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PACKAGING SYSTEMS INCLUDING RECYCLING

# A scoping review of food packaging life cycle assessments that account for packaging-related food waste

**Samadhi Hemachandra**[1] · **Michalis Hadjikakou**[2] · **Simone Pettigrew**[1]

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## Abstract

**Purpose** The aims of this scoping review were to examine the extent to which food packaging life cycle assessment studies included food waste specifically attributed to food packaging, overall and by food category; synthesise outcomes in terms of the ability of packaging solutions to minimise food waste; and identify areas of future research to provide a comprehensive understanding of where future packaging LCA efforts could be directed.

**Methods** This article presents a scoping review of 23 peer-reviewed papers on food packaging LCAs that explicitly accounted for packaging-related food waste. The articles were analysed by the major food product categories examined in the LCAs. The review examined the: (i) distribution of LCAs across food product categories, (ii) packaging materials/solutions assessed, (iii) food waste related packaging functions evaluated, and (iv) additional factors that influence packaging-related food waste (e.g., consumer behaviour).

**Results and discussion** Most of the reviewed LCAs focused on food categories associated with high environmental impacts such as animal-based products (meat and dairy) and highly perishable products (fresh fruits and vegetables). Plastic was the most frequently evaluated packaging material. Shelf-life extension was the most evaluated food waste related packaging attribute, and was found to play an important role in preventing food waste, especially within high impact food categories.

**Conclusions** The small number of studies identified in this review highlights a need for greater attention to food waste across more food categories in future food packaging LCAs. Similarly, there is considerable potential for greater consideration of packaging attributes relevant to different food product categories.

**Keyword** Life cycle assessment · Food packaging · Food waste · Packaging sustainability

## 1 Introduction

The global food system accounts for around 30% of global greenhouse gas (GHG) emissions (Crippa et al. 2021). GHG emissions occur across all major components of the food system, including agricultural production and food processing, distribution, consumption, and waste disposal (Crippa et al. 2021; Poore and Nemecek 2018). Urban lifestyles have increased demand for convenience foods, which in turn has resulted in rapid growth in the consumption of packaged foods (Knorr et al. 2018). Packaging is an aspect of the food system that has attracted considerable attention due to the environmental impacts associated with its production and disposal (Deshwal et al. 2019; Ncube et al. 2021; Wohner et al. 2020).

The main packaging material categories used in the food industry are paper, glass, metal, and plastic, which are used in varying combinations to constitute different packaging

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Samadhi Hemachandra
shemachandra@georgeinstitute.org.au

Michalis Hadjikakou
m.hadjikakou@deakin.edu.au

Simone Pettigrew
spettigrew@georgeinstitute.org

[1] The George Institute for Global Health, University of New South Wales, Sydney, L18, Barangaroo International Tower 3, Barangaroo Ave, Sydney 2000, Australia

[2] School of Life and Environmental Sciences, Deakin University, Burwood, Melbourne 3125, Australia

solutions (Marsh and Bugusu 2007). The direct negative impacts of food packaging include the use of natural resources, pollution from manufacturing processes, littering, landfill issues, energy consumption, and GHG emissions during manufacturing, transportation, and end-of-life management of packaging waste (Boesen et al. 2019; Kroyer 1995; Langley et al. 2021). These negative impacts have spurred the development and use of alternative materials such as biodegradable plastics which are less dependent on the use non-renewable resources (Song et al. 2011). These materials are primarily produced from renewable materials (e.g., cellulose or starch etc.), and unlike petrochemical plastics can degrade due to activities by living organisms such as bacteria (Song et al. 2009). Many packaging solutions also incorporate new technologies such as modified atmosphere packaging (MAP) and active packaging (AP). MAP provides a tailored gas environment to slow down the degradation of food, while AP involves the use of materials that interact with the food to improve preservation (Rodriguez-Aguilera and Oliveira 2009).

Food packaging can also have important positive impacts (known as indirect impacts) through the provision of various functions (Boz et al. 2020; Brennan et al. 2021; Wikström et al. 2019). The main functions of food packaging are to contain food; protect food from mechanical damage, contamination, and microbial spoilage; and communicate information (expiry/use by dates, storage instructions etc.) about the food to consumers (Otto et al. 2021). These functions can play a crucial part in minimising food waste, which is food discarded during distribution, retail, and consumer activities (Verghese et al. 2015).

Food waste is attracting increasing attention as a serious problem affecting the sustainability of the global food system (Brennan et al. 2023; Nabi et al. 2021). It has been estimated that food waste contributes up to 10% of global GHG emissions, and that 60% of total food waste is generated at the household level (United Nations Environment Programme 2021). Per capita household food waste generation is relatively similar between middle-, and high-income countries, making food waste mitigation a relevant issue to all countries (United Nations Environment Programme 2021).

The relationship between food packaging and food waste has emerged as an area of interest in packaging sustainability research (Brennan et al. 2021). It is a complex relationship because packaging can both prevent and cause food waste, as well as contributing to waste in its own right (Williams et al. 2012). For example, in some cases the GHG emissions saved from preventing food waste can be considerably higher than the GHG emissions associated with the packaging (Shrivastava et al. 2022). A case in point is the food waste reduction achieved by wrapping cucumbers in protective plastic film for shelf-life extension. This has been found to prevent 4.9 times more GHG emissions than those resulting from the production and end-of-life management of the plastic packaging (Shrivastava et al. 2022). Therefore, depending on the circumstances such as the environmental intensity of the food products under consideration, the benefit to the environment from packaging may outweigh the environmental damage caused by its usage.

On the other hand, it has been estimated that up to half of household food waste can be attributed to inefficient food packaging (Williams et al. 2020). Some packaging solutions can increase residual food waste due to poor emptiability (Wohner et al. 2019b, 2020), and pack size can have an effect on food waste by how it influences consumer behaviour (Brennan et al. 2021). For example, a large proportion of bread is wasted in households, which is partially attributed to the portioning of packaged bread being too large for smaller households (Wikström et al. 2019).

