (to check the robustness of the results). The purpose of scenario analyses is to investigate how the study results change if the overall framework conditions were significantly different from the base case (for example if the product was produced in another country). Scenario analyses are important to evaluate how context and

Table 4 The analytical framework that evaluates the inclusion of each packaging-related life cycle step in the scope, the sensitivities and scenarios as well as the conclusions and recommendations of the analysed food LCAs

	Scope	Sensitivity and scenario analyses	Conclusions and recommendations
Primary packaging material (direct)	Included in all selected studies	Yes/no	Yes, including discussion of limitations
			Yes, not discussing limitations
			No
Secondary and tertiary packaging material (direct)	Included	Yes/no	Yes, including discussion of limitations
			Yes, not discussing limitations
	Not included		No
Transport from producer to retail (indirect)	Included	Yes/no	Yes, including discussion of limitations
	Not included		Yes, not discussing limitations
			No
Food waste in transport, distribution and retail (indirect)	Included	Yes/no	Yes, including discussion of limitations
	Not included		Yes, not discussing limitations
			No
Food transport, storage and preparation by households (indirect)	Included	Yes/no	Yes, including discussion of limitations
	Not included		Yes, not discussing limitations
			No
Food waste in households (indirect)	Included	Yes/no	Yes, including discussion of limitations
	Not included		Yes, not discussing limitations
			No
Packaging end-of-life (direct)	Included in all selected studies	Yes/no	Yes, including discussion of limitations
			Yes, not discussing limitations
			No
Food waste end-of-life (indirect)	Included	Yes/no	Yes, including discussion of limitations
	Not included		Yes, not discussing limitations
			No

time-specific the results of a LCA study are and, therefore, provide information about the generalizability of LCA results.

3.2.3 Review of conclusions and recommendations

Thirdly, the conclusions and recommendations provided in the food LCAs were analysed for each packaging-related life cycle step. For this part of the analysis, all statements related to the eight packaging-related life cycle steps provided in the conclusions or discussion sections of the articles were analysed independent from whether they were directly related to packaging or not. The reason for considering all recommendations given for each packaging-related life cycle step was the following: The review aimed to capture both what the studies concluded about packaging as well as whether or not other conclusions or recommendations about the packaging-related life cycle steps considered their interrelationship with packaging. Furthermore, we analysed whether limitations to the validity of the results are discussed in parallel to packaging-related conclusions and recommendations. We considered any kind of statement that described the conditions under which the packaging-related results were applicable or that identified areas for further research as a discussion of limitations to the validity of the results. Due to time and resource restrictions, cut-offs are made in all LCAs and their influence on the results can only be estimated (Van den Berg et al. 1999). The conclusions taken regarding packaging in food LCAs and the recommendations for packaging improvements should accordingly be presented including an indication about the existing uncertainties.

4 Results

The results section is organised as follows. First, a brief overview of the results is provided. Second, the results are presented in detail for each packaging-related life cycle step from the analytical framework.

Overall, the results of the review show that the choices regarding scope and sensitivities/scenarios made in food LCAs as well as conclusions about packaging focus on the consideration of the direct environmental impact of packaging. Table 5 summarises the results of the analysis quantitatively. It shows that with regard to the scope, a consideration of the direct environmental impact of packaging in food LCAs is seldom coupled with a parallel consideration of its indirect impact. Not shown in Table 5 is the fact that only three studies consider the complete scope of packaging-related life cycle steps included in the analytical framework. With regard to the direct environmental impact of packaging, it is important to note that many studies exclude secondary and/or tertiary packaging from the scope, indicating that food LCAs commonly analyse primary packaging and not packaging systems. Moreover, Table 5 shows that while the primary packaging material is commonly part of sensitivity or scenario analyses food LCAs, the other life cycle steps of our framework are seldom scrutinised in sensitivities/scenarios (with the exception of transport to retail). The analysis of the conclusions and recommendations of the food LCAs shows that primary packaging material and transport to retail are most commonly mentioned. The review also revealed that ten studies provide recommendations about packaging without examining the life cycle step(s) affected by the suggested improvement in a scenario analysis. In addition, few of the reviewed studies discuss limitations of the provided packaging recommendations.

