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Life cycle assessment methods for investigating novel food packaging systems

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The high volume of plastic waste generated and its potential harm to wildlife and ecosystems are negative consequences of poor end-of-life food packaging management. An essential part of designing food packaging is minimizing its environmental impact, which is a significant challenge for the industry. The aim of this study was to examine existing life cycle assessment (LCA) approaches for investigating the environmental advantages of novel food packaging systems in the field of ready-to-eat fish and meat products. The scope of studies differed, with some including food products and others focusing on the direct and/or indirect environmental impacts of packaging. The reviewed LCA performances showed how different focuses could be used as sequential steps in obtaining a comprehensive understanding of the environmental impact of a food-packaging system. By considering a holistic LCA approach and evaluating the environmental performance of different packagings, industry stakeholders can make informed decisions. Therefore, playing an active role that balances necessity and wastefulness and creates efficient and sustainable packaging solutions.

Environmental significance

Addressing food and packaging waste is vital for protecting the environment. Research on eco-friendly packaging systems serves as a catalyst for re-evaluating our current practices undertaken to reach the overarching goal of minimizing adverse environmental impacts. Exploring various life cycle assessment (LCA) methodologies offers a robust framework for evaluating the environmental implications of packaged food products, packaging materials, and alternative packaging systems. Careful consideration of methodologies, breadth of scopes, and delineation of system boundaries are crucial for better eco-friendly solutions and imperative for equitable comparisons against existing packaging paradigms. These methodological intricacies are fundamental in the pursuit of novel food packaging solutions that offer superior environmental benefits. Emphasizing tailored LCAs for alternative packaging for ready-to-eat seafood can reveal targeted strategies to reduce packaging-related environmental impacts.

Introduction

Improving the environmental impact of packaging is a challenging task. Eco-packaging design aims to include sustainable performance in the core requirements of packaging[1] to decrease the environmental impact of food packaging compared to traditional packaging. Successful and sustainable innovations depend on a clear understanding of the impacts and benefits of innovative packaging systems throughout the entire life cycle. Attributes such as biobased, recyclability or biodegradability were proven as no direct indicators for reducing the life cycle environmental impact of food packaging.[2] The environmental sustainability of a product or process can be quantified using LCA. Additional sustainable categories that are not included in LCAs are economic (life cycle costing (LCC)) and social (social life cycle assessment (SLCA)), which are the other two pillars of sustainability, can also be included to provide a holistic sustainable performance investigation.[3] Nevertheless, studies combining all three aspects are difficult to perform and have been less widely studied.[4]

LCA is defined in ISO standard 14040 (ref. 5), focusing on the principles and frameworks, and 14044 (ref. 6) gives more detailed requirements and guidelines. Further instructions on LCA based on ISO 14044/44 are given in the International Reference Life Cycle Data System (ILCD) Handbook[7] or the handbook on LCA Operational Guide to the ISO standards.[8] LCAs are divided into four steps according to ISO 14044, which are interrelated throughout the entire assessment, and each plays an important role. (1) Goal and scope definition: defining the functional unit, system boundaries, impact categories and geographical scope. (2) Life cycle inventory analysis (LCI): collection of data to meet the objective of the LCA study. (3) Life cycle impact assessment (LCIA): converting the collected LCI into related environmental impacts. (4) Interpretation: summary of the LCI and LCIA, sensitive analysis, conclusions and recommendations. It can be used with different focuses for developing eco-food packaging. IT can be used to investigate environmental hotspots of a packed food product, identify the

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Table 1 LCA studies of packed RTE seafood products or similar products published in the last 10 years (2014–2023)

Food product	Functional unit	Impact categories	Packaging details	System boundary	Main conclusions on packaging	Source
RTE pork and bean stew	1 kg of prepared stew	16 Midpoint categories 1 End point category (carbon footprint)	Primary packaging of RTE products: steel cans or aluminium cans Secondary packaging of RTE products Primary packaging of intermediate products: cradle to the gate, without EoL	Cradle to grave	Tinplate used in metal can fabrication contributes significantly to packaging impact Recycling tinplate can yield overall environmental savings Substituting tinplates with aluminium is not recommended primarily due to lower environmental savings during aluminium recycling Recommendation to reduce packaging impacts: reducing weight, increasing recycled content and/or increasing recyclability	12
RTE wet/dry baby porridge	Consumption of 1 porridge meal (125 g)	Global warming potential, abiotic depletion potential of elements and fossil resources, acidification and eutrophication potentials, freshwater aquatic ecotoxicity potential, human toxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential, photochemical oxidants creation potential, and ozone layer depletion potential	Primary packaging: Dry porridge: plastic bag in cardboard box Wet porridge: glass jars using a metal cap with an aluminium and plastic lining	Cradle to grave	Packaging is only a hotspot for the wet porridge option The main hotspots for the wet product are the manufacturing and packaging of raw materials Using a plastic pouch instead of a glass jar would decrease most environmental impacts of wet porridge by 7–89%	13
Ready-made meals (*e.g.*, Fisherman's pie)	Chilled ready-made meal for one person consumed at home in the UK	Global warming potential, abiotic depletion potential of elements, fossil fuels, acidification potential, eutrophication potential, freshwater aquatic ecotoxicity potential, photo-chemical oxidation potential, ozone depletion potential, and terrestrial ecotoxicity	Primary, secondary, and tertiary packaging of RTE meal Additional packaging stages Raw material packaging and plastic bags at consumption	Cradle to grave (including food loss and waste)	Impact of packaging is below 10% in all impact categories exception ADP fossil with around 22%	14
Three types of dinner meals	One unit of RTE meal (507 g food)	Greenhouse gas emission, energy use, and waste generation	Primary, secondary, and tertiary packaging	Cradle to grave	Packaging greatly affects the environmental impact of RTE products Consumers criticize overpackaging of RTE food products RTE meals had higher packaging weight compared to other meals	15