Taking into account the interplay between packaging functions and food waste, sustainability strategies should involve changing physical features of packaging (e.g., material selection, volume, thickness, or shape) to minimise food waste, as opposed to only attempting to eliminate packaging altogether (Fresán et al. 2019; Licciardello 2017). Identifying such strategies requires acknowledging both (i) the direct impacts of packaging from raw material extraction, packaging production and transportation, end-of-life waste disposal, and (ii) the indirect impacts in the form of food waste saved or exacerbated as a result of packaging functions (Conte et al. 2015; Heller et al. 2019; Pauer et al. 2019).

The Life Cycle Assessment (LCA) methodology is commonly used to measure the environmental impact of products from cradle to grave (Hauschild and Huijbregts 2015; Herrero et al. 2013). This involves taking into account the entire life cycle, including impacts associated with raw materials, manufacture, consumption, and waste management (Grant et al. 2015; Herrero et al. 2013). Environmental inputs such as energy, land use, and water use relevant to each stage of the product life cycle are identified and quantified to calculate outputs in the form of multiple environmental impacts (global warming potential, land and water use, acidification, freshwater/marine/terrestrial toxicity, eutrophication etc.) that affect human health, ecosystems, and natural resources (Guinée 2015; Hauschild 2018). LCAs address questions specific to the product or process being studied (Molina-Besch et al. 2019; Silvenius et al. 2011), which in the context of evaluating packaging-related food waste can include the different packaging functions that affect food waste (Grönman et al. 2013).

The United Nations' Sustainable Development Target 12.3 seeks to halve global food waste per capita by 2030 (Ardra and Barua 2022). An impediment to this task is a lack of understanding about how food waste attributed to food packaging varies by product category. This information is needed to develop and implement product-specific strategies designed to minimise the food waste caused or prevented by food packaging (Otto et al. 2021). LCAs can play a crucial role by enabling the quantification and comparison of the impacts of packaging-related food waste across different food categories, which in turn can facilitate identification of categories that should be prioritised due to their greater potential to produce negative environmental impacts (Karwacka et al. 2020; Otto et al. 2021; Willett et al. 2019).

Despite the recognised need to address packaging-related food waste in food packaging LCAs, few published studies appear to have taken this approach (Molina-Besch et al. 2019; Pauer et al. 2019). Furthermore, it appears that no reviews specifically focusing on LCA studies of packaging-induced food waste across different food product categories have been published to date. The aims of this scoping review were to address current evidence gaps by: (i) assessing the extent to which LCA food packaging studies have incorporated food waste attributable to packaging properties, overall and by food category; (ii) synthesising outcomes in terms of the ability of different types of packaging to minimise food waste; and (iii) identifying areas of future research to provide a more comprehensive understanding of where future packaging LCA efforts could be directed.

## 2 Method

A scoping review was conducted to map the current literature on LCAs that include packaging-related food waste and identify knowledge gaps in areas where evidence is lacking. The protocol involved a systematic search of relevant articles identified based on predefined criteria (as per Pham et al. 2014). The Web of Science, Scopus, and ProQuest databases were searched for relevant articles with the search string: ((Food wast*) AND ("life cycle assessment" OR “life cycle analysis”) AND (food packag*)). The date range defined for the search was 2007 to 2023, and the search covered only academic peer-reviewed research articles. The start date reflects previous research demonstrating that studies published before 2007 did not include consideration of the indirect impacts of food packaging (Molina-Besch et al. 2019).

Details outlining how search results were screened are outlined in Fig. 1. Once duplicate results were removed, the resulting articles were screened by reviewing abstracts based on the inclusion and exclusion criteria, and the full text was reviewed for selected articles. Included articles were required to satisfy the following criteria: evaluated environmental impacts of packaged food products using LCA methodology, evaluated the impact of one or more functions of packaging solutions on food waste, specified the food product under investigation, and published in English. The following exclusion conditions were applied: analyses relating to alcohol or fast food (including dine-in, take-away, or delivered fast food), analyses relating to tertiary packaging, and where the reason for food waste was not specified. Citation chaining (forward and backward) was also applied to identify and include relevant citations within the selected articles.

Table 1 lists the 23 articles included in this review and provides an overview of the LCAs reported within these articles. The studies were reviewed based on (i) the LCA methodologies used, (ii) food product category(s) investigated, (iii) packaging materials/solutions assessed, and (iv) food waste related packaging function evaluated. The food product categorisation system used in this review was derived from the Food Standards Australia New Zealand (FSANZ) classification system (Food Standards Australia New Zealand 2023).

The following major packaging materials were observed in the analysed articles: plastic, paper, metal, biodegradable plastics, glass, MAP, and ‘other’. The ‘other’ category encompassed packaging substances such as nanomaterials and antimicrobial additives for active packaging.

## 3 Results

The initial search identified 554 potentially relevant articles. Upon application of the exclusion criteria mentioned above, only 23 articles were found to be eligible. In most instances, ineligibility was due to incidental mention of the term food waste, without any effort in the study to measure the impact of packaging on food waste. In some other cases, ineligibility was due to the articles being reviews of LCA methodologies. Of the 23 eligible articles, some examined multiple product categories, resulting in a total of 31 LCA studies that included food waste. The main observations of the reviewed studies are summarised in Table 2.

Of the 31 LCA studies, 16 examined highly perishable food product categories such as fresh meat, vegetables, and fruits. The most frequently evaluated packaging material was plastic, which was included in all studies (n = 31). The most common food waste related packaging attribute examined was shelf-life extension (n = 21).