4.1 Primary packaging material (direct)

Primary packaging material was included in the scope of all reviewed food LCAs, and all studies provided conclusions or recommendations about primary packaging. Primary packaging material was also the life cycle step from the analytical framework that was most frequently evaluated in sensitivities or scenarios. Table 6 provides a

Table 5 Summary of the results

	Scope	Part of sensitivity/ scenario analyses	Conclusions and recommendations
Primary packaging material (direct)	Included in all analysed food LCAs	Yes: 20 No: 12	All studies (including a discussion of limitations: 11)
Secondary and tertiary packaging material (direct)	Secondary and tertiary included: 14	Yes: 1	Yes: 2 (not discussing limitations)
	Secondary included: 11 Not included/not mentioned: 7	No: 31	No: 30
Transport from producer to retail (indirect)	Included in all analysed food	Yes: 12	Yes: 21 (including a discussion of limitations: 5)
	LCAs	No: 20	No: 11
Food waste transport, distribution and retail (indirect)	Explicitly included: 7	Yes: 1	Yes: 4 (including a discussion of limitations: 1)
	Not included/ not mentioned: 26	No: 31	No: 28
Food transport, storage and preparation by households (indirect)	Explicitly included: 19	Yes: 2	Yes: 12 (including a discussion of limitations: 2)
	Not included/not mentioned: 13	No: 30	No: 20
Food waste in households (indirect)	Explicitly included: 12	Yes: 5	Yes: 9 (including a discussion of limitations: 1)
	Not included/not mentioned: 21	No: 21	No: 23
Packaging end-of-life (direct)	Included in all analysed food LCAs	Yes: 4	Yes: 7 (not discussing limitations)
		No: 27	No: 25
Food waste end-of-life (indirect)	Explicitly included: 9	Yes: 1	Yes: 2 (not discussing limitations)
	Not included/ not mentioned: 23	No: 31	No: 30

Table 6 Provided packaging recommendations and related discussed limitations by life cycle step

	Recommendations for packaging [a]	Limitations discussed in relation to provided recommendations
Primary packaging material (direct)	- Change packaging material [1,3, 5, 6 7, 10, 11, 13, 14, 20, 22, 23, 26, 32] - Reduce amount of packaging material [2, 3, 4, 10, 13, 19, 20, 22, 24, 26, 27, 28, 31, 32] - Increase recycled content in primary packaging material [2, 3] - Switch to more energy-efficient processes to form packaging [31] - Carefully select packaging material suppliers [8] - Sell products without packaging [29]	- Changing packaging material might negatively influence product quality [2,3, 13, 17] - Changing packaging material type can affect production, marketing and logistics [17] - Consumer acceptance of plastics as packaging material for certain food products is questioned [23] - Selling products without packaging might lead to increased food waste [29]
Secondary and tertiary packaging material (direct)	- Use reusable secondary packaging [29]	No limitations discussed
Transport from producer to retail (indirect)	- Reduce weight of packaging [13, 18, 20, 24] - Develop more transport-efficient packaging [19, 32] - Bulk shipping [2]	- Risk of contamination in containers that are reused several times for bulk shipping and negative consumer perception of bulk shipping [2] - Recommendation for lighter packaging is more important for long transport distances than for short [13]
Food waste transport, distribution and retail (indirect)	- Both packaging and food waste in the supply chain should be reduced [28]	No limitations discussed
Food transport, storage and preparation by households (indirect)	- No packaging-related recommendations provided	No limitations discussed
Food waste in households (indirect)	- Develop packaging that prolongs product shelf life [9, 12, 17] - Develop packaging of right size for consumer needs [9, 11, 12] - Develop packaging that is easy to empty and convenient to use [12]	No limitations discussed
Packaging end-of-life (direct)	- Increase packaging recycling [1, 2, 3, 14, 23] - Use reusable/returnable packaging [1, 8, 26] - Use biodegradable/compostable packaging [6, 16, 17]	No limitations discussed
Food waste end-of-life (indirect)	- Use biodegradable/compostable packaging to reduce the amount of food waste going to landfill (since packaging and food waste are often discarded together) [6]	No limitations discussed