Table 1 (*Contd.*)

Food product	Functional unit	Impact categories	Packaging details	System boundary	Main conclusions on packaging	Source
					Optimize RTE meal packaging for environmental improvements and to align with consumer preferences	
RTE steamed Indonesian canned crab	1 ton of canned product at market	Global warming, acidification, eutrophication, and abiotic depletion	Primary packaging: can, plastic cup, or pouch	Cradle to market	Processing stage has the highest impact for most impact categories mainly due to tin can use Substituting cans with plastic cups or pouches reduces impact by 70–85% per FU.	16
RTE cooked European pilchard (*Sardina pilchardus*)	Amount of protein supplied by one can of sardines in olive oil (eq. to 17.26 g protein)	Climate change, ozone depletion; human toxicity; photochemical oxidant formation; particulate matter formation; ionizing radiation; terrestrial acidification; freshwater eutrophication; marine eutrophication; terrestrial ecotoxicity; freshwater ecotoxicity; marine ecotoxicity; agricultural land occupation; urban land occupation; water depletion; metal depletion; fossil depletion	Primary packaging: can Secondary packaging: cardboard boxes	Cradle to grave	Packaging has a significant impact on canned products	17
RTE cooked sardine	1 kg of edible product of canned sardine	Abiotic depletion potential, acidification potential, cumulative energy demand, eutrophication potential, global warming potential in 100 years, ozone depletion potential, marine aquatic ecotoxicology potential, and photochemical oxidation potential	Primary packaging:aluminium cans and boxboard Secondary packaging: corrugated board boxes, pallets and LDPE film	Cradle to factory gate	Aluminium can production has the highest impact, except for ozone depletion potential and eutrophication potential, due to energy demand and raw material extraction -Recommendation for optimising packaging environmental performance: replacing packaging material	18

interaction between packaging and products, or compare the environmental effects of alternative packaging systems to a benchmark product-packaging system. LCA has evolved in recent years and has been further standardised, but limitations such as the complexity of the analysis and the required full transparency of the selected methods, data sources and results are hurdles.[3,9]

When developing eco-packaging solutions, it is important to investigate the environmental influences of the proposed eco-design option to minimize the environmental impact of a packaging material, packaging system or food-packaging system. Almeida *et al.*[10] highlighted that food packaging systems that can improve product shelf life and simultaneously limit the negative environmental impact of food packaging are of growing interest. LCAs can generate valuable outputs and support the decision-making process about more sustainable packaging. However, there are many different approaches to investigating the environmental impact of food packaging. The aim of this state-of-the-art review paper is to study the applied LCA approaches to support the development of novel eco-packaging solutions with a focus on solutions for ready-to-eat (RTE) seafood products. RtE seafood products are in high demand considering the current consumer trends of convenience, healthy, nutritious, mildly preserved foods and products with an enhanced shelf life and controlled product quality.[11] This review focus points are divided into four subsections: (1) LCA studies focusing on food-packaging systems, (2) LCA studies comparing different packaging materials, (3) LCA studies comparing different packaging systems, and (4) LCA studies with alternative innovative (novel) packaging systems.

Experimental procedure

A literature search was carried out by investigating publications in peer-reviewed indexed journals through electronic databases (Scopus, Google Scholar and Science Direct). Only publications in English published from 2014 to 2023 were considered. The search terms used were combinations of LCA and fish, meat or RtE food products, and/or packaging. Studies in the range of three digits could be found with the search words 'meat and LCA' or 'fish and LCA', while only studies in the range of two digits could be found for the search terms 'meat and LCA and packaging' or 'fish and LCA and packaging'. Limited studies were found when using the search terms 'LCA and RtE' or 'LCA and RtE and packaging'. This provides a broad overview of the consideration of packaging in LCA studies and indicates a lack of research on LCA studies with RtE products. The gathered articles were further investigated and considered only when they fit into the previously described focus areas of this review.