### 3.1 LCA methodologies used in the reviewed articles

Table 1 summarises the key methodological approaches used in the included articles in terms of geographical context, impact categories reported, functional units, and allocation methods. A majority of the articles (n = 20) carried out LCAs using data relevant to Europe (Büsser and Jungbluth 2009; Casson et al. 2022; Conte et al. 2015; Flysjö 2011; Frigerio et al. 2023; Gutierrez et al. 2017; Hutchings et al. 2021; Lorite et al. 2017; Manfredi et al. 2015; Matar

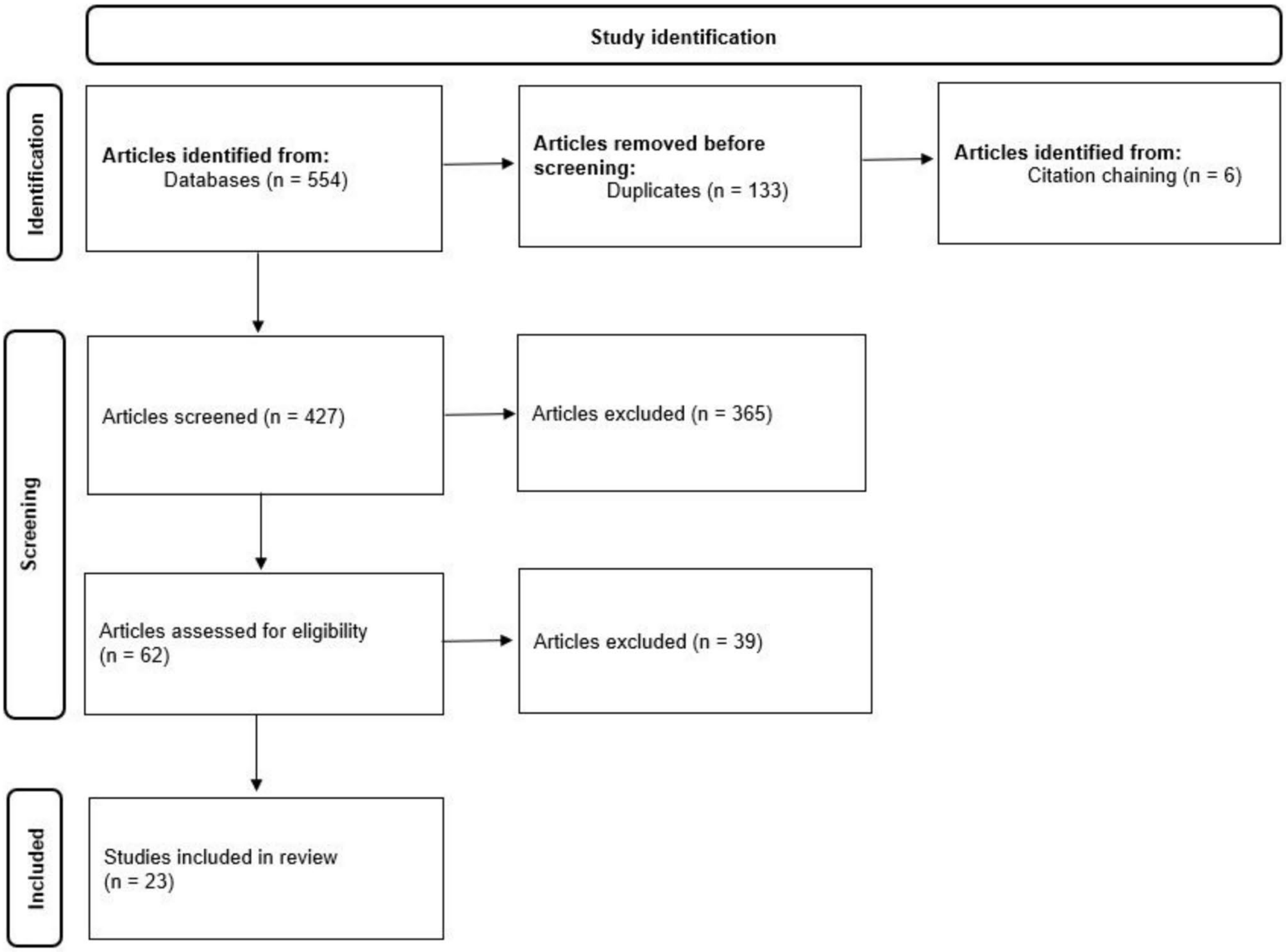

**Fig. 1** Research article screening process and results

et al. 2021; Settier-Ramirez et al. 2022; Shrivastava et al. 2022; Silvenius et al. 2014; Tsouti et al. 2023; Vigil et al. 2020; Wikström et al. 2016; Wohner et al. 2019b, 2020; Zhang et al. 2015, 2019). One LCA was carried out using Asian data (Yokokawa et al. 2019), one used Australian data (Dilkes-Hoffman et al. 2018), and one used a combination of North American and European data (Espinoza-Orias et al. 2011).

In food packaging LCAs, a functional unit generally defines the specific quantity of product delivered to the consumer and should include both the food and its packaging (Dobon et al. 2011; Vignali 2016). The selection of functional units can vary depending on the LCA to reflect the specific goals of the study (Frigerio et al. 2023). Consumption-based functional units were commonly observed (10 articles) (Espinoza-Orias et al. 2011; Flysjö 2011; Manfredi et al. 2015; Matar et al. 2021; Silvenius et al. 2014; Tsouti et al. 2023; Wikström et al. 2016; Wohner et al. 2019b, 2020; Yokokawa et al. 2019). Similarly, many of the selected functional units related to the amount of packaging or packaging required for a fixed amount of food product (10 articles) (Büsser and Jungbluth 2009; Casson et al. 2022; Conte et al. 2015; Dilkes-Hoffman et al. 2018; Frigerio et al. 2023; Gutierrez et al. 2017; Hutchings et al. 2021; Settier-Ramirez et al. 2022; Vigil et al. 2020; Zhang et al. 2019). Lastly, some functional units were related to the delivery of product to retail or consumers (3 articles) (Lorite et al. 2017; Shrivastava et al. 2022; Zhang et al. 2015).

There were notable differences in the selection and reporting of impact categories. Many studies included midpoint impact categories such as GHG emissions, land use, water use, ecotoxicity, and particulate matter formation. GHG emissions was the only impact category that was common to all the LCAs in the reviewed articles, and 5 articles only reported results based on GHG emissions (Espinoza-Orias et al. 2011; Flysjö 2011; Shrivastava et al. 2022; Yokokawa et al. 2019; Zhang et al. 2019). For this reason, this review examined the main conclusions and recommendations based on GHG emissions.