[a] *Please observe* that the numbers included in brackets [ ] in Table 6 refer to the number of the food LCAs provided in Table 3. The sum of the studies listed in Table 6 does not agree with the number of studies providing conclusions or recommendations for each packaging-related life cycle step in Table 5 for three reasons. First, Table 5 lists all studies that provide conclusions or recommendations per life cycle step including those that were unrelated to packaging. Second, Table 6 lists only concrete recommendations for packaging improvement while in Table 5 also includes general conclusions about packaging. Third, some studies provide several different recommendations for packaging within one life cycle step (e.g. to reduce the amount of packaging material and to switch to another type of material)

list of the recommendations for packaging provided in the reviewed food LCAs. As Table 6 shows, recommendations for primary packaging are by far most common in the reviewed food LCAs. While 14 studies recommend reducing the amount of primary packaging material and 14 studies recommend switching to another type of primary packaging material, none of the studies discusses how this might affect the other levels of the packaging system (secondary and tertiary packaging). However, five studies discuss the potential financial effects of a change of primary packaging material in the form of its influence on product quality, production, marketing and logistics.

4.2 Secondary and tertiary packaging material (direct)

While 25 (of 32) studies include several levels of the packaging system in their scope, secondary and tertiary packaging are rarely evaluated in sensitivities/scenarios. In addition, secondary packaging material is only addressed in the conclusions section of two studies.

4.3 Transport from producer to retail (indirect)

The transport of packed products to retail is a life cycle step that is included in all analysed studies and for which 21 studies provide conclusions or recommendations; moreover, it was part of the sensitivity/scenario calculations in 12 studies. However, it is important to mention that only one study evaluates the impact of fill rate improvements while all other sensitivities/scenarios are related to transport distance or type of transport vehicle. In the same manner, many conclusions and recommendations about transport to retail relate to means of transport or to distance and do not discuss the influence of packaging on transport efficiency. Only nine of the reviewed food LCAs explicitly recognise the influence of packaging on transport efficiency, and seven provide transport-related recommendations for packaging. These studies in general recommend developing more transport efficient packaging or the use of lighter packaging. One study suggests also bulk transportation and packaging postponement and discusses the risks involved with reusable bulk containers. Another study specifies that the recommendation for lighter packaging is mainly applicable to long transport distances.

4.4 Food waste in transport, distribution and retail (indirect)

Food waste in transport, distribution and retail is the life cycle step in the analytical framework that is included in the smallest number of studies (7 out of 32 studies). It was only part of the sensitivity/scenario analyses of one food LCA. Conclusions or recommendations about food waste in this step are also rare (four studies) and kept at a general level. Two studies conclude that the environmental implications of packaging choices are more affected by the amount of food loss/waste in the supply chain than by the impact of the packaging material(s) production and end-of-life. One study recommends that packaging and food waste in the supply chain should be reduced simultaneously.

4.5 Food transport, storage and preparation by households (indirect)

Transport, storage and preparation of food by households are commonly included (19 out of 32) in the scope of the food LCAs but seldom analysed in more detail in sensitivities or scenarios (2 studies). There is a high variability in food related household activities included in the LCAs. These include food preparation (cooking or baking), refrigerated or frozen food storage, dishwashing and motorised transport for food shopping. Twelve studies present conclusions or recommendations for this life cycle step. However, none of the recommendations relate directly to packaging.

4.6 Food waste in households (indirect)

Food waste in households is included in the scope of 12 studies and five of those studies include this life cycle step in sensitivity/scenario analyses. While three studies evaluated how a reduction of the food waste rate affects the results, two studies evaluated the effect of a worst-case scenario (increased food waste rate). Nine food LCAs consider food waste in households in their conclusions or recommendations. The most common packaging recommendations are shelf life-prolonging packaging and packaging of the right size (adapted to consumer needs). None of the studies that provide recommendations for packaging development in order to reduce food waste discuss limitations in relation to their advice.

4.7 Packaging end-of-life (direct)

Packaging end-of-life is included in the scope of all analysed food LCAs, but interestingly, only rarely is it part of sensitivity/scenario analyses (4 out of 32). In addition, only seven of the LCAs present conclusions or recommendations about packaging end-of-life, most probably due to its low relative contribution to most impact categories. At the same time, there was only one study that explicitly highlighted that the relative environmental impact of packaging end-of-life was small. The few provided recommendations include increased recycling rates, the use of biodegradable packaging and reusable packaging.

4.8 Food waste end-of-life (indirect)

Food waste end-of-life is included in the scope of nine food LCAs and in one scenario analysis. Two studies provided recommendations related to food waste treatment, but only one of them relates to packaging. This study suggests that biodegradable packaging was preferable since it allowed for composting of food and packaging waste together.