Findings

LCA studies focusing on food-packaging systems

The investigated LCA studies focusing on the food supply chain and the packaging supply chain for RTE products are summarised in Table 1. These studies focus on a comprehensive LCA of food products, including the package *inter alia*, to investigate environmental hotspots. Important considerations for calculating the food impact in a food-packaging LCA study were raw material sourcing, product production, transportation, retailing, use phase and end-of-life (EoL) phase. Food loss and waste should also be included at the different stages of the food life cycle.[19] The global warming potential for seafood products was investigated ranging from 0.7 to 31 CO_2 eq. per kg^{-1} product (Table 2). The wide range of environmental impacts is due to different supply chain factors, such as fish species, fishing methods, transportation, storage, or production.

Regarding the packaging, some studies included the direct impact of the primary packaging of the final product, some other studies included secondary or tertiary packaging, and then others considered intermediate product packaging. The direct environmental impact of packaging includes raw material sourcing, packaging material production, packaging production, and EoL material management. In general, it could be observed that the share of the direct environmental impact of packaging of the total impact of the food-packaging system can vary significantly within different LCA studies. The food to packaging ratio (FTP) in terms of greenhouse gas emissions of different products was compared by Heller *et al.*,[26] who reported large differences in ratio values from 0.06 to 700. Fish and seafood products were identified, besides dairy, cereals and meat as a food category with a higher FTP ratio.[27] A high ratio indicates that the impact of packaging is minor compared to the impact of a product. Therefore, changes in packaging

Table 2 Overview of RTE seafood products (or similar) environmental impacts

Product	Environmental impact category	Environmental impact [kg CO_2 eq. per kg product]	Source
Fresh seafood products (chilled)	Climate change	1.9 to 31	10
Fresh seafood products (herring to salmon)	Carbon footprint	0.7–14 (average 3.2)	20
RTE baked tuna in tomato sauce	Greenhouse gas effect	11.87[a]	21
RTE surimi (minced fish paste)	Global warming potential	1.3–7.1	22
Fresh chicken	Global warming potential	2.93[a]	23
Fresh fish: all species combined	Global warming potential	4.41	24
US beef (consumed, boneless)	Global warming potential	48.4	25

[a] Adjusted to kg CO_2 eq. per kg packed product.

configuration that lead to food waste reduction would more likely result in a net system decrease in the environmental impact, even when the packaging impact increases.[26] Almeida *et al.*[10] conducted a meta study of LCA studies by evaluating the environmental impact of packaging on seafood supply chains. The research concluded *inter alia* that packaging for seafood products presents only a small portion of around 5% of the climate change impact of products, which represents less than 1 kg CO_2 eq. kg^{-1}, and packaging represents on average 6% of the product weight. Exceptions were found when the product was packed in heavy materials, such as glass or metal.[13,16,17,28] Molina-Besch[28] investigated hotspot categories of different product groups, such as meat products, fish and seafood products and complete meals, and showed that the contribution of product primary production to the total global warming potential is high. When the contribution of packaging is low, the contribution of transport and distribution is low to medium and the contribution of EoL is low too. Additionally, the use phase can have a significant influence on the total global warming potential for complete RTE meals.

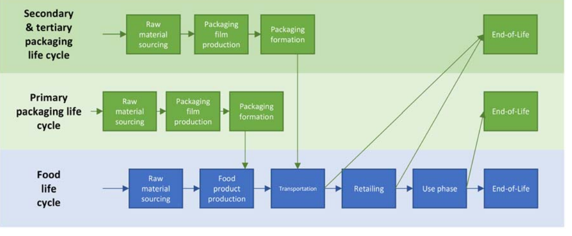

Fig. 1 Schematic overview of direct environmental impacts of food and packaging life cycle.

The investigated studies showed that the focus on food-packaging LCAs is mostly to investigate the complete food-packaging life cycle and to identify high environmental impact phases. Therefore, only direct packaging impacts were considered (Fig. 1), while the consideration of indirect impacts was more common when comparing packaging systems.