**Table 1** Overview of the packaging LCAs included in this review

| Title | Authors | Food | Geographical focus | Functional unit | Impact categories | Allocation method |
|---|---|---|---|---|---|---|
| Investigating the environmental benefits of novel films for the packaging of fresh tomatoes enriched with antimicrobial and antioxidant compounds through life cycle assessment | (Tsouti et al. 2023) | Tomatoes | Europe | Consumption of 1 kg of tomatoes by the end consumer, within the shelf life of tomatoes | **6 midpoint categories** FET, CC, WU, PMF, ADPf, and ADPe | Mixed allocation used for transportation |
| Comparison of different methodological choices in functional unit selection and results implication when assessing food-packaging environmental impact | (Frigerio et al. 2023) | Raspberries | Europe | Inherent functional unit: Conservation of one pack containing 250 g of fresh raspberries until the end of its shelf-life<br>Explicit functional unit: Conservation of 250 g of packaged fresh raspberries over an 11-days timespan | **18 midpoint categories** GWP, OD, IR, PMF, POe, POh, TA, FE, ME, HTc, HTnc, TET, FET, MET, LU, WU, MS | Mass allocation for end-of-life processes |
| Beyond the eco-design of case-ready beef packaging: The relationship between food waste and shelf-life as a key element in life cycle assessment | (Casson et al. 2022) | Beef | Europe | One unit of packaging containing 500 g of sliced beef | **10 midpoint categories:** ADPf, GW, OD, HT, FET, MET, TET, POF, acidification, eutrophication | Mass allocation at different stages |
| Assessing the environmental consequences of shelf-life extension: Conventional versus active packaging for pastry cream | (Settier-Ramirez et al. 2022) | Pastry cream | Europe | A bag of 200 mL capacity for empty package<br>A 218 g of packed pastry cream for packaged system | **18 midpoint categories:** CC, PMF ADPf, WU, FET, FE, HTc, HTnc, IR, MET, ME, metal depletion, POe, POh, OD, TA, TET | Economic allocation |
| To wrap or to not wrap cucumbers? | (Shrivastava et al. 2022) | Cucumbers | Europe | 1 metric tonne of cucumbers sold at retail | GWP | Not specified |
| Comparative life cycle analysis of a biodegradable multilayer film and a conventional multilayer film for fresh meat modified atmosphere packaging – and effectively accounting for shelf-life | (Hutchings et al. 2021) | Beef | Europe | Amount (g) of film required for 1 kg of produce | GWP, and non-renewable energy use | Mixed allocation methods: Economic and mass |

**Table 1** (continued)

| Title | Authors | Food | Geographical focus | Functional unit | Impact categories | Allocation method |
|---|---|---|---|---|---|---|
| Benefit of modified atmosphere packaging on the overall environmental impact of packed strawberries | (Matar et al. 2021) | Strawberries | Europe | 1 kg of strawberries eaten by the consumer from farm to fork | **18 midpoint categories:**<br>TA, FA, HTc, HTnc, CC, FET, TET, ME, FE, IR, LU, OD, photochemical ozone formation, ADPf, ADPe, respiratory inorganics and water scarcity | Mixed allocation methods:<br>Volume and economic |
| Sustainability analysis of active packaging for the fresh cut vegetable industry by means of attributional & consequential life cycle assessment | (Vigil et al. 2020) | Fresh-cut lettuce | Europe | A packaging unit intended to contain a 130 g serving of fresh cut lettuce | **18 midpoint categories:**<br>WU, urban LU, TA, PO, PMF, OD, natural land transformation, ADPe, ME, MET, IR, HT, FE, FET, ADPf, CC, agricultural LU | Circular footprint allocation |
| Environmental and economic assessment of food-packaging systems with a focus on food waste. Case study on tomato ketchup | (Wohner et al. 2020) | Tomato ketchup | Europe | Consumption of 3.8 kg ketchup | **16 midpoint categories:**<br>CC, ADPf, WU, FE, acidification, PMF | Mixed methods:<br>Biophysical and mass |
| Technical emptiability of dairy product packaging and its environmental implications in Austria | (Wohner et al. 2019b) | Milk, caffe latte, cream, sour cream, yogurt | Europe | 1 kg of consumed dairy product at room or refrigerator temperature in the home of the consumer | 16 midpoint categories were assessed<br>Only 6 were considered relevant categories were normalised and weighted:<br>Acidification, PMF (inorganics), CC, TE, FE, ADPf | Biophysical and circular footprint allocation |
| Assessment of carbon footprint of nano-packaging considering potential food waste reduction due to shelf-life extension | (Zhang et al. 2019) | Apricots, tomato paste, orange juice, and ham | Europe | 1 kg of food product and the required amount of nano-packaging materials | CC | Not specified |
| Environmental analysis of packaging-derived changes in food production and consumer behaviour | (Yokokawa et al. 2019) | Milk and cabbage | Asia | The specific amount of food consumed in a household:<br>1 L of milk consumption<br>1 kg of fresh SH cabbage consumption | GWP | Not specified |

**Table 1** (continued)

| Title | Authors | Food | Geographical focus | Functional unit | Impact categories | Allocation method |
|---|---|---|---|---|---|---|
| Environmental impact of biodegradable food packaging when considering food waste | (Dilkes-Hoffman et al. 2018) | Beef and cheese | Australia | 1 kg of packaged product at the house | GWP and WU | Economic allocation |
| Food losses, shelf-life extension and environmental impact of a packaged cheesecake: A life cycle assessment | (Gutierrez et al. 2017) | Cheesecake | Europe | A tray containing two cheesecakes, with a total weight of approximately 300 g | **17 midpoint categories**: CC, HH, OD, HT, POF, PMF, IR, TA, FE, TE, FET, MET, agricultural LU, urban LU, natural land transformation, ADPf, ADPe<br>**Endpoint categories**: Resource use, human health and ecological consequences | Not specified |
| Evaluation of physicochemical/microbial properties and life cycle assessment (LCA) of PLA-based nanocomposite active packaging | (Lorite et al. 2017) | Melon | Europe | Providing customers with 100 000 kg of fresh fruits during one year | **16 midpoint categories:** HTc, HTnc, PMF inorganics, IR, OD, PMF organics, aquatic ecotoxicity, TA, LU, aquatic acidification, aquatic eutrophication, GWP, non-renewable energy, ADPe, bulk waste | Not specified |
| The influence of packaging attributes on recycling and food waste behaviour - An environmental comparison of two packaging alternatives | (Wikström et al. 2016) | Beef | Europe | 1 kg eaten minced meat | GWP, acidification, OD | Not specified |
| The effect of active packaging on minimizing food losses: Lifecycle assessment (LCA) of essential oil component-enabled packaging for fresh beef | (Zhang et al. 2015) | Beef | Europe | Delivering 1 kg fresh beef to the retail gate and displaying it until the end of shelf life | GWP, ADPf, acidification potential, eutrophication potential | Not specified |