5 Discussion and recommendations

While the indirect environmental impact of packaging has been discussed in packaging LCAs for almost 10 years (Williams and Wikström 2010) based on this review, it appears that food LCAs still focus on the direct environmental impact of primary packaging. While it is clear that not all food LCAs need to analyse packaging in detail, there are great opportunities to increase the validity of packaging-related conclusions in future food LCAs. On one hand, it is important to acknowledge the fact that the environmental assessment of packaging in food LCAs requires more than including production and waste management of packaging materials. On the other hand, we recommend food LCA practitioners to aim for

a more systematic consideration of both the indirect environmental impact of packaging and the interrelationship between the different levels of a packaging system (primary, secondary and tertiary). Both aspects are insufficiently considered in most of the reviewed food LCAs. The following paragraphs briefly discuss the main results and provide recommendations for a more systematic consideration of the influence of packaging on transport efficiency and on food waste. In addition, we discuss how to handle packaging in food LCAs that do not intend to provide directions for packaging development.

As described above, only three of the reviewed LCAs consider the complete scope of packaging-related life cycle steps included in the analytical framework. These three studies are LCAs of cooked meals (Davis and Sonesson 2008; Schmidt Rivera et al. 2014; Hanssen et al. 2017) that include food preparation and therefore have a wider scope than LCAs of single food items. Two of the meal LCAs provide packaging recommendations that address both the indirect and the direct environmental impacts of packaging, but one of them mainly/only deals with the direct impact and suggests to reduce the amount of packaging material. These results indicate that the inclusion of all packaging-related life cycle steps in food LCAs can support but does not guarantee the formulation of packaging recommendations that balance the direct environmental impact of packaging with its indirect one. A more systematic consideration of the indirect environmental impact of packaging in food LCAs is accordingly not achieved by simply increasing the scope of the LCAs but requires additional efforts.

The results of this review show that many food LCAs focus on analysing and providing improvement recommendations for primary packaging without considering its interrelationship with secondary and tertiary packaging. The interrelationship between the different packaging system levels is not discussed in any of the provided recommendations for packaging, indicating that the importance of this aspect is not in the awareness of food LCA practitioners. On one hand, it appears understandable that life cycle steps with relatively low environmental impact, such as secondary and tertiary packaging, are excluded from sensitivity/scenario analyses. On the other hand, it appears somewhat neglectful that many studies calculate the improvement potential of reduced primary packaging without considering that this might require an increase of secondary packaging material. Based on these results, we recommend food LCA practitioners to evaluate the effect of any suggested packaging improvement at the other levels of the packaging system.

Moreover, the review results show that from a methodological perspective, many food LCAs have a good basis for considering the influence of packaging on transport efficiency, but in many cases, the aspect is overlooked. Since transportation is an environmental hotspot for food products with either energy-intensive modes of transport such as airfreight (Sim et al. 2007) and/or long-distance road transport (Gazulla et al. 2010), in these types of food supply chains, it is important to consider the specific fill rates of different packaging solutions in LCAs. Although it was most common in the reviewed food LCAs to calculate the environmental impact of transports based on the total weight of the food product and its packaging, packaging LCAs can provide guidance for considering the volume efficiency of packaging systems. Guiso et al. (2016) is a good example for how to evaluate packaging transport efficiency under different supply chain conditions. Claussen et al. (2011) demonstrate how to consider differences in transport temperature and fill rates between different food packaging and distribution systems.

While the influence of packaging on food waste along the supply chain is an extensively discussed topic in packaging-related research, the results of this review show that many food LCAs still neglect this aspect. Recent packaging LCAs highlight factors such as the potential environmental benefit of shelf life-prolonging packaging to reduce food waste in transport, distribution and retail (Gutierrez et al. 2017; Zhang et al. 2015). Surprisingly, this topic receives little attention in the reviewed food LCAs. It is also interesting that more of the reviewed LCAs consider and discuss food waste in households than food waste in transport, distribution and retail. This might be because the size of the environmental problem related to food waste in households is bigger in the industrialised world (Gustavsson 2011) than the problem related to food waste in transport, distribution and retail. Our results indicate that some food LCA practitioners have taken up the knowledge about the relation between packaging and food waste in households but that there is still a need to increase awareness of this aspect in the food LCA community. Another interesting result related to the food waste issue is the way food LCAs handle treatment of food waste in comparison to the treatment of packaging waste. Approximately two thirds of the reviewed studies exclude the treatment of food waste from the scope while the treatment of packaging waste is included in all studies. One explanation might be that it is difficult to calculate specific emissions from waste treatment for different types of food waste and that the emissions connected to food waste treatment are considered as less environmentally problematic. As highlighted by Williams and Wikström (2010), from a climate perspective, emissions from landfilling of food waste can be high (compared to landfilling of packaging materials) and should accordingly be included in food LCAs.