LCA studies comparing different packaging materials

In LCA studies of the whole food-packaging system, it was demonstrated that packaging contributes to only a low percentage of the total environmental impact for RTE or fish products, whereby the main environmental impact is related to the food supply chain. Nevertheless, even when the environmental impact per mass of the product is low, huge amounts of products are produced and packed, accumulating food packaging waste.[29] A comparison of packaging materials alone can support decision-making processes regarding material selection and the improvement of environmental performance. Reviewed life cycle studies focusing on packaging material are summarized in Table 3. The most comment packaging materials used for food packaging are paper and paperboard, plastics, metals and glass, in descending order of usage in weight in the EU. In the RTE market, plastic packaging is the most dominant one because it provides diverse properties and can be tailored to high product needs, such as oxygen barrier, water

Table 3 Overview of recent publications on LCAs of various packaging materials for on meat, fish or RTE products[a]

Packaging materials	Functional unit	Approach	Source
XPS closed cells, XPS open cells, XPS-EVOH, PS-EVOH, aPET, rPET, rPET-PE, PP and PLA	Tray (with/without absorption pad) with a volume of 1 L preserving 500 g meat	Cradle to gate with end-of-life approach	30
PS, PLA, and PLA/starch	10 000 units of trays with a fixed dimension (different materials have different weights)	Cradle to consumer gate	31
Composite lidding films for MAP: LDPE/EVOH/LDPE *vs.* PHA/BVOH/PHA	Amount (g) of film required for 1 kg of produce (A) with the same carbon dioxide transmission rate (B) CDTR providing the same shelf life	Cradle to grave (without packaging, retail and consumer stage)	32
PA/PE film, PE/EVOH film, PA/PE bag, PA/PE bag, PE/PVdC shrink bag, and PA/EVOH/PE shrink bag	550 cm^2 multilayer film for packaging 500 g bacon product	Cradle to grave	33
Foamy PS tray	1 kg of packed trays	Cradle to grave (raw material extraction, tray production, transportation, EoL)	34
Multilayer multi-material tray (PE/PET) Multilayer mono-material tray (PET)	1 tray with a sealed lid for sliced meat (volume: 0.54 L, 30 g) with similar properties	Cradle to grave (manufacturing films, tray production, transport, assembly and EoL)	35
PP film (commercial) Chitosan film (lab scale)	1 m^2 packaging film	Cradle to grave (material extraction, film manufacturing, EoL)	36
PHA-TPS layered material (biodegradable) PP (commercial)	1 kg of packaged product at the house	Cradle to grave	37

[a] aPET: amorphous polyethylene terephthalate, BVOH: butenediol vinyl alcohol, CDTR: carbon dioxide transmission rate, EVOH: ethylene vinylalcohol, LDPE: low density polyethylene, MAP: modified atmosphere packaging, PA: polyamid, PE: polyethylene, PHA: polyhydroxyalkanoates, PLA: polylactic acid, PP: Polypropylene, PS: polystyrene, PvdC: polyvinylidene chloride, rPET: recycled polyethylene terephthalate, TPS: thermoplastic starch, XPS: expanded polystyrene.

barrier or grease resistance. In this tailored approach, either mono materials or composite materials (blended or layered) were used. Common conclusions of the listed studies can be drawn, besides the differences in the materials investigated, impact categories, or used system boundaries. Overall, the reviewed LCA studies focused on comparing the direct impacts of the packaging materials. The selected functional units were per square meter of material, per tray or the amount of material needed for a defined product volume. Only two studies compared materials with similar properties,[32,35] allowing for the assumption of a similar product-packaging effect. Additionally, Hutchings *et al.*[32] factored in the indirect impact of packaging materials by selecting a functional unit as material thickness, providing a similar product shelf life. This approach includes direct and indirect packaging impacts and simultaneously avoids the difficulties of finding a relationship between shelf life extension and food waste reduction. The remaining challenge is to find materials with equal barrier properties and comparable other functions to allow for a fair comparison.[19]

It was shown that LCAs are useful tools for assessing the environmental influences of packaging materials, revealing high impact steps of the individual supply chains and differences between packaging materials. The main environmental impact of the packaging could be allocated to the material production and waste management process.[10] The use of recyclate or product waste streams can improve the environmental performance of packaging materials[30,35] Mono-material solutions should be preferred to multi-material solutions mainly owing to the non-recyclability of the later.[30,35] However, recyclable packaging does not directly mean the most environmentally friendly packaging because technical recycling does not automatically lead to actual recycling, especially for plastic films[28,33]. It was identified that the energy source used during production can have a significant influence on the LCA results. The use of renewable energy sources has been shown to improve the environmental performance of foamy tray materials.[31,34] Additionally, the amount of material used and weight reduction were identified as the most important factors in improving the environmental performance of food packaging. It often even outweighs possible recyclability benefits.[30,33]

Comparative LCAs can be useful tools for assessing differences in the environmental performance of packaging materials to support decision-making processes concerning a more sustainable solution or to identify improvement options. Nevertheless, due to the significantly higher impact of the product compared to the packaging, a clear priority for material selection is product protection[33] and avoidance of food waste, followed by packaging environmental performance. An LCA of packaging materials can give useful insights for developing an eco-packaging solution but also has limitations. The material LCA should be a complementary element of an LCA study in which the complete food-packaging system is investigated using a holistic approach to the decision-making process in regards to an eco-packaging solution.