**Table 1** (continued)

| Title | Authors | Food | Geographical focus | Functional unit | Impact categories | Allocation method |
|---|---|---|---|---|---|---|
| Environmental assessment of antimicrobial coatings for packaged fresh milk | (Manfredi et al. 2015) | Milk | Europe | 1 L of consumed milk | **15 midpoint categories:** HTc, HTnc, PMF(inorganics), HTc, HTnc, respiratory inorganics, respiratory organics, IR, OD, aquatic eco-toxicity, terrestrial eco-toxicity, TA, aquatic acidification, aquatic eutrophication, LU, GWP, non-renewable energy, ADPe | Not specified |
| Environmental implications of food loss probability in packaging design | (Conte et al. 2015) | Sheep milk cheese | Europe | 100 g of packaged portioned sheep's milk cheese | AD, potential acidification, potential eutrophication, FET, GWP, HT, MET, PO, TET | Mass allocation |
| The role of household food waste in comparing environmental impacts of packaging alternatives | (Silvenius et al. 2014) | Soy yogurt, ham, and bread | Europe | 1000 kg of each product consumed by the consumer | CC, eutrophication, acidification | Mass allocation |
| Potential for improving the carbon footprint of butter and blend products | (Flysjö 2011) | Butter and blends | Europe | 1 kg of packaged butter or blend provided at the customer level in Denmark<br>1 kg of packaged butter or blend consumed in Denmark | CF | Physical causality allocation,<br>weighted fat and protein content allocation: subdivision and economic allocation |
| The carbon footprint of bread | (Espinoza-Orias et al. 2011) | Bread | Europe and North America | One loaf of sliced bread (800 g) consumed at home | CF | Economic allocation |
| The role of flexible packaging in the life cycle of coffee and butter | (Büsser and Jungbluth 2009) | Butter, coffee | Europe | One cup of coffee ready to drink at home or in small offices<br>The provision of 1 kg of butter ready to be eaten at home | Non-renewable cumulative energy demand, CC, OD, acidification, eutrophication | Not specified |

*FET* Freshwater Ecotoxicity, *CC* Climate Change, *WU* Water Use, *PMF* Particulate Matter Formation, *ADPf* Abiotic Depletion: fossil, *ADPe* Abiotic Depletion: mineral, *GWP* Global Warming Potential, *OD* Ozone Depletion, *IR* Ionizing Radiation, *PO* Photochemical Oxidant Formation, *POe* Photochemical Oxidant Formation: terrestrial ecosystems, *POh* Photochemical Oxidant Formation: human health, *TA* Terrestrial Acidification, *FE* Freshwater Eutrophication, *ME* Marine Eutrophication, *HTc* Human Toxicity: cancer, *HTnc* Human Toxicity: non-cancer, *TET* Terrestrial Ecotoxicity, *MET* Marine Ecotoxicity, *LU* Land Use, *MS* Mineral Resource Scarcity, *CF* Carbon Footprint

**Table 2** Main results for packaging materials and packaging attributes included in reviewed papers

| | Number of studies[a] | Number of LCA studies for each packaging material[b] | | | | | | | Number of LCA studies for each packaging attribute | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Plastic | Paper | Metal | Other | MAP | Biodegradable plastics | Glass | Shelf-life extension | Package size | Emptiability |
| **Non-alcoholic beverages** | 2 | 2 | 1 | 1 | 1 | | | | 1 | 1 | |
| **Cereal and cereal products** | 2 | 2 | 2 | | | | | | | 2 | |
| **Cereal based products and dishes** | 2 | 2 | | | 1 | 1 | | | 2 | | |
| **Fats and oils** | 2 | 2 | 2 | 2 | | | | | | 2 | |
| **Fish and seafood products and dishes** | | | | | | | | | | | |
| **Fruit products and dishes** | 4 | 4 | | | 2 | 1 | 1 | | 4 | | |
| **Egg products and dishes** | | | | | | | | | | | |
| **Meat, poultry, and game products, and dishes** | 8 | 8 | | 1 | 1 | 2 | 2 | | 6 | 1 | 1 |
| **Milk products and dishes** | 4 | 4 | 3 | 2 | 1 | | 1 | 1 | 3 | 1 | 1 |
| **Dairy and meat substitutes** | 1 | 1 | 1 | 1 | | | | | | | 1 |
| **Seed and nut products and dishes** | | | | | | | | | | | |
| **Savoury sauces and condiments** | 1 | 1 | | 1 | | | | 1 | | | 1 |
| **Vegetable products and dishes** | 5 | 5 | 1 | | 2 | | 1 | | 5 | 1 | |
| **Legume pulse products and dishes** | | | | | | | | | | | |
| **Snack foods** | | | | | | | | | | | |
| **Sugar products and dishes** | | | | | | | | | | | |
| **Confectionary and cereal/nut/fruit/seed bars** | | | | | | | | | | | |
| **Special dietary foods** | | | | | | | | | | | |

[a] The sum of column 1 is higher than 23 as some studies evaluated more than one product category

[b] The numbers reported for packaging materials correspond to the number of studies that included each packaging material type. Therefore, some studies have been recorded more than once to reflect the inclusion of multiple product categories in analyses

Allocation methods varied significantly between LCAs. It is well established that the choice of allocation method can have a significant bearing on the final results, especially in livestock systems that produce multiple products (Kyttä et al. 2022). The most widely used allocation methods in this review included mass allocation, economic allocation, and/or circular footprint allocation (Casson et al. 2022; Conte et al. 2015; Dilkes-Hoffman et al. 2018; Espinoza-Orias et al. 2011; Frigerio et al. 2023; Settier-Ramirez et al. 2022; Silvenius et al. 2014; Vigil et al. 2020; Wohner et al. 2019b). Some LCAs used mixed allocation methods for the different stages within the system boundaries under investigation, while some articles did not specify the allocation methods used.