To increase the validity of packaging-related recommendations provided in food LCAs, all studies that include packaging in their goal and scope definition must consider the influence of packaging on the amount of food waste. Food LCAs that compare different packaging alternatives should analyse how specific food waste rates for the different packages affect the results. This aspect is especially important for products

with high environmental impact from agriculture or food processing (Wikström et al. 2014). If data about specific food waste rates for different packaging solutions are lacking, the use of scenarios appears to be a feasible solution to evaluate this aspect based on assumptions. Overall, there seems to be a high potential to increase the validity of packaging recommendations provided in food LCAs through the use of scenarios, e.g. considering different food waste rates or different types of user behaviour for different packaging solutions. For example, Flysjö's (2011) LCA of butter considers specific food waste rates for the different packaging alternatives it compares. Davis and Sonesson (2008), as well as Espinoza-Orias et al. (2011), include food waste in scenarios and discuss the influence of packaging on food waste rates. Packaging LCA literature provides more examples of how to consider food waste in LCA methodology. Conte et al. (2015) calculates food waste rates for different packaging alternatives based on product shelf life. Silvenius et al. (2014) and Wikström et al. (2014) provide direction about how to evaluate different packaging alternatives including their influence on household food waste and on sorting behaviour.

Lastly, for food LCAs where time and resources do not allow for a detailed analysis of packaging, LCA practitioners should be more open about the limitations of any provided packaging recommendation. Tasca et al. (2017) and Dalla Riva et al. (2017) are two examples who discuss the potential influence of packaging on food waste rates and on user behaviour. With regard to how to consider the influence of packaging on transport efficiency, there are several liquid food or beverage LCAs that qualitatively discuss this aspect well (see, e.g. Amienyo et al. 2014; Fusi et al. 2014; Manfredi and Vignali 2014). As another option, LCA practitioners should refrain from providing any recommendations about packaging whenever they perceive that there is too little publication space available to discuss packaging. Garofalo et al. (2017) simply highlight for example that more research is needed to analyse the impact of alternative packaging solutions for whole-peeled tomatoes.

6 Conclusions and future research

Packaging LCA research has shown that environmental assessments of packaging must consider both its direct and its indirect environmental impact (Büsser and Jungbluth 2009; Wikström and Williams 2010). Food LCAs commonly include packaging in their scope. However, it is unclear to what extent the discussion about the direct and indirect environmental impacts of packaging has influenced food LCA methodology. Based on the results of a review of 32 food LCAs from the last decade, we conclude that the indirect environmental impact of packaging is insufficiently considered in current food LCA practice. It appears that during scope definition and result interpretation, many food LCAs treat packaging methodologically like packaging LCAs have done for a long time, i.e. putting most of the focus on the direct environmental impact of (mainly primary) packaging material. The analysis of the sensitivities/scenarios and packaging recommendation in the food LCAs supports the conclusion that there seems to be a lack of awareness among food LCA practitioners about the importance of the indirect environmental impact of packaging. Most packaging recommendations address the direct environmental impact of packaging, and very few studies discuss the limitations of their recommendations. However, there are some examples of studies that consider the influence of packaging on food waste in households and on transport efficiency, which appears to be a growing trend in the right direction. The results of this article contribute to the development of food LCA methodology towards a more balanced consideration of all relevant environmental impacts of food packaging. Based on the review results, we recommend a more systematic consideration of the indirect environmental impact of packaging in future food LCAs. In addition, there is a need for more packaging research that can provide the empirical data that many food LCA practitioners currently lack. LCA practitioners would benefit if there were more knowledge and data about the influence of certain packaging characteristics (e.g. shape, weight, type of material) on consumer behaviour (Wikström et al. 2016). Important areas for future research include the influence of packaging on how private households transport, store and prepare food and on how people sort food waste and packaging waste. In addition, there is a need for more research about the actual impact of shelf life-prolonging packaging on food waste rates in retail and in households.

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