LCA studies comparing different packaging systems

A packaging system can not only differ in the material but also in other design aspects, such as shape or size, *e.g.*, a tray with a lidding film, a bag, or a tube. An overview of the reviewed LCA studies comparing different packaging systems with a focus on RTE seafood products or similar products is summarized in Table 4. The reviewed LCA studies observed various packaging systems, system boundaries, and functional units and used diverse approaches to compare the environmental performance of different packaging systems. Many LCA studies focused on environmental sustainability, while only few studies included economic or social sustainability aspects such as life cycle costing analysis, consumer behaviour scenario analysis, consumer preference analysis, or circular analysis.[41,44] It was highlighted that there is a need for a balanced decision-making approach that includes all aspects, *e.g.*, using multi-component analysis. Nevertheless, the focus of this review was on LCA studies.

Functional unit selection was related to the study approaches; examples are packaging material amount, one unit of packaging system containing a specific amount of product, amount of product eaten by consumer and amount of packed product. An approach is to compare packaging systems focusing on direct environmental impacts such as material production, packaging production and EoL options.[50] However, indirect impacts based on different packaging systems were neglected. Others performed LCA studies focusing on direct packaging effects by comparing packaging systems with equal packaging properties, thereby assuming the same indirect environmental effects, such as product shelf life.[39,46,51] Schenker *et al.*[39] proposed the first approach to study the direct environmental impact of the packaging material with a functional unit of 1 kg packaging material, which can be transferred to compare the direct impact of different packaging systems with a functional unit of one packaging unit to pack a specific product amount. Another proposed approach includes indirect environmental packaging effects besides considering direct environmental impacts, as packaging not only influences the environmental impact of a food-packaging system by direct impacts but also indirectly by interacting with the food supply chain.[28] It has been discussed whether LCA studies that consider only the direct impact of packaging may lead to misleading conclusions regarding the effects of the packaging.[19,52] Indirect environmental impacts were investigated to various extents. The potential indirect environmental impacts of packaging are summarised in Fig. 2. Multiply indirect effects combining packaging system design and consumer behaviour, such as easy to empty, easy to clean, easy to separate, easy to fold, product quantity, and on pack communication information, were considered in the study by Wikström *et al.*[45] Other studies focused on a specific indirect impact, such as food loss reduction, due to shelf life extension,[38,40,43] emptiability,[41,53] content amount[19] or consumer behaviour;[43] effect on transportation and storage phase due to packaging weight and shape;[49] or effect on product preparation at the factory or the consumer phase.[46]

The challenge when considering indirect packaging effects is the quantification of the relationship between food packaging and indirect effects. Relations between packaging and indirect effects were drawn using experimental data, literature data,

Table 4 Overview of recent publications on comparative LCA studies for food-packaging systems for meat, fish and RTE products

Packaging systems	Functional unit	Approach	Impact categories	Source
Overwrap, high oxygen MAP, or vacuum skin packaging	1 unit of packaging containing 500 g of sliced beef	LCA of packaging[a] LCA of food-packaging system (food waste reduction based on empirical model)	Abiotic depletion, global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication	38
Cellulosic fiber-based stand up poaches, flexible flow wrap, food trays and moulded pulp *vs.* BOPP flexible flow wrap, OPP/PE stand up poach, PET thermoformed tray, and PP thermoformed lid	1 kg of packaging material, amount of packaging for a specific product amount	LCA of packaging material[a] LCA of packaging systems with equal protection functions for unspecified products	Climate change	39
EMAP standard, EMAP optimized and MPP	1 kg of strawberries eaten by the consumer	LCA of the food-packaging system (direct and indirect effects, mainly food waste and loss)	Acidification of terrestrial and freshwater, cancer human health effects, climate change, ecotoxicity in freshwater, eutrophication of marine and freshwater, eutrophication of terrestrial, ionizing radiation, land use, non-cancer human health effects, ozone depletion, photochemical ozone formation, resource use – energy carrier, resource use – mineral and metals, respiratory inorganics, water scarcity	40
(1) Coloured PP bottle with coloured PP cap, multilayer seal (PE/PET/adhesive/AL), and PP label; (2) clear transparent PP bottle, coloured PP cap, multilayer seal and PP label; (3) clear transparent PP bottle, coloured PP cap, multilayer seal, and paper label; (4) flint packaging glass, tinplate screw cap, paper labels	Per average consumption per capita in Austria (3.8 kg consumed product)	(A) Food loss quantification: Determination of food waste due to poor emptiability (B) LCA and LCC-VA (C) Combining the results of LCA and LCC-VA using multi-criteria decision analysis	Climate change, resource use, fossils, water use, eutrophication, freshwater, acidification, and particulate matter	41
Diverse dairy product packaging systems	1 kg of consumed product	Streamline LCA of a food-packaging system (including food waste based on packaging emptiability)	Acidification, respiratory effect, inorganics, climate change, eutrophication terrestrial and freshwater, resource use – fossils	42
XPS tray with film *vs.* high barrier vacuum skin pack	1 kg of food eaten by consumer	Food-packaging LCA (CtGr, direct and indirect effect: On food loss reduction at consumer phase) Break-even rate calculation Consumer behaviour scenario analysis	GHG emission	43
PET tray with wrapping with air headspace *vs.* tray with wrapping with MAP headspace	A tray containing two cheesecakes (total 300 g)	(A) Food-packaging screening LCA (CtGa + disposal of food and packaging, direct and indirect effects: Shelf life extension) (B) Economic and environmental-based decision making	Climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, climate change ecosystems,	44