### 3.2 Distribution of packaging LCAs by food product categories

As shown in Table 2, distribution by major food product categories was highly uneven across the reviewed LCA studies. The most frequently studied product categories were *meat products and dishes* (n = 8 studies), *vegetable products and dishes* (n = 5), *fruit products and dishes* (n = 4), and *milk products and dishes* (n = 4). The remaining studies reported results relating to *non-alcoholic beverages* (n = 2), *cereal and cereal products* (n = 2), *cereal-based products and dishes* (n = 2), *fats and oils* (n = 2), *dairy and meat substitutes* (n = 1), and *savoury sauces and condiments* (n = 1). There were no studies covering food products from the categories of *fish and seafood products and dishes*, *egg products and dishes*, *seed and nut products and dishes, legume and pulse products and dishes, snack foods, sugar products and dishes, confectionary and cereal/nut/fruit/seed bars*, and *special dietary foods*.

The importance of including food waste in food packaging LCAs was noted in all of the reviewed studies. In addition, two studies highlighted the need for analyses of potential trade-offs between product type and product packaging. These studies showed that for products with high levels of environmental impact or perishability (beef and strawberries, respectively), the direct impacts of packaging can be less consequential than the impacts of the food waste (Casson et al. 2022; Matar et al. 2021). Both these studies recommended to better understand the trade-offs between food waste and packaging for other product categories.

### 3.3 Types of packaging materials assessed

Most of the packaging types assessed in the reviewed studies were packaging solutions that included multiple materials (n = 23: see Table 2). A notable exception was the study that examined the effect of plastic packaging on cucumbers by directly comparing plastic shrink wrap to no packaging (Shrivastava et al. 2022). The plastic-based packaging solutions included polyethylene (PE), low density polyethylene (LDPE), high density polyethylene terephthalate (HDPE), polyethylene terephthalate (PET), polypropylene (PP), and polystyrene (PS). Paper, the second most commonly evaluated packaging material (n = 10), was typically observed in packaging solutions where it was laminated with plastic or aluminium.

The 'other' category (n = 8) mostly involved plastic-based packaging solutions combined with one or more other solutions. Metal (n = 8) was typically examined in combination with wrappings for butter and butter blends in the *fats and oils category*, and laminates and foil covers were used for *milk products and dishes*. All MAP solutions (n = 4) were evaluated in combination with plastic packaging solutions within the *cereal-based products and dishes*, *fruit products and dishes,* and *meat products and dishes* categories.

Biodegradable plastics (n = 5) were less frequently evaluated. These were evaluated for *meat products and dishes* and *milk products and dishes, fruit products and dishes,* and *vegetable products and dishes* categories. Glass packaging was also infrequently evaluated (n = 2), and was only observed for the *milk products and dishes* (n = 1) and *savoury sauces and condiments* (n = 1) product categories.

### 3.4 Packaging attributes affecting food waste

The packaging attributes that influence food waste that were addressed in the papers included in this review were 'emptiability', shelf-life extension, and pack size. Almost all of the studies evaluated a single type of packaging attribute, the exception being a study that examined shelf-life and pack-size implications of alternative packaging solutions for milk and cabbage products. Most of the studies assessed the ability of packaging solutions to extend shelf life (n = 21); this was particularly notable for the *meat products and dishes* (n = 6), *vegetable products and dishes* (n = 5), and *fruit products and dishes* (n = 4) categories. All studies examining shelf life found that the environmental benefit gained through the reduction of food waste achieved through shelf-life extension significantly outweighed the direct impacts of the packaging solutions. It was noted in one study that for highly perishable food products such as strawberries, shelf-life extension should be prioritised over other packaging-related waste-minimisation attributes such as emptiability or pack size because these products are highly prone to spoilage prior to being consumed (Matar et al. 2021).

Pack size was the second most commonly evaluated packaging function in terms of food waste (n = 8). The relevant food product categories were *cereal products* (n = 2), *fats and oils* (n = 2), *non- alcoholic beverages* (n = 1), *meat products and dishes* (n = 1), *milk products and dishes* (n = 1), and *vegetable products and dishes* (n = 1). These studies noted that the impacts of the packaged food products are influenced by the amount of packaging material used per unit of food (e.g., smaller pack sizes result in more material usage per unit). However, it was also noted that using more material per unit of food for smaller portion sizes of products can be justified if those smaller portions help minimise food waste by consumers. These studies recommended that manufacturers consider pack size in relation to consumption patterns when designing food packaging to help consumers minimise the amount of food discarded (Büsser and Jungbluth 2009; Espinoza-Orias et al. 2011; Flysjö 2011; Yokokawa et al. 2019).

Emptiability was the least frequently evaluated packaging function in the context of food waste (n = 4). The relevant food product categories were *meat and meat products* (n = 1), *milk and milk products* (n = 1), *dairy substitutes* (n = 1), and *savoury sauces and condiments* food product categories (n = 1). Although certain packaging solutions that are easier to fully empty may have a higher environmental burden, several studies found that they ultimately reduce the overall environmental impact of packaged food by reducing residual food waste. For example, while a plastic tray solution for minced beef had higher direct impacts compared to a lightweight plastic tube alternative because it used more raw material, it was more efficient in emptying the food out of the container, thereby reducing residual food waste and overall impact (Hutchings et al. 2021).

### 3.5 Other considerations

Fourteen of the 23 papers reviewed provided recommendations focused solely on the ability to reduce food waste through the use of one or more alternative packaging solutions selected for the individual studies. The recommendations for the remaining 10 papers related to both packaging alternatives and additional considerations. Of these, seven examined the effects of consumer behaviours and two included economic evaluations. Recommendations made on how to minimise impacts of food packaging are summarised in Table 3.