Table 4 (*Contd.*)

Packaging systems	Functional unit	Approach	Impact categories	Source
			terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, metal depletion, and fossil depletion	
Tube *vs.* tray	1 kg eaten minced meat	Simplified food-packaging LCA (direct and indirect effects: consumer behaviour as easy to empty, clean, separate, and fold, mass, sorting information, and shelf life)	GHG emissions, acidification, ozone depletion	45
PS-based tray *vs.* Al-bowl	One tray (for one piece of poultry product) with the same function and same performance (shelf life)	Packaging LCA (CtGr, direct impact and indirect impact: energy use during cooking)	GHG emission, cumulative energy demand, climate change, ozone depletion, human toxicity, particulate matter, ionizing radiation, photochemical ozone formation, acidification, terrestrial-fresh water and marine eutrophication, freshwater ecotoxicity, land use, water resource depletion, mineral, fossil and resource depletion	46
Daypacks, glass jars, and steel cans	Packages for one ton of olives for aperitif and cooking usage	Packaging LCA (direct impact)[a]	Climate change, human toxicity, particulate matter formation, fossil depletion and ionizing radiation	47
Metal can *vs.* plastic retort pouches *vs.* plastic retort cup	A retail unit containing 80–85 g tuna	Food-packaging system (CtGr, direct impact)[b]	Total carbon footprint, greenhouse gas emission	48
Tin can, PP bag, PET bag, glass jar, PLA bag and TPS bag	1 kg of packaging material 1 kg of packed product	(A) LCA packaging material (CtGr) (B) Food-packaging LCA (CtGr, direct impacts and indirect impact: packaging weight)	Land use, fossil fuels, respiratory inorganics, minerals, carcinogens, acidification/eutrophication, marine aquatic ecotoxicity, fresh water ecotoxicity, acidification, eutrophication, abiotic depletion, global warming, terrestrial ecotoxicity, climate change, and ozone	49
PP; tin – PE; and carton – PE	Packaging unit for 1 kg cheese	Comparative packaging LCA (CtGr without consumer phase)	Cancer human health effect, respiratory effect, climate change, radiation, ozone layer, ecotoxicity, acidification potential, eutrophication potential, land use, mineral extraction, and fossil fuels	50
Glass jar, plastic pot	One baby food unit of 200 g, with equal properties (shelf-life)	Packaging LCA (CtG)	Cancer human health effect, non-cancer human health effect, respiratory effect, ionizing radiation, ozone depletion potential, photochemical oxidation potential, ecotoxicity, terrestrial	51

Table 4 (*Contd.*)

Packaging systems	Functional unit	Approach	Impact categories	Source
			ecotoxicity potential, terrestrial acidification, land occupation, acidification potential, eutrophication potential, global warming potential, non-renewable cumulative energy, and metal depletion	
PE/PP/PA/EVOH, Carton/PE/EVOH, APET/EVOH/PE, PE/EVOH/PET	1000 kg of each product consumed by the consumer	Food-packaging LCA (direct and indirect impacts)	Climate change, eutrophication potential, and acidification potential	19

[a] LCA of packaging: material production, packaging production and EoL. [b] AL: aluminium, BOPP: biaxially-oriented polypropylene, CtGa: Cradle to Gate, CtGr: Cradle to Grave, EMAP: equilibrium modified atmosphere packaging, LCA: Life cycle assessment, LCC-VA: life cycle costing – value added, MAP: modified atmosphere packaging, MPP: macro perforated packaging, OPP: oriented polypropylene, PE: polyethylene, PET: polyethylene terephthalate, PS: polystyrene, PLA: Polylactic acid, TPS: thermoplastic starch, XPS: expanded polystyrene.