Of the seven papers that considered consumer behaviours (Table 3), three evaluated the relationship between pack

**Table 3** Additional considerations included in packaging evaluations

| Intervention scenarios | Solution insights | Studies |
|---|---|---|
| Packaging alternatives only | • Packaging solutions that reduce food waste demonstrate better environmental profiles | Casson et al. 2022; Conte et al. 2015; Dilkes-Hoffman et al. 2018; Frigerio et al. 2023; Hutchings et al. 2021; Lorite et al. 2017; Manfredi et al. 2015; Settier-Ramirez et al. 2022; Shrivastava et al. 2022; Tsouti et al. 2023; Vigil et al. 2020; Wohner et al. 2019b; Zhang et al. 2015, 2019 |
| Consumer behaviour | • The effectiveness of packaging attributes in reducing food waste depends on consumer behaviour<br>• Packaging attributes that require additional food processing steps by the consumer tend to increase overall environmental impact<br>• Smaller/individual portions require more packaging material per unit of food but may help prevent wastage depending on consumption patterns<br>• The effects of packaging on the life cycle of high-impact products such as butter are minor. The role of packaging in avoiding food waste due to spoilage is important high environmental intensity of these products.<br>• For highly perishable products such as strawberries, identifying more environmentally friendly packaging solutions must consider consumer behaviour around storage times and temperatures | Büsser and Jungbluth 2009; Espinoza-Orias et al. 2011; Flysjö 2011; Matar et al. 2021; Silvenius et al. 2014; Wikström et al. 2016; Yokokawa et al. 2019 |
| Economic considerations | • Packaging solutions with better shelf-life extension attributes can potentially reduce financial losses for retailers caused by discarded food (i.e. food not purchased by consumers as they expire too soon)<br>• Packaging solutions that demonstrate better emptiability (for ketchup) are economically beneficial to consumers as they are able to fully access and consume the purchased product<br>• While in the short-term packaging solutions that demonstrate better emptiability are not as economically beneficial to the manufacturers as they can potentially reduce overall sales, manufacturers should consider longer-term benefits gained through improved consumer satisfaction. | Gutierrez et al. 2017; Wohner et al. 2020 |

size and consumer behaviours (Büsser and Jungbluth 2009; Espinoza-Orias et al. 2011; Flysjö 2011), one explored the effects on consumer behaviour of pack size and emptiability (Wikström et al. 2016). A fifth paper assessed how consumer behaviour can influence food waste produced when using products with varying shelf lives and pack sizes (e.g., non-refrigerated milk versus refrigerated milk) (Yokokawa et al. 2019). A sixth paper evaluated the impacts related to food waste influenced by practical emptiability, which is measured by surveying consumers about how they empty food products (as opposed to laboratory-based technical emptiability studies) (Silvenius et al. 2014). The seventh paper considered how the impacts of different packaging solutions differed according to how consumers stored strawberries (i.e. different storage times and temperatures) (Matar et al. 2021). All these studies emphasised that while packaging design should aim to minimise environmental impacts caused by food waste, understanding how different consumer behaviours affect food waste levels is also crucial to improve the accuracy of future packaging LCAs.

Of the two papers that combined LCA studies with economic evaluations, one evaluated packaging alternatives for cheesecake and concluded that the packaging solution that produced better shelf-life outcomes was also more economically beneficial for the business (Gutierrez et al. 2017). The second evaluated the impact of better emptiability of ketchup containers and found that packaging solutions associated with less food waste were more economically beneficial for consumers because of the economic value of being able to use all of the food product they purchased (Wohner et al. 2020). However, this study showed that better emptiability was not found to be as economically beneficial for manufacturers because less waste corresponds with reduced sales.

## 4 Discussion

The present review identified LCA studies that included consideration of food waste and drew comparisons across food product categories, types of packaging materials, and packaging attributes that influence food waste. While there is growing recognition that food packaging LCAs should account for both the positive and negative impacts of packaging on food waste (Heller et al. 2019; Molina-Besch et al. 2019; Wikström et al. 2019), this review found limited published research taking this approach. Most of the identified LCA studies that included consideration of food waste related to *meat, poultry, and game products, and dishes*; *vegetable products and dishes*; *fruit products and dishes*; and *milk products and dishes*. There were small numbers of studies focusing on the categories of *non-alcoholic beverages, cereal and cereal products, cereal based products and dishes, fats and oils, dairy and meat substitutes,* and *savoury sauces and condiments,* and no studies relating to *fish and seafood products and dishes, egg products and dishes, Seed and nut products and dishes, legume pulse products and dishes, snack foods, sugar products and dishes, confectionary and cereal/nut/fruit/seed bars,* and *special dietary foods*. Plastic was the most commonly evaluated packaging material and shelf-life extension was the most widely studied food waste related packaging attribute. The following sections discuss the key findings of the included studies and their implications for the development of more sustainable food packaging.

### 4.1 Comparison of LCA methodological choices in the reviewed articles

There is a relatively wide variation in the selection of functional units for food packaging LCAs. As was observed for the packaging LCAs of raspberries (Frigerio et al. 2023), while there can be substantial variation in results depending on if food waste is accounted for within the functional unit, researchers should also consider the nature of the food product such as varying rates of spoilage. It is evident that selection of functional units that include food waste can provide valuable insights for developing food packaging solutions that minimise food waste while also accounting for the impact of the food packaging itself.

Reporting on multiple impact categories is considered ideal and could improve comparability of LCA results, but it can be a highly complex task requiring specific expertise (Smurthwaite et al. 2023). This complexity was highlighted by the diversity in the selection and reporting of impact categories for the LCAs examined in this review. Additionally, some studies reported solely on a single impact category, potentially compromising the comprehensiveness of those individual studies. In such instances, there is a likelihood that the unaccounted impacts can far outweigh the benefits observed by measuring a single impact category (Saleh 2016; Smurthwaite et al. 2023). Moreover, although GHG emissions maybe highly relevant to food waste, considering other impact categories is crucial in making more accurate comparisons between packaging materials. For example, it has been shown that although paper bags are higher in GHG emissions compared to plastic bags, the litter potential of plastic bags is considerably higher than paper bags (Arunan and Crawford 2021). The findings of this review emphasise the importance of considering more consistent and broader range of environmental impacts in LCA research.

While the International Organisation for Standardization (ISO) provides a hierarchy for LCA allocation methods, it leaves room for LCA practitioners to select allocation methods based on the varying goals of LCAs (Aldama et al. 2023). This was evident in the varied allocation methods observed for the studies reviewed. Moreover, many of the studies did not clearly specify their allocation method. It is important to ensure a high degree of transparency in all critical methodological choices such as the allocation method.

## 4.2 Coverage of food product categories by LCAs that include packaging related food waste

The agricultural processes involved in producing meat and dairy products are typically associated with higher environmental impacts compared to those for plant-based food products (Willett et al. 2019). As a consequence, the emissions resulting from animal-derived food waste are likely to be relatively high, resulting in a need to prioritise the reduction of food waste via improvements in packaging in these categories. This appeared to be reflected in the strong focus on meat products and dishes in the reviewed LCAs. The second-highest prevalence of vegetable and fruit categories in the reviewed articles is potentially attributable to high perishability of these products and associated high levels of household waste (Joardder and Masud 2019).

Although a majority of the high-impact food categories was well represented within the reviewed studies, there was a notable absence of some high-impact food product categories such as *fish and seafood products and dishes* and *egg products and dishes*. This could potentially be attributed to the limited influence of packaging on the food waste generated within these categories. For example, a considerable proportion of food waste generated from *fish and seafood products and dishes*, and *egg products and dishes* is due to the inedible components such as bones and shells (Schott and Andersson 2015; de la Caba et al. 2019). Therefore, the higher proportion of unavoidable food waste generated in these categories could reduce the perceived need to evaluate packaging-related food waste in these categories.

## 4.3 Packaging materials

The use of fossil fuels for plastic production, complexities surrounding the circularity of single-use plastics, and the longer degradation time of plastics compared to other packaging materials have catalysed interest in the sustainability of plastic (Ncube et al. 2021; Singh et al. 2022). The dominance of plastic in the assessed LCAs may also be due to it being the most commonly used packaging material in the food industry (Ncube et al. 2021). The development of alternative materials to plastics such as biodegradable materials may be a reason for the emerging number of LCAs that include these materials. The main concerns surrounding these materials are that their environmental impacts are less well understood compared to the impacts of conventional plastic packaging (Goel et al. 2021). However, as evidenced by the reviewed studies, it is evident that for high-impact food categories (e.g., meat and dairy products) or highly perishable food categories (e.g., fruit and vegetables), the use of complex packaging systems and novel materials can be justified despite the higher direct impacts associated with the relevant materials.

## 4.4 Packaging attributes that impact food waste

Shelf-life extension is considered to be the most important packaging attribute for minimising food waste in high-impact categories (meat and dairy) and highly perishable products (fresh vegetables and fruits) (Afif et al. 2021). The finding of the present review that shelf-life extension was the most commonly examined packaging attribute is likely due to the much greater representation of LCAs within high-impact and highly perishable food categories. In many of the assessed studies, packaging solutions that demonstrated better shelf-life extension capabilities were associated with greater direct environmental impacts due to the use of heavier or additional materials compared to solutions that were less packaging-intensive. However, when the food waste saved due to shelf-life extension was factored in, the more packaging-intensive solutions in these categories demonstrated better overall environmental outcomes.

Emptiability was studied for minced meat, ketchup, and a range of dairy products such as yoghurt, milk, and milk-based beverages. While these products generally belong to high-impact food categories, they are also relatively high in viscosity and could thus be expected to generate greater levels of food waste compared to less viscous products (Wohner et al. 2019a). This highlights the need to consider the complex interactions between packaging materials, packaging design, and the intrinsic properties of food when attempting to reduce packaging-related food waste. Although a majority of the packaging solutions for high-impact or highly viscous products had high direct environmental impacts (e.g., glass bottles for ketchup), their superior emptiability properties mitigated food waste leading to overall better impacts compared to the packaging solutions that had lower emptiability (Wohner et al. 2020). These observations provide further support for calls to routinely include consideration of the effects of packaging on food waste in food packaging LCAs (Brennan et al. 2021; Kakadellis and Harris 2020; Molina-Besch et al. 2019).

## 4.5 Other considerations

The assessed studies that examined the influence of consumer behaviour on packaging-related food waste found that frequency of consumption, storage habits (e.g., cold storage or storage at room temperature), food preparation methods, and packaging waste-handling practices can have a material impact on packaging-related food waste. However, it was noted that the outcomes of the LCAs are highly dependent on the quality of data for food waste generated by varying consumer behaviours (Schanes et al. 2018). Reviews have shown that there is a need to more accurately quantify the amount of food waste generated within households, making this an important area of future research that could help facilitate more LCAs that consider packaging-related food waste and solutions to minimise it (Schanes et al. 2018; Stancu et al. 2016).

## 5 Conclusions

There is mounting evidence to support the notion that holistic sustainability assessment of food packaging must explicitly consider the role of packaging in mitigating food waste (Licciardello 2017; Otto et al. 2021; Pauer et al. 2019). However, this review shows that such LCAs are limited in the academic literature, and the few that exist focus on specific food categories such as *meat, poultry, and game products, and dishes*; *vegetable products and dishes*; *fruit products and dishes*; and *milk products and dishes*. The particular interest in these categories is likely driven by the higher environmental intensity of the food waste generated. While this review shows that although current packaging LCAs have identified these product categories as important, there is a need to cover a broader range of products from high-impact food product categories. Additionally, analysis of the LCA methodologies showed that greater transparency in methodological choices is required to gain a more balanced view of the environmental impacts of the packaged food product. This review also highlights the need for more empirical data explicating the potential food waste saved via packaging attributes. Moreover, further research is required to gain a deeper knowledge of how packaging-related food waste is influenced by consumer behaviours and attributes (e.g., age, sex, and socioeconomic position).

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