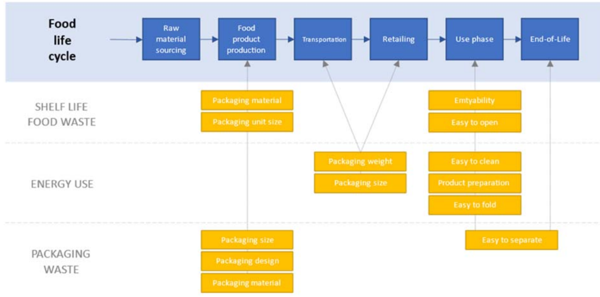

Fig. 2 Schematil overview of indirect environmental packaging impacts on food waste, energy use and packaging waste, and the site of action in the food life cycle.

mathematical models or consumer surveys. Another approach was the investigation of the break-even point or trade-off situation. Heller *et al.*[26] calculated the relative increase in packaging system impact in two impact categories that could be afforded by a hypothetical food waste reduction of 10% based on the food waste rate estimated by the U.S. Department of Agriculture. Wikström *et al.*[54] concluded that a 1% reduction of red meat waste allows a threefold increase in the packaging impact without increasing the climate impact of the entire product-packaging system. The packaging in this study only contributed to 0.3% of the GHG emission of the product. A model for the calculation of trade-offs between product protection, packaging environmental footprint, packaging recycling, and FLW was presented by Williams *et al.*[55] A consumer survey of Swedish households determined that 20 to 25% of household food waste was related to packaging design attributes, including the attributes easy to empty and containing the correct quantity. When such attributes are considered from the standpoint of reducing food waste, the potential of packaging to improve system environmental performance may be achieved.[26] In relation to seafood or RTE products, further studies about the relationship between the effect on food packaging and product waste are needed.[10]

In addition to the variations in LCA studies comparing different packaging systems, it can be summarized that different conclusions about the sustainability of packaging systems can be drawn when only direct environmental impacts or both the direct and indirect impacts are considered. When only direct packaging impacts were reviewed, design options to reduce material amount, improve transportation, or switch to light weight options can have a higher positive environmental effect. When additional indirect effects were included, other packaging systems were favoured. Packaging systems with the highest preservation properties often permit the lowest food loss and lead to the lowest environmental impacts, especially for high-impact food groups. The use of highly functional packaging systems was often justified by the counterbalance between higher direct environmental impacts and indirect impacts, such as food loss reduction or energy savings (break-even rate). In addition to the importance of indirect effects, it was shown that consumer behaviour and economic aspects were important when assessing the eco-design of packaging systems. Ignoring consumer behaviour and preferences during packaging selection and only focusing on environmental aspects can be difficult to be suitable in the real market. Overall, it was highlighted that there are different important aspects in the LCA of packaging systems, such as packaging weight, packaging functionality (format options), energetic mix used in the supply chain, logistics, food waste reduction, household waste collection system, selection technology for waste treatment and EoL options, such as recycling and incineration with energy recovery. Therefore, to identify eco-design packaging options, it is important to study the present individual case scenario.

LCA studies with alternative packaging systems

The identified studies with innovative and novel packaging systems are summarized in Table 5. The studies were reviewed with a focus on the investigated packaging system, the used functional unit, and the applied approach. The studies investigated different types of alternative packaging systems, including active coatings applied to packaging films,[56,57,60,62,63] smart-active packaging,[57] and packaging with active nanoparticles.[58,59,61] Similar functional units were selected based on a defined packaging unit for a specific amount of product, but different approaches were used to study the environmental effects of alternative packaging systems. Only direct impacts of packaging systems were compared,[60,61] a food-packaging system LCA approach including the indirect effects was applied,[59,62,63] or both approaches were combined.[56–58] Additionally, Venkatesh *et al.*[60] combined economic and environmental aspects for a broader approach. Different strategies were used to include indirect packaging impacts. Stramarkou *et al.*[57] studied different waste reduction scenarios from 30% food waste generation with conventional packaging, and for the alternative packaging system, food waste production of 5, 10 and 20% was assumed. Zhang *et al.*[59] used a survey approach to generate a relationship between shelf life extension and food waste. Zhang *et al.*[62] calculated the break-even point to estimate the minimal required waste reduction of the tested alternative packaging systems for four impact categories, including global warming, fossil energy demand, acidification potential and eutrophication potential. In addition, the different approaches adopted in the analysed studies agreed with their main conclusions. In nearly all the studied cases, the additional packaging material increased the environmental burden of the packaging, in which the amount depended on the additional material needed. Nevertheless, when the product-packaging system or the indirect impacts of the alternative packaging systems in regard to shelf life extension and food waste reduction were considered, all alternative packaging systems showed an overall reduction in the studied environmental impact categories. The effect depended on the packed product, as demonstrated by Zhang *et al.*[59] with an off-set of negative impact of 2.3 times for fresh fruits and up to 112 times for processed meat. It was highlighted that an important advantage of using

Table 5 Overview of LCA studies with alternative packaging systems[a]

Packaging system	Function unit	Approach	Source
Bioactive bag (PE coated with active coatings: PVOH and nisin producing LAB) *vs.* conventional PE bag	Bag with a capacity of 200 mL (or 218 g pastry cream)	LCA of packaging LCA of the food-packaging system	56
Active packaging (OEO) and sensor *vs.* conventional packaging	Packaging container for about 10 kg of sensitive food product	LCA of packaging LCA of the food-packaging system	57
PLA-coated film with NP (ZnO) *vs.* PP-coated film with NP (ZnO) *vs.* PP film	Packaging unit for 130 g of fresh cut lectures	LCA of packaging LCA of the food-packaging system	58
Four nano-packaging systems for different food products	Amount of packaging to pack 1 kg of food product	LCA of food packaging-system with a trade-off calculation and a consumer study to investigate the relationship between food waste and shelf life extension	59
Packaging film (PE) with alternative barrier coatings: Starch based, latex + kaolin, EVOH + kaolin PE	1 kg of films with the same functionalities	Partial LCA of packaging with a focus on production and end-of-life	60
PLA + silver NP, PLA + titanium dioxide NP, PLA + mixture of both	1 kg active packaging material that provides equivalent effectiveness to ensure food safety and quality	LCA of packaging	61
Conventional MAP packaging (PP/EVOH) *vs.* PP/EVOH + active coating (thymol/carvacrol)	Packaging unit for 1 kg fresh beef	LCA of a food-packaging system (with a focus on food waste)	62
Tetra top beverage container coated with active coating *vs.* Tetra top beverage container	1 L of consumed milk	Food-packaging system (with a focus on food waste)	63

[a] EVOH: Ethylene-vinyl alcohol-copolymer, LAB: lactic acid bacteria, NP: nanoparticles, OEO: oregano essential oils, PE: polyethylene, PLA: polylactic acid, PP: polypropylene, PVOH: polyvinyl alcohol, ZnO: zinc oxide.

alternative, novel packages was higher product protection, which should also be valued when assessing the environmental impact. Including the shelf life extension is a decisive aspect when assessing the environmental impact of novel packages. Besides, the challenges regarding waste estimation should be considered in all assessments of packaging solutions.[56,58,63]

Summary and perspectives

Life cycle assessment is a tool to support the decision-making process for improving the environmental impact of packaging. Only packaging reducing the environmental impact of the commercial or currently used food-packaging system is a better solution for the environment, assuming that other core requirements such as product protection, transport and communication are assured. This review emphasizes that approaches taken to investigate the environmental performance of packaging can vary and support different developing stages.

(A) Packaging can be investigated as an integrated part of the food supply chain, indicating the environmental fraction of packaging in the whole food-packaging impact. Moreover, the focus was often on direct packaging impacts, such as raw material sourcing, packaging material production, packaging production, and EoL management. For products with a high environmental impact, the impact of the packaging represented only a small fraction of the overall environmental impact. This emphasises, the importance to protect the product and ensuring it is used as nutritional source for consumption instead of ending as waste, therefore accumulating all environmental impacts of the supply chain without any use, which represents the worst-case scenario. Nevertheless, even when the portion of packaging units' environmental impact on high-impact food products is small, it should be considered that the accumulated environmental impact of the required packaging units and their waste accumulation impact can be huge. (B) Consequential LCA of packaging materials can be a useful tool for selecting the most appropriate material, *e.g.*, comparing a mono-material with a multilayer material. In this category, different approaches were considered: only the direct effects of the materials were compared, or studies were designed to compare materials with potentially similar indirect effects, such as providing the same shelf life. The latter comes with more hurdles but provides a more realistic outcome. These approaches focus on the packaging material and can be extended by additionally considering the food-packaging system, *i.e.* the third approach (C). Having the advantage that a more holistic decision can be made. LCA comparing different packaging systems often included indirect packaging impacts in addition to direct impacts. However, quantifying the relationship between food packaging and the food supply chain can be challenging. Additionally, studies often focused on specific indirect impacts, whereas fewer studies with multiple indirect impacts were published.

By reviewing LCA studies of novel packaging systems, it could be observed that when only considering the direct environmental impact, the novel packaging systems have a higher environmental impact; therefore, including direct impacts is important. When including direct impacts, the environmental advantages are on the side of the novel packaging system mostly due to waste reduction resulting from shelf life extension. Overall, it was highlighted that besides the reduced environmental effect, consumer preferences concerning the novel food packaging system should also be included when selecting the packaging.

In conclusion, different LCA approaches were considered, and each one covered a specific goal. By observing the selected categories, such as sequential steps, a holistic understanding of the environmental impact of novel food packaging can be achieved. A clear understanding of the impacts and benefits of innovative packaging systems is an important driver of successful and sustainable innovations.

Data availability

No primary research results, software or code has been included and no new data were generated or analysed as part of this review.

Author contributions

I. B. conceived the work, conducted the literature review, data extraction and drafted the manuscript. M. S. G. edited, developed and approved the final version.

Conflicts of interest

There are no conflicts to declare.